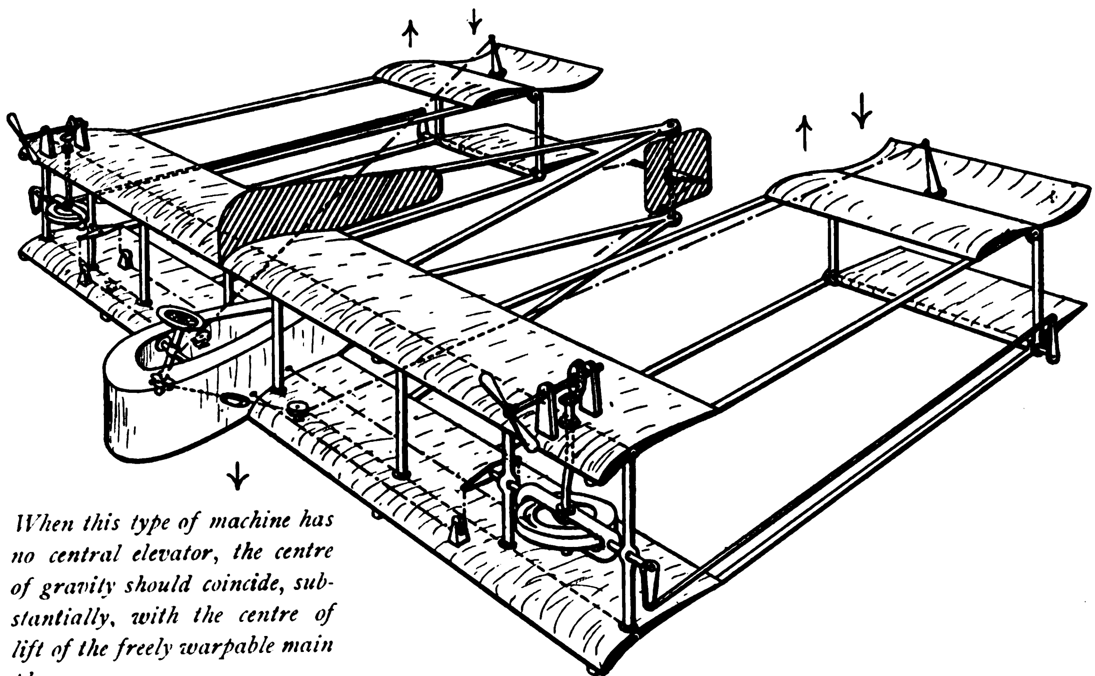
AEROPLANES IN GUSTS.

SOARING FLIGHT

AND THE

STABILITY OF AEROPLANES



When this type of machine has no central elevator, the centre of gravity should coincide, substantially, with the centre of lift of the freely warpable main planes.

Walkden, Aeroplanes in Gusts.] [*Frontispiece.*

A NEW TYPE.

(*See p.* 237 *and* "*Frontispiece*" *in the Index to Supplement.*)

AEROPLANES IN GUSTS.

SOARING FLIGHT
AND THE
STABILITY OF AEROPLANES

BY

S. L. WALKDEN

SECOND EDITION GREATLY ENLARGED

FOUR PLATES
SEVENTY-EIGHT ILLUSTRATIONS

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CONTENTS

SUPPLEMENT ON LATERAL STABILITY

ERRATA AND ADDENDA.

Page vi. *Against* "Automatic Wheeling Soaring" *read* "page 105."

Page 200. By "centre of lift," in the fifth line, is to be understood the centre of lift of the main planes, before the addition of the lifting planes M_1 M_1.

Page 216. At the end of line 7, *for* "$V^2{}_f/a$" *read* "V_f^2/a."

Page 229. In the last line but one, *for* "Vf" *read* "V_f."

Page 237. Make the end of the first footnote read, "by *the pilot*. (See pp. xiv, xv of Preface.)"

Page 250. Among the preventives of slow and permanent changes of lateral pose include side fans or manual equivalents operating lateral elevating planes placed behind warpable wings, as exemplified in the illustration on page 261.

Page 260. In the first line, *for* "affecting" *read* "effecting."

To face p. viii. Walkden, Aeroplanes in Gusts.

S. L. W.
August 1913.

to justify the delay that their removal would have entailed in issuing this edition and its supplement. In addition to such reasons, the author is actually desirous of having the original matter, and even its shortcomings (which it is felt certain cannot embarrass the reader), remaining on record for the present.

FACE TO THE SECOND EDITION

by itself, it is very gratifying to the author k, that a new edition, containing the con- at was foreshadowed on page xix. of this copy ıal preface, and in the footnote remaining at of page 8, should be so soon in demand. The ry educational value" of the book proved so ry that, in circumstances that are amusing ble, according to the point of view, the led mode of longitudinal stability, in which isturbance of pose is prevented by the use ard mass effect, became almost universal thin a month of the book's publication.

edition a new frontispiece has been added, iginal one has been made to face page 20, "Errors," "Additions," and "Notes" of the have been embodied in the text. In every ect, however, this edition is, as far as page ical with the first edition, for there appeared errors of sufficient importance to the reader the delay that their removal would have n issuing this edition and its supplement. In add... n to such reasons, the author is actually desirous of having the original matter, and even its shortcomings (which it is felt certain cannot embarrass the reader), remaining on record for the present.

In view of a few slightly misleading criticisms of the book, the reader is advised to peruse the first chapter carefully enough to notice and understand that the "acceleration of headway" in the definition (page 2) of the strength and direction of a gust, is the stated *impressed* acceleration of headway, and not necessarily the actual acceleration of headway. The distinction between an impressed acceleration and a real acceleration is made clear on pages 3 and 4, but the proper use made of the two in the subsequent pages is likely to lead to a still clearer understanding of the distinction.

In connection with Chapter II., the path of the machine relative to still air is always determined by the constants of mass and resistance of the machine, the strength and direction of gravity, and the initial conditions of the launching. Chapter II. takes that for granted, but adds the knowledge that, in a gust, the strength and direction of the dynamical representative of gravity, in the relationship of the machine to the air, are virtually changed, and the behaviour of the machine is changed accordingly, but, at every instant, quite conformably to its usual behaviour in still air and to its ordinary constants of mass and resistance.

One critic, after regarding dubiously the fundamental postulates, says, grudgingly for such a subject, the author "*may* have obtained correct results in connection with wheeling soaring." This is a very obscure and amusing form of criticism; if the postulates are wrong (which they are not), there would hardly be one chance in a thousand, in a subject like soaring, of obtaining correct results by their aid. The author is reading "has" for this critic's "may have."

In one criticism of the book, Prof. Bryan has remarked, irrelevantly, that "it is quite legitimate in the problem of the man in the mine cage or steam roundabout to compound the acceleration of gravity with an acceleration equal and opposite to that of the cage or roundabout car in order to obtain a result which will determine the pressure of the man on the supporting floor, because in this case the man and car move together and therefore have the same acceleration."

Since this book itself says as much, the author would not for one moment dispute the above with Prof. Bryan, provided he limits the case to the man being in rigid contact with the floor of the cage, and leaves out the extraordinary clause "*because* in this case the man and car move together and *therefore* have the same acceleration." In that Prof. Bryan is wrong.

Things moving together have the same velocity, but unless they are rigidly attached, their accelerations are not necessarily related to their velocities. For instance: a weight allowed to drop in a mine cage obviously has the same velocity as the cage at the moment of its (the weight's) release, but it has a very different acceleration. Prof. Bryan has only to study the case of a man suspended by a spring in the cage, to realise the error of his qualifying clause. The readiest way of studying this last case is to use the ordinary oscillation formulæ with g replaced by the new g obtainable by compounding the acceleration of gravity with that of the cage. Even a grandfather clock in the accelerating mine cage alters its rate and performs exactly as if gravity had altered in strength.

I would forbear from returning Prof. Bryan's delicate compliments, but it does appear that, in that clause, at least, he has wandered into the company of the "weak examinees" he alludes to.

Chapter VII., on "Mechanical Analogies to Soaring," has interested many, but some friendly criticism leads the author to point out that the *complete* enclosure of the air in the tramcar of fig. 26, II., is not to be overlooked. There is, of course, no intention of associating the free air of the atmosphere with the phenomena described as taking place in the closed tramcar; the tramcar is only a convenient box to give, at will, certain accelerations to a definite bulk of air, and so counterfeit, for experiments, the arbitrary accelerations normally existing as gusts in the free atmosphere.

For the flattering and wholly appreciative criticisms that have appeared, and that suggest nothing to amend or explain, the author would like to tender his sincere thanks, and express the hope that the present extensions will merit the same approval.

The appendix on Aviation Disasters is now of obsolete interest as regards the formerly frequent "Disasters Caused by an Inverse Stable Attitude" (pages 164 to 168). A month after the book was published there were no machines being constructed, except here and there by unsophisticated amateurs, that had not their centres of gravity designed so far forward that their inverse centres of pressure had no opportunity of keeping in front of the centres of gravity. Almost all the disasters that now occur are of the type caused by "front-heaviness" (page 164), when the pilot, through inattention or indisposition and absence of a spring and slow-fan, relaxes the substantially constant pull on his elevator control lever.

The universal forsaking of the old type of machine for the new out-of-balance type has, however, raised the number of miles flown per fatality from about the order of magnitude of 10,000 miles to something exceeding 100,000 miles, and has correspondingly increased the amount of, and enthusiasm for, flying. The further developments now recommended in this edition, though more difficult to apply by rule-of-thumb methods, ought, before very long, to raise, similarly, the 100,000 miles per fatality up to 1,000,000 per fatality, and correspondingly increase, again, the number of men who are able and willing to fly, and the enthusiasm for flying.

The leading feature of this edition is the Supplement on Lateral Stability, commencing at page 189, which, without being tediously exhaustive, deals with its subject, it is believed, in a logical, practical, and sufficiently conclusive manner. Attention is directed to the superior type of machine that results from this study of the problem, and illustrated diagrammatically in the frontispiece; for it is a type that has a great future before it. It is, in fact, as superior to the machine of to-day as that is superior to the machines that were flown in this country up to a few weeks after the book was first published in the autumn of 1912. The strength required in personally controlling that type of machine, so far as it need be designed to require any personal control at all beyond guiding, is so slight, that there is likely to be seen, very soon, a large increase in the size and weight of aeroplanes, especially those used for military and naval purposes.

Reading through the text of the supplement, too late to have it extended, the remarks made on the upper half of page 237 appear too brief; they may excite curiosity without satisfying it. The result of not connecting the two gyroscopes, and so leaving them to tilt independently, is that when purposely executing, for example, a sharp right-hand turn, the aviator finds the left-hand gyroscope trying to tilt itself, and its elevating plane, right over through 180 degrees, and finds it doing even that not consistently, but tilting forward or backward according to whichever way it happened to have a slight initial tilt when the aviator commenced the turn. Needless to say, this action dangerously disorganises the flight. At the same time, the other gyroscope tries to set itself without any tilt—a less dangerous action, but, nevertheless, one which may not at the moment be required. When the two gyroscopes are cross-connected, they exactly neutralise each other's objectionable tendencies of this character, and so permit any turning or steering desired. If a machine had not to turn to either side, but had only to fly substantially straight forward, one horizontal gyroscope would usually suffice for the lateral control.

There is another point not explained in connection with these gyroscopes, and that is that, although horizontal gyroscopes as shown are preferable to other arrangements. the fundamental requirement is that the axle of each gyroscopic wheel shall normally be substantially at right angles to a line drawn parallel to the longitudinal axis of the machine. Accordingly, vertically revolving gyroscopes, edge-on to the direction of flight, can be employed to operate the auxiliary planes, although they have some disadvantages. These gyroscopes, again, had better be in pairs, and cross-connected, this time to prevent disturbance by pitching movements of the machine.

With regard to a gyroscope for longitudinal control, that must, theoretically, have its axle substantially at right angles to a line drawn parallel to the transverse axis of the machine, and have the journals of its containing frame in a plane parallel to the plane of symmetry of the machine; but according to whether these journals are normally in a vertical line or a horizontal line with respect to the machine, lateral tilting or lateral steering of the aeroplane will, respectively, disturb the gyroscopic longitudinal control unless, as is advisable, a pair of oppositely rotating and cross-connected gyroscopes is again employed.

Wind-driven gyroscopes always take some little time to acquire their full speed and full controlling power, but no real inconvenience ensues, as personal control is always expected in starting a flight.

Another feature of this edition is the frequent reference to the author's patents, and the printing of the British Specifications at the end. This is justifiable because many readers are presumably so interested in the industry, that it is essential for them to know what, and to whom, protection has been granted in the new line of development now being initiated. The pages at the end devoted to some information supplied to the British Government should prove of similar interest. Needless to say, all new features of design that are disclosed are adequately protected by patents.

S. L. WALKDEN.

August 4th, 1913.

PREFACE TO THE FIRST EDITION

THE object of this book is to convey substantial information upon the elements of the subjects included within its title, and remove them from the domain of speculation and empiricism into the domain of scientific deduction from established principles.

The mathematics, which some pages of the book may appear to contain, will, on inspection, be seen to be hardly more than symbolic arithmetic; and, moreover, owing to the use made of graphical constructions, the physical meanings of the steps of the arguments may often be followed quite independently of the quantitative work.

Since progress in all the sciences has depended, as is well known (though the knowledge is not always applied), upon satisfactory measures being employed for the quantities concerned, the very first duty of this work is to state, in Chapter I., a suitable measure of a gust, or, in other words, the "how much" of a gust. That done, a great part of the rest of the book is mere routine work, that, for academic purposes, but not without sacrificing the simple pioneer character of the book, could have been carried much further into details.

In Chapter II., the principles underlying disturbances of pose by gusts are presented in the most general manner conceivable, so that, however much designers may differ as to the precise means of making their machines react to the gusts to avoid disturbance, the character of the necessary reactions should be regarded as placed beyond controversy and individual opinion.

In Chapter III., the interesting subject of soaring flight is entered upon. Now this subject seems, for some reason, to have placed itself in a false position. Possibly the reason is that the early students and writers, in the days when flying—for reasons since justified—was taboo, could not attract attention, or excuse their own interest, except by showing an innocent tendency to marvel in places. These easily read, but unimportant, portions of their writings seem to have induced a popular impression that here was a phenomenon which could not be explained by orthodox methods, and, as a result, anyone who believed in some new kind of radium, in moonshine, anti-gravitating substances, hydrogen-filled bones, electrical repulsions, animal magnetism, aspirations, forward components, and so on, as the cause of soaring, readily obtained publicity and an attentive hearing for his opinions.

Now those qualified, even in the most modest degree, to have an opinion, are in agreement that the irregular movements of the air, or Prof. Langley's "internal work of the wind," are the sources of soaring. The principal room for discovery consisted, therefore, in the way of presenting the *details* of the bird's operations, in a sufficiently simple and convincing manner, and it has been in the difficulty of doing *this* that the so-called "mystery" of the subject really lay. The present work, it will be seen, finds in the adoption of acceleration as the measure of a gust, and its graphical representation by vectors, a means, or intellectual tool, whereby the elucidation of hitherto obscure details of soaring may be carried out in a somewhat comprehensive and conclusive manner.

In Chapter XII., appliances are described which react to the gusts in the manner that Chapter II. and the subsequent chapters show to be necessary for stability and soaring. The results already obtained on full-size machines, with rough partial applications of these appliances, almost surpass belief, and they are still in course of development.

Since the first thirty-three figures, or illustrations, are more or less related to each other and referred to throughout the book, it has been thought better to group them together in plates, at the end, to facilitate reference and comparison.

The word "relative" is a much-used word[1] in the book, but, notwithstanding its frequent occurrence, it is many times left to be understood. The general failure to recognise that all the quantities of mechanics—position, displacement, velocity, acceleration, momentum, force, and energy—involve the principle of relativity is apparently one of the stumbling-blocks in the study of aviation. As a recent example: In one of the flying journals published only a few days ago, the question of the momentum of a flying machine is suggested to have been a worthy subject of profound technical discussion by those to whom the public may be looking for a lead in these matters. Leaving to oblivion the characteristic opinions that defined the momentum as a "force," there remains the question,

[1] Used, it may be noticed, more as a term than as a word.

—What is the momentum of a flying-machine? The answer is simple, even obvious:—The momentum is the (mass × velocity relative to the ground) or the (mass × velocity relative to the air) according to whether the momentum relative to the ground or to the air is required. If the machine is about to collide with a hill or house, the former momentum concerns the aviator; if flying freely in the air, or involved in a gust, the latter momentum concerns the aviator.

In the ordinary teaching of elementary mechanics, it appears that the student is implicitly allowed, for convenience, to regard the ground as being in a state of absolute rest, in one problem after another, until he forms the working impression that the reference to the ground is always of an absolute and essential nature. The problems of the flying-machine are among the few likely to betray his error, and also, as it happens, give such student the uncomfortable and false impression of having to learn fresh mechanics. For these reasons, it is just possible that the most instructive problems an up-to-date text-book of mechanics could contain would be those connected with flight, particularly soaring flight.

The book is not at all a compilation, and dealing, as it does, almost entirely with disturbed-air phenomena, it is intended more to supplement than supersede good existing books on the theory of the aeroplane. Chapter XVI. alone shows a tendency to revert to the well-worn groove, but it is hoped the Lift Diagram of fig. 44, in being a new contribution, is sufficient justification. Moreover, a corrective to some current views of "natural stability" is certainly demanded in the cause of truth and progress. In insisting on the attitude with respect to the trajectory not being confused with the consequent direction with respect to the horizontal, the author is only recalling, as seems so strangely necessary, the sense of § 4 of Mr Lanchester's *Aerodonetics*. The rate of diffusion of truths in aviation is, however, so very slow that there must be some impediment somewhere. No doubt it will be disclosed or removed with time.

S. L. WALKDEN.

September 3rd, 1912.

SYMBOLS

THE following symbols are used consistently, and with the assumption usually made that the reader knows what they stand for. The number of the page where each symbol is first introduced, or most importantly used, is placed in brackets after the explanation of each symbol.

R = The radius, in feet, of the bird's or aeroplane's orbit relative to the air. (Pages 14, 18, 19.)

T = The time, in seconds, of each complete circle described by the air, bird, or aeroplane; or, in other cases, the time of a gust cycle consisting of a head gust and return gust. (Pages 17, 23, 27.)

V = The ordinary gliding headway, usually in feet per second. In other words, it is the velocity relative to the air during a steady glide. In some places, where no confusion can exist, this symbol is used instead of V_a or V_f. (Pages 12, 19.)

V_a = The actual headway, in feet per second, of a bird or aeroplane in other flights than the ordinary steady gliding flight. (Page 19.)

V_f = The headway, in feet per second, of a glider, when flying steadily and horizontally in straight *driven* flight. (Page 21.)

a = The acceleration of the air denoting, at a given instant, the strength of a gust. In some cases it is used for other stated accelerations. Usually in feet per second, per second. (Pages 16, 17.)

a_1 = The acceleration of a bird or aeroplane relative to the air. Usually in feet per second, per second. (Page 38.)

a_d = The difference of velocity of two air particles, at a given instant, one foot apart in the flight path. Usually in feet per second. (This is, in the limit, the instantaneous dv/ds at a point in the flight path.) (Pages 45, 46.)

a_m = The maximum acceleration, of the air, denoting the maximum strength of a harmonic gust. Usually in feet per second, per second. (Pages 23, 25, 28.)

g = The acceleration due to common gravity. Feet per second, per second. (Page 15.)

h = The vertical change of height of a soaring bird. In feet. (Pages 24, 28.)

k = The mechanical strength factor of safety of the wings of an aeroplane. (Page 162.)

k_1 = The ratio of the maximum thrust or torque, producible by the engine, during a flight, to the torque or thrust required in the ordinary straight level flight. It may be called the "thrust factor." (Pages 162, 163.)

n = The cotangent of the ordinary gliding angle of a bird or aeroplane. In other words, the n of the gliding path when the latter is said to be at a slope of "1 in n" with the horizontal. (Page 16.)

n_e = The *effective* n of a bird or aeroplane while circling and banked. It is shown to equal $n \cos \zeta$. (Pages 18, 19, 163.)

r = The radius, in feet, of the path of the air particles of a soarable wind. In other cases, the full displacement, each way, of a harmonic gust. (Pages 17, 19.)

s = A displacement or distance, usually in feet. Often used for the distance moved under the influence of an acceleration. (Pages 32, 38.)

t = Time, usually seconds, used variously. (Pages 24, 28, etc.)

v = Velocity of the air or wind. Usually in feet per second. (Page 21.)

v_m = The maximum wind-velocity fluctuation, to each side of the mean, in a harmonic gust. (Pages 26, 30.)

α = The angle, in degrees, the trajectory or flight path makes with the horizontal. (Pages 114, 148.)

β = The angle, usually in radians, through which the relative gravity is tilted with respect to the true vertical. (Pages 24, 28.)

γ = The ordinary gliding angle, usually in degrees, of which n is the cotangent. (Page 21.)

γ_e = The *effective* gliding angle, usually in degrees, of which n_e is the cotangent. (Fig. 11.)

ζ = The banking angle, in degrees, or angle which the transverse axis of the bird or aeroplane makes with the horizontal. (Page 18.)

ϕ = The angle of friction, or angle of repose, for solids sliding on solids. It is the angle which has μ, or the coefficient of friction, for its tangent. (Page 60.)

ω = Angular velocity, or $2\pi/T$. (This concerns the general expression for centripetal acceleration,—radius $\times \omega^2$.) (Page 19.)

A SPECIAL TERM.

Headway:—This term is employed specifically for the velocity of the flying body relative to the air. (Page 2.)

NOTE.

Positions, displacements, velocities, and accelerations *relative* to the ground are, for convenience, usually distinguished as *absolute* positions, displacements, velocities, and accelerations, respectively.

ADDITIONAL SYMBOLS IN THE SUPPLEMENT

K_1, K_2, K_3, etc. = The supporting effect of a surface moving at unit headway. Usually in lbs. for a headway of one foot per second. (Page 211.)

M = Twice each lateral stabilising mass, in lbs. (Page 227.)

P_2, P_3, (see fig. 67, page 232, and the text on page 233).

d_1, d_2, d_3, (see fig. 67 and the text on page 232).

r_1, r_2, etc. = Distances in feet from the longitudinal axis of the machine. (Page 210.)

ω_1 = Angular velocity of spin of the gyroscopic flywheel. (Page 232.)

ω_2 = Angular velocity of lateral tilt of the aeroplane. (Page 232.)

AEROPLANES IN GUSTS.

SOARING FLIGHT AND THE STABILITY OF AEROPLANES.

CHAPTER I

INTRODUCTORY—THE MEASURE OF A GUST

UNTIL within the last few months the literature of the theory of flight dealt almost exclusively with flight in still air, regardless of the fact that the real problems are concerned with flight in disturbed air. Even on the few occasions when gusts were referred to, the necessity for first defining a proper measure of the gusts, before reasoning about their actions, did not seem to be realised. Generally, the gusts were referred to as instantaneous alterations, of considerable magnitude, in wind velocity; but nothing can have its velocity changed at an infinite rate, and such an artificial conception of a gust, though not always useless, is often misleading.

The proper measure of a gust, as regards a body immersed in and supported by the air, is undoubtedly the acceleration tendency of the air with respect to the body; and while this proposition can be quite easily independently supported, the best argument for its truth is the orderly manner in which it explains all the questions connected with stability, stresses, and soaring flight, in disturbed air.

The adoption of acceleration as the measure of a gust was first advocated by the author in a simple article, "Aeroplanes and Gusts," published in *Flight* of 5th August, 1911,—an article that was an abstract of a much longer and more complete article previously submitted to the same paper on 7th May.[1] Its general adoption by those who debate flight phenomena from the technical standpoint is now so complete that the time is ripe for publishing the simpler uses to which the proposition may be put, independently of explaining it at length, or defending its truth.

Using, therefore, the term "headway" in place of the cumbersome "velocity relative to the air," it will be taken for granted the reader knows, that:—

> (1) The instantaneous *strength* of gust at any point of the air, as regards a given flying machine flying at that point, is measured by the acceleration of headway which any singularity of the air at that point is impressing upon the flying machine, and the *direction* of the gust is opposite to the direction of the impressed acceleration.

For example:—If the air is accelerating downwards at 40 ft. p.s. p.s., it is impressing upon the flying machine an upward acceleration of headway of 40 ft. p.s. p.s., and this is the measure of the downward gust. In other words, the gust is of strength 40 ft. p.s. p.s., downwards. Simple velocity, as distinct from rate of change of velocity, is, it will be

[1] It dealt with figs. 1 to 4, the phenomena in tramcars (fig. 26, II.), and other matters of the present work.

noticed, completely ignored. Now, acceleration has magnitude and direction, and being, in consequence, a vector quantity, it may be represented completely by a straight line of corresponding length and direction drawn to scale on a sheet of paper. Therefore, we have :—

> (2) A gust may be represented by a straight line of length and direction corresponding, respectively, to the magnitude and direction of the gust.

In the above example, a line 4 inches long, drawn downwards, will represent the gust completely on a scale of 1 inch = 10 ft. p.s. p.s., and the same line measured upwards is the impressed acceleration of headway. The impressed acceleration is what we usually want to know, and when it is known before or independently of the gust, the latter often escapes mention.

Again, in the above, the downward acceleration of the air is only the most convenient example of the production of the impressed upward acceleration of headway; and by "impressed acceleration" is meant not necessarily an actual acceleration, but an acceleration tendency, just in the same way that gravity is a perpetual impressed acceleration or acceleration tendency for a flying machine or other body though the actual acceleration is rarely in accordance therewith. An impressed acceleration, however, always becomes a real acceleration when there is none other operating upon the body at the same time.

The inkwell on the desk before the writer is at rest. Everyone knows sufficient graphic statics to draw the balanced forces and explain why it remains at rest. But, what may be called "graphical dynamics" may be used instead; that is to say, the inkwell may be regarded as remaining at rest in consequence of its having a downward impressed acceleration due to gravity, and an equal upward acceleration due to the reaction of the desk. The dynamical point of view is really more fundamental than the statical one, and, though cumbersome and unnecessary in ordinary engineering problems, it greatly facilitates the understanding of many flight problems.

The general method for finding the impressed accelerations acting at a given instant upon a flying machine consists in first answering the question:—

> If, at the given instant, the flying machine could be suddenly transformed to a small, smooth, concentrated mass, how would it accelerate relatively to the air?

The acceleration answering the above question is the "resultant relative gravity" of the following discussion, and when common gravity is subtracted, *in vector sense*, the result is the acceleration tendency or impressed acceleration due to the gusts. When, from this result, the impressed acceleration due to the absolute acceleration of the air at the place of the flying machine is also subtracted, *in vector sense*, there will usually be found an impressed acceleration remaining. This is due to the air having what is called "velocity structure" at the point, and to the flying machine, in crossing that structure, creating for itself a rate of change of headway.[1] The measure

[1] See also Mr Lanchester's *Aerodonetics*, p. 253, where the alteration of air velocity from place to place is referred to as a source of soaring.

of this "structure gust" is again acceleration, not velocity; but the fact that the gust is strengthened in proportion to the machine's headway is commended to the notice of those who consider high speed the certain means of improving stability. Their view may not be incorrect, but structure gusts must be admitted into the opposing argument.

CHAPTER II

AEROPLANES IN GUSTS

A Horizontal Head Gust

Let A (fig. 1) be the position of the aeroplane *relative* to the air. Draw AB downwards 32·2 units in length to represent common gravity, and CAC_1, at right angles, to represent the true level with respect to which the self-righting aeroplane flies to the left in still air. Assuming the sudden gust of the example to be 40 ft. p.s. p.s., draw DB, 40 units in length, to represent the gust, so that BD represents the opposite impressed acceleration of headway due to the gust. Draw AD to complete the triangle of accelerations ABD. Then AD, being the resultant acceleration tendency *relative to the air* during the gust, entirely supersedes AB in controlling the flying of the aeroplane, on which account it is called the "resultant relative gravity" during the gust. Similarly, FAF_1, at right angles to AD, supersedes CAC_1, on which account it is called the "virtual level" during the gust. The flying *relative to the air* now proceeds exactly as if gravity had been tilted through the angle BAD, and increased in strength from AB to AD. But, just at the moment, the aeroplane is flying steeply down AC with respect to AD and AF; it proceeds, therefore, to pursue the familiar undulatory righting path AH with respect to AF, unless well damped, as it should be, in which case the path may be improved to resemble AI. If the gust grows slowly in strength, so that D moves out slowly through the harmonically placed positions 1, 2, and the virtual level through the corresponding positions 1, 2, the righting path AI is further improved to the more slowly curving path AJ. *The greatest possible improvement, however, occurs when the self-righting tendency of the aeroplane is momentarily abolished, or even reversed, at the onset of the gust.* The path AI may then be changed to resemble the very satisfactory path AL. Means of doing this are now known. (See Chapter XII.)

In interpreting gust disturbance, by means of the relative gravity diagram, it is always a good plan to view the diagram along DA, so that AD may be really thought of as gravity. Since the disturbance of pose arises from the self-righting tendency provided for flying in still air, it is obvious that *the prompt self-righting tendencies, once thought so desirable,*[1] *must be avoided, and only weak, slow righting tendencies, sufficient to control the average pose, be used instead.*

The above remarks apply without reference to the nature of the righting tendency so long as it pays respect to gravity. It is, for instance, futile putting a pendulum on the machine to indicate the direction AB

[1] Such as those due to a pronounced longitudinal dihedral angle, or strong forward movement of the centre of pressure. Natural selection has already operated so powerfully upon the thousands of machines designed and tried that argument is now unnecessary to ensure the use of weak dihedrals. Actually, a machine should have *no rigid positive dihedral effect*, because, if serviceable enough in other respects, it acts promptly in gusts, in a way this work shows is not required.

in the gust, for such pendulum cannot be prevented from paying allegiance to AD, as gravity, when the gust commences.[1]

A Side Gust

Suppose the aeroplane at A to be flying away through the paper when the gust DB attacks. The gust is a side gust, and the lateral righting tendency will start the aeroplane up paths like AH, AI, AJ, or AL, according to the circumstances of the damping, etc., but with the usual left-hand circling movement. Those readers who are familiar with the behaviour of gliders in still air will realise the movement quite easily on looking at the diagram along DA and noticing that the glider at A is virtually launched at too low a headway for the gravity AD, and tilted steeply to the left. It is impossible to show the path, except in a perspective drawing, or by a bent wire in space.

Here again, *a slow lateral righting tendency, well damped, is the very least essential demanded by the aeroplane seeking the minimum disturbance.*[2] Along

[1] This is true of short-period quick-acting pendulums, such as many designers, led by the obvious, usually arrange for. But a long-period pendulum (several times the period of the average gust) might conceivably show, on an aeroplane already fairly steady, a direction of gravity never differing much from the true vertical. The author believes such a pendulum, perhaps using a gyroscope to lengthen its period, may be profitably added as a *supervising* control to a machine already designed to be free from severe gust disturbance; but its addition is usually proposed for the gross purpose of itself fighting disturbance of the sudden gusts, by powerful elevator wagging. This seems doomed to failure as a practical engineering proposition, and is absurdly unnecessary in view of there being simple and comparatively perfect ways of effecting the same object.

[2] In more advanced aeroplane design it may be found necessary to have, in sudden gusts, a momentary reversal of lateral righting tendency; but the solution of this problem, and the whole problem of lateral stability, may be allowed to follow after others of greater urgency and preliminary educational value.

the present lines of design this may take the form of very little dihedral angle and underhung weight, and considerable keel surface.

A Rear Gust

Assuming the aeroplane to be flying to the right at A, the gust DB is a rear gust. Taking the same point of view as before, it will be easily seen how the disturbed paths are of the forms of AH_1 (undamped), AI_1 (damped), AJ_1 (slowly growing gust), and AL_1 (with momentary reversal of righting tendency).

An Upward Gust

When the same gust is an upward one its vector becomes the DB of fig. 2, and the relative gravity becomes the AD of that figure. This is in the usual direction, but being about $2\frac{1}{4}$ times as strong as common gravity it requires about $\sqrt{2\frac{1}{4}}$, or $1\frac{1}{2}$ times as much headway in the machine. The machine at A, therefore, acts similarly to a glider launched at too low a headway in still air, and it is easy to see, from experience of launched gliders, that paths like AH (undamped), AI (damped), and AJ (slowly growing gust), will resemble those taken by the machine.

All the paths so determined by means of the relative gravity diagram are necessarily *relative to the air*, but these are all we want to know to determine changes of pose, since the direction of pose never differs by many degrees from the direction of the relative path. The absolute paths, or paths relative to the ground, may always be determined, when desired, provided the relative paths can be dotted with "time-spots," or places the machine occupies at the ends of successive intervals of time. In fig. 2 the path AH has been dotted with such positions for the ends of the 1st, 2nd, 3rd, etc., seconds of time from leaving the air particle at A. It follows that straight lines from A, to each of these spots, are the corresponding *displacement vectors* of the machine relative to the air particle A. But A is accelerating upwards with the air at a ft. p.s. p.s., in consequence of which its displacement upwards, or s feet, at the end of t seconds, is given by $s = at^2/2$. The vertical line from A is accordingly dotted with these displacements at the ends of the numbered seconds of time, and combining with these displacements the relative displacements of the machine relative to A, the absolute path of the machine's centre of mass is easily found to be that passing through the numbered points of AM. If the machine is to be drawn at each point of the path AM, its pose must be made to accord with the direction of the relative path at the correspondingly numbered point.[1]

The exact determination of the absolute path for a specified machine is seen to depend on the exact determination of the relative path for the same machine, as obtained by regarding the air as still and common gravity superseded by a new gravity differing in both strength and direction. Several mathematical methods have been published for determining the relative path of an irregularly launched machine in still air, and these methods may be applied to the present case, after substituting the new gravity for g in their formulæ, and the direction DA for the vertical in their system

[1] It goes without saying, that a superimposed wind adds another displacement vector to each point, but as that vector would have been there without the gust, it is properly ignored.

of co-ordinates.[1] The object of the present work is to lay down general principles relating to the disturbing effect of gusts, and it should be kept in mind, that, when a broad view of a mechanism has suggested obvious improvements in its design, exact determinations of how it would have operated without such improvements lose a great deal of their practical interest.

A Downward Gust

When the gust DB is downward (fig. 3), the relative gravity AD becomes only one-quarter of common gravity, and acts *upside down.* The disturbed path then takes the form of AH (undamped), AI (damped), or AJ (slowly growing gust). In each case the machine *turns upside down,* but only slowly in comparison with the transient nature of this extreme gust. If the pilot at A is either moving slowly or refusing to allow his machine to turn upside down, he is liable to be separated from his machine by the *upward* relative gravity. Spanners, or anything loose, are also liable to fall out *upwardly,* and the gravity feed of his petrol is likely to be interrupted, and the petrol itself discover unexpected places from which to leak.[2]

This will, no doubt, be recognised as the somewhat dreaded "hole in the air" condition[3] in which the downward gust acceleration is greater than g.

When the downward gust DB is of strength 32·2,

[1] The suggestion is plain: Analytical methods may be extended to disturbed air by expressing g as a harmonic function of the time.

[2] An unsuspected cause, no doubt, of many engine-stoppages and fires, in mid-air.

[3] It is in connection with these gusts—or it would be if they were not so transient—that there is some scope for the employment of gyroscopic *supervising* control.

the relative gravity AD vanishes, and the aeroplane, *if it consists of narrow planes and is of very small size*, will turn in a vertical circle so small that $V^2/R = g$, where V is the headway in ft. p.s., and R the radius of the circle, in feet. The reason is, of course, that the lift commences to accelerate the machine at *right angles to its path*, with an acceleration equal to g,— the acceleration which, before the gust occurred, balanced the lift acceleration. The radius R is therefore equal to V^2/g, but putting $\frac{VT}{2\pi}$ for R, (in this, T is the time in seconds to complete the circle), we get $T = 2\pi V/g$, or about 20 seconds for a 100 ft. p.s. (68 m.p.h.) aeroplane. The simplest device to increase R and T is empennage, by which is meant a *pair* of neutral surfaces a considerable fore-and-aft distance apart, and not simply a neutral tail plane. Longitudinal moment of inertia, however, on a machine that will take it (see Chapters XII. and XIII.), resists the commencement of such vertical circling, and prolonged resistance is not required. Very powerful empennage has the defect of increasing the liability to disturbance by eddies.

A Downward Rear Gust

In fig. 4, in which the machine is assumed to be travelling to the left at A, a downwardly inclined rear gust, DB, is shown bringing the relative gravity AD to a horizontal direction. The disturbed paths then become AH (undamped) and AI (damped); a *back somersault* through three right angles being turned, even in the case of the damped path. When the gust grows slowly, so that the virtual level dwells near positions 1 and 2 for appreciable intervals of time, the path AJ, turning *downwardly* through only one right angle, resembles the disturbed path. This gust and all those intermediate between fig. 3 and fig. 4 probably constitute the most dangerous class of gusts.

The most marked and dangerous feature of the disturbed paths AH and AI is the rapid loss of headway at their commencement; but the author has had some success in designing apparatus that not only directly helps to maintain the headway, but at the same time resists the back somersault *in proportion to the sudden loss of headway associated with it.* The control differs from elevator control in *not depending upon the existence of headway for its operation.* (See Chapter XII. p. 97.)

A Downward Head Gust

When the machine is travelling to the right in fig. 4, the gust is a downward head gust, and the disturbed paths are easily seen to be of the less serious forms of AH_1 (undamped), AI_1 (damped), and AJ_1 (slowly growing gust).

Stresses produced by Gusts

Seeing that, in ordinary steady flying in still air the stresses in the wings of an aeroplane are determined by the gravitational weight upon the air, it may be anticipated that the relative gravity gives a measure of the stresses during steady flight in a gust. The greatest relative gravity of the diagrams is that due to the upward gust of fig. 2, where AD is $2\frac{1}{4}$ times common gravity; but the stress in the machine will be more than $2\frac{1}{4}$ times normal, when it is at such a place as point 4 of the path AH, because of the path being concave, and the machine weighing upon the air with an additional acceleration V^2/R, where V is the headway at point 4, and R the radius of path. The determination of the greatest stress is thus seen to depend, finally, on the determination of the actual V and R of the given aeroplane for each point of its disturbed path, and this determination may be made by such methods as have now been published dealing with flight in still air, with a given *g*. When there is a pilot on board, the stress in excess of the 2½ times normal depends on his operation of the elevator, but pilots ought always to make a practice of avoiding sharp turns relative to the air.

In fig. 3, the loading of the planes and stresses in the machine tend to be reversed.

CHAPTER III

SOARING FLIGHT[1]

Soaring flight may be defined as being that kind of flight practised by birds in which they keep aloft, without loss of headway, while using none of their own energy beyond that necessary to actuate their rudders, elevators, and warping, or bird equivalents.[2]

In fig. 5 a simple relative gravity diagram is again drawn, but for a weak gust; and since the virtual level plane has superseded the true level during the gust, *the bird, if frictionless, may glide in any direction in the virtual level, including direction AE, without loss or gain of headway and without effort, because it is then running neither uphill nor downhill with respect to the relative gravity AD.* Now AE has been arranged tilted at an angle of 1 in 5 to AF, by making BD exactly one-fifth of gravity AB, and if the bird is one having a gliding angle of 1 in 5, instead of being frictionless, it obviously cannot glide nearer to AE than the truly level path AF, which, however, can be pursued. Thus, a gust of strength $g/5$ will keep a "1 in 5" bird afloat in level flight at constant headway. The rule is quite general, so that, calling the horizontal gust acceleration a ft. p.s. p.s., and assuming the bird to *be acting* as a 1 in n bird, it will be maintained in at least level soaring, when :—

$$a \nless \frac{g}{n} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

[1] Some readers may find it profitable to read Chapter VII. in conjunction with, or before, this chapter.

[2] This defines *complete* soaring flight, but it will be seen, after the matter has been discussed further, that flapping and soaring may proceed simultaneously as independent partial causes of the whole ascent or support of the bird.

Now the air never accelerates for many seconds in one direction, because of the limits to wind velocity, but at every point it is always accelerating more or less in some direction, in a manner that is represented by the vector BD continually altering its magnitude and direction (in three dimensions). These changes sometimes occur very quickly, but never discontinuously, and so far as the bird is able to follow, by wheeling about, the corresponding changes in the direction of AE, *it may keep itself in a continuous head gust, and so continue soaring.*

This soaring is appropriately known as :—

Wheeling Soaring

The acceleration BD need not remain horizontal to tilt AE, and make this constant-headway gain of height *relative* to the air, and soaring *relative* to the air, possible; but if, as is usual, the up and down components of BD result, in the long run, in no upward displacement of the air, it is obvious they do not contribute to the soaring *relative to the ground.* Soaring by such upward displacements, or velocities, is a class of soaring practised by birds on fewer occasions than commonly supposed. (See page 81.)

Horizontal acceleration soaring (*i.e.* by horizontal air accelerations) at substantially constant headway is probably the rule with birds, and wheeling soaring the favourite of that variety; upward velocity soaring (see page 81) and the still rarer soaring by up and down accelerations of the air, are probably no more than occasional aids to the above wheeling soaring that is usually practised by the birds.

Uniform Wheeling Soaring

It has been pointed out the air cannot accelerate for long in one direction, so that uniform soaring in a straight line, for more than a few moments, is not possible; but, in tropical countries, birds are observed, on apparently calm days, to move in practically perfect circles, and at uniform headway, when the air is known not to be ascending.

To explain this we have only to assume the acceleration vector BD turns steadily through all the points of the compass in the time T seconds in which the bird completes each circle; and such turning of BD will occur if the whole block of atmosphere turns in a horizontal circle of radius r feet, so that *every air particle moves in a circle of the same size and moves in the same direction at any given instant of time.*

Let such air be moving right-handedly, and be moving eastward at this moment. Then, the southward centripetal acceleration a is $r\left(\frac{2\pi}{T}\right)^2$, and the bird will be able to soar by facing north, in accordance with formula (1), if:—

$$r\left(\frac{2\pi}{T}\right)^2 \nless \frac{g}{n}$$

or

$$r \nless \frac{g}{4\pi^2} \cdot \frac{T^2}{n} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

This soaring relationship of the bird to the air is only a momentary one if the bird continues to face north, but *if it turns circles in the same time and direction as the air, it keeps facing BD, and so maintains the soaring relationship constant.*

Now formula (2) tacitly assumes that n in the vertical plane remains the common n of the bird in straight gliding, but, when circling, the effective gliding angle of the bird is more or less degraded, and n numerically reduced to an effective value n_e.

In fig. 6 the bird is shown in its relative orbit centred on the single air particle O, and in front are shown the vectors of the relative gravity diagram, or AB, AC, BD, and AD. But there is shown another vector AE, or BL, which is equal and opposite to the centripetal acceleration, *relative to the air*, that the bird must itself obtain to keep in its *relative* orbit of radius R feet. The length of this vector is given by :—

$$AE = R\left(\frac{2\pi}{T}\right)^2.$$

This AE, combining with AB, produces a resultant weight upon the air, at right angles to the path, represented by AL, and, in the absence of much keel surface to resist side-slipping, the bird must bank to set itself at right angles to AL. Now, it is a property of gliders moving at steady headway to have the drift force equal to $1/n^{th}$ the lift force, or, in the alternative view, the forwardly impressed acceleration (propeller produced, or air produced, or gravity produced) equal to $1/n^{th}$ the resolved acceleration upon the air at right angles to the path. In other words :—

$$AC = \frac{1}{n} AL.$$

But

$$AL = AB/\cos\zeta,$$

where ζ is the banking angle BAL ; therefore

$$AC = AB/(n\cos\zeta)$$

or

$$a = \frac{g}{n\cos\zeta}. \qquad (3)$$

which, compared with formula (1), shows that, in circling, $n \cos \zeta$ takes the place of the common n, or $n_e = n \cos \zeta$.

Accordingly, rewriting formula (2) with n_e (which is $n \cos \zeta$) in place of its n, we have :—

$$r \nless \frac{g}{4\pi^2} \cdot \frac{T^2}{n_e} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

With the aid of fig. 6 it is easy to derive the following formulæ, additional to (4), where ω is temporarily written for $2\pi/T$:—

$$n_e = n \cos \zeta = \frac{ng}{\sqrt{g^2 + (R\omega^2)^2}} \quad . \quad . \quad . \quad . \quad (5)$$

$$AD_1^2 = g^2 + (r\omega^2)^2 + (R\omega^2)^2 \quad . \quad . \quad . \quad . \quad . \quad (6)$$

and

$$R\omega = V_a = V\sqrt{\frac{AD_1}{g}} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

In formula (7), V is the common gliding headway of the bird, in ft. p.s., and V_a is the actual headway while circling, and notice is taken of the fact that the steady headway is proportional to the square root of the weight upon the air at right angles to the path.[1]

From these formulæ a complete formula from which R may be found in terms of T, for a bird of given V and n, is :—

$$R^2 = \frac{V^4}{2g^2}\left\{\left(1 + \frac{1}{n^2}\right) + \sqrt{\left(1 + \frac{1}{n^2}\right)^2 + 4\left(\frac{gT}{2\pi V}\right)^4\left(1 + \frac{1}{n^2}\right)}\right\}. \quad (8)$$

and the formula for r is :—

$$r = \frac{1}{n}\sqrt{\left\{g^2\left(\frac{T}{2\pi}\right)^4 + R^2\right\}} \quad . \quad . \quad . \quad (9)$$

Formula (8), it may be noticed, is not solely connected with soaring, but is true, like fig. 6, for any

[1] This would not be quite so true for an nert rigid aeroplane having considerable size compared to the size of the orbit.

bird or aeroplane moving steadily in a horizontal circle relative to the air.[1] (See Chapter XVII.)

In fig. 7 is shown, to scale, the absolute orbit of a bird having $V=29{\cdot}3$ ft. p.s. (20 m.p.h.), and $n=10$, when uniformly soaring in a circle with $T=12$ seconds. The radius R, by formula (8), is 60 feet, and the radius r of the circular wind is, by formula (9), about 13 feet. At O is the single air particle that was shown at the centre of the relative orbit in fig. 6. This particle moves in the circle of radius r, like the particle at A and every other particle. AE is the centripetal acceleration of the bird at A relative to the air, and AC the absolute acceleration of the air at A; therefore, AK, the resultant, is the absolute acceleration of the bird at A to the point Q at the centre of its absolute orbit. As these relationships remain constant, the triangle AOQ, bearing the bird at A, travels round the centre Q. The radius AQ of the absolute orbit is obviously given by:—

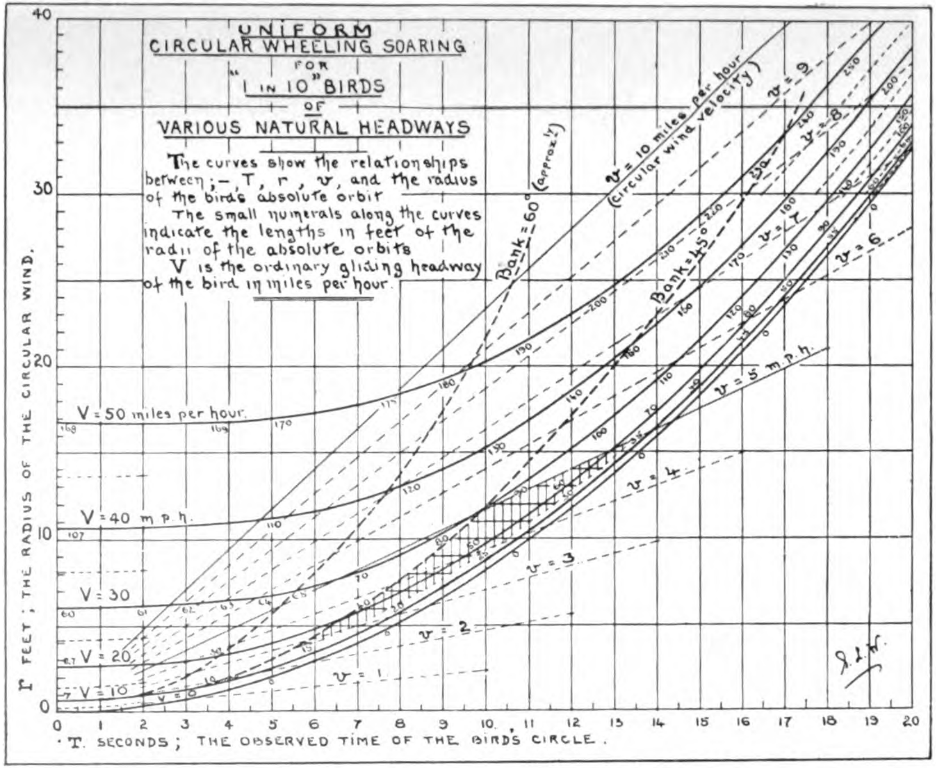
$$AQ=\sqrt{R^2+r^2} \quad . \quad . \quad . \quad . \quad (10)$$

but for birds with good gliding angles under these soaring conditions AQ is never much greater than R.

In the soaring chart of fig. 8 the value of r, as a function of T, has been plotted, after calculation by formulæ (8) and (9), for 1 in 10 birds of $V=15$, 30, and 50 miles an hour, and numerals showing the radii of the absolute orbits, in accordance with formula (10), have been placed at a few important points on the curves. Birds with gliding angles of 1 in 10 have been selected in the belief that they are likely to represent the best existing soaring birds.[2]

[1] See the preceding footnote.

[2] The large-scale chart showing more details (such as the orbital radii all along the curves), was published in *Aeronautics* of December, 1911, and is reproduced facing this page.



Walkden, *Aeroplanes in Gusts.*] [*To face p.* 20.

THE SOARING CHART OF FIG. 8.

Enlarged, with details.

Straight radial lines showing the loci of all points on the chart where the wind velocity v equals 5, 4, and 3 miles per hour, respectively, have been drawn in accordance with the obviously applicable formula:—

$$r=\frac{vT}{2\pi} \quad . \quad . \quad . \quad . \quad . \quad (11)$$

When the aeroplane is circling with the banking angle ζ (refer to fig. 6), and the actual headway V_a :—

$$\tan\zeta = R\left(\frac{2\pi}{T}\right)^2\Big/g$$
$$=\frac{V_aT}{2\pi}\cdot\left(\frac{2\pi}{T}\right)^2\Big/g$$
$$=\frac{2\pi V_a}{gT} \quad . \quad . \quad . \quad . \quad . \quad (12)$$

But

$$\frac{V_a^2}{V^2}=\frac{AD_1}{AB}=\frac{AL}{AB}\times\frac{AD_1}{AL}$$
$$=\frac{1}{\cos\zeta}\times\frac{1}{\cos\gamma} \quad . \quad . \quad . \quad (13)$$

—because angle D_1AL is γ, the common gliding angle of the bird.

From (12) and (13) we find:—

$$T=\frac{2\pi}{g}\cdot\frac{V}{\sqrt{\cos\gamma}}\cdot\frac{1}{\sqrt{\sin\zeta\tan\zeta}}$$

which, with

$$\frac{1}{1+\tan^2\gamma} \quad \text{or} \quad \frac{1}{1+\frac{1}{n^2}}$$

for $\cos^2\gamma$, becomes[1] :—

$$T=\frac{2\pi}{g}\left(\frac{V}{\sqrt[4]{1+\frac{1}{n^2}}}\right)\frac{1}{\sqrt{\sin\zeta\tan\zeta}} \quad . \quad . \quad (14)$$

---

[1] Physically, $\sqrt[4]{\left(\frac{1}{1+\frac{1}{n^2}}\right)}$ is $\frac{V}{V_f}$, or the ratio of the common gliding headway to V_f—the headway the bird would have if propeller driven in straight *horizontal* flight.

The stress in the circling bird's wings is greater than that in ordinary straight flying in the ratio of AL to AB, or $1/\cos\zeta$. If we assume the bird does not wish to fatigue itself by more than double the normal stress, ζ is limited to 60°. But, in actual soaring, the birds seldom bank more steeply than 45°; therefore, 45° will be taken as the limit of ζ.

With 45° substituted for ζ in formula (14), T is found for the points on the various V curves where the banking is 45°, and a line drawn through these determines the "bank 45°" curve of the chart. The "bank 60°" curve is, in similar manner, roughly plotted to show in which direction the banking becomes greater.

Now, it is very unlikely any of the 1 in 10 soaring birds, even the lightest, has a less V than 15 m.p.h. We decided that greater banking angles than 45° are not employed. Finally, if the circular wind velocities, v, were often greater than about 5 m.p.h., these winds would hardly have so long escaped direct observation, even allowing for the fact that ground friction greatly interferes with such jelly-like oscillations of the atmosphere in its lowest strata. Therefore, the area of the chart representing the circumstances of actual soaring is that within the shaded triangle, and the following approximate limits may be read off the chart:—

Time T to fly round circle, about	6 to 15 seconds.
Diameter of circular wind, or $2r$	8 to 40 feet.
Velocity of the circular wind, or v .	3 to 5 m.p.h.
Headways of the birds, or V . .	15 to 30 m.p.h.
Diameters of orbits, or 2R, about .	50 to 200 feet,—

—which estimate for 2R will do for the absolute as well as the relative orbits.

Among other things, a careful study of the chart will disclose that ***high speed in a bird militates strongly against this class of soaring*** in the lighter and more frequent circular winds, and a heavy bird with greater V than 30 m.p.h. will practically never be able to accomplish this variety of soaring without helping itself out with a certain amount of flapping. The infrequency of such a bird's soaring is not only due to the reduced frequency of the stronger winds, but due to its only being able to use them when they come within a restricted range of T seconds. The chart also discloses why the high-speed bird moves in large long-period circles on the few occasions when it is able to soar. The Plate facing page 20 is superior to the small fig. 8 for these studies.

To-and-fro Wheeling Soaring

In this class of soaring the bird is seen to dart back and forth in paths that, viewed from above, are approximately parallel straight lines joined by sharp turns at the ends. When these paths are, say, north and south, the gust is no doubt reciprocating in a north and south direction, and the best plan is to assume it reciprocates harmonically.

The gust is represented in fig. 9, where it swings harmonically to a maximum *acceleration* amplitude a_m each way, and has a total periodic time T seconds. Notice, at this early stage, that a_m is neither a displacement nor a velocity, but an *acceleration*. The thick line perpendicular from A having been drawn 32·2 units in length to represent common gravity, it is evident the relative gravities, at equal intervals of time during the gust cycle, are represented by the lines drawn radiating from A. Since the constant-headway soaring path of the frictionless bird keeps at right angles to the relative gravity, it is necessarily the path EF of fig. 10, in which each little equal section, 1, 2, 3, etc., has been drawn at right angles to its corresponding relative gravity in fig. 9. Every section of the path is, to scale, equal to V, the distance the bird moves in each of the 14 seconds of the assumed gust cycle T. To continue the soaring at F, and each time the relative gravity crosses the centre on the reversal of the gust, the bird must wheel round 180°. *This wheeling must be a true wheeling action relative to the air*, like that of a turning motor-car or skater, and not like that of a skidding motor-car or incompetent slider. That is to say, the headway of the bird must be reversed simultaneously with the direction in which it faces. By the time of reversal of the gust is meant, of course, the time of reversal of the gust *acceleration*, which is T/4 seconds in advance of the time of reversal of the gust velocity.[1]

If, at a given instant, the relative gravity is tilted through an angle β, it is evident, that, for the bird ascending at right angles to this gravity, at headway V, the vertical rate of ascent, or increase in h, is expressed by :—

$$\frac{dh}{dt} = V \sin \beta$$

which, for feeble gusts with β very small, may be written :—

$$\frac{dh}{dt} = V\beta \quad . \quad . \quad . \quad . \quad . \quad (15)$$

[1] Many readers should be able to verify this, later on, by inspection of figs. 22, 23, and 24, for the reciprocating displacement, velocity, and acceleration vectors for fig. 9 are only the projections of the corresponding rotating vectors of figs. 22, 23, and 24. Notice, therefore, that the thick-line radii of the latter figures are successively at right angles.

Now, where a is the momentary strength of the feeble gust, inspection of fig. 9 shows that :—

$$\beta = a/g$$

and since, for the harmonic gust,—

$$a = a_m \sin \frac{2\pi t}{T}$$

it follows that :—

$$\beta = \frac{a_m}{g} \sin \frac{2\pi t}{T} \quad . \quad . \quad . \quad . \quad . \quad (16)$$

Putting this for β in formula (15), and integrating between $t=0$ and $t=T/2$, the rise up EF, or to half the gust cycle, is found to be :—

$$NF = \frac{1}{\pi} \cdot \frac{a_m}{g} \cdot V.T \quad . \quad . \quad . \quad . \quad (17)$$

The mean angle of rise is, therefore, NF in EN, or

$$a_m V.T/(\pi g) \text{ in } V.T/2$$

or

$$2a_m/(\pi g) \text{ in } 1$$

or

$$2a_m n/(\pi g) \text{ in } n$$

so that, for a 1 in n bird to be kept afloat in such soaring, we must have :—

$$2a_m n/(\pi g) \nless 1$$

or

$$a_m \nless \frac{\pi g}{2n} \quad . \quad . \quad . \quad . \quad . \quad (18)$$

The above reasoning is only without error for an indefinitely feeble gust and corresponding gliding angle in the bird, but large-scale graphical constructions like fig. 10,—even when certain small allowances are made for the variations in the strength of the relative gravity and for the centripetal perturbation due to curvature of path,—will always be found in practical agreement with formula (18), provided a *practical* case of level soaring is being investigated.

If the gust continued steady at the value a_m the frictionless soaring path would be EH in fig. 10, and the fact that NF is about 2/3rds, or $2/\pi$, of NH suggests that, in this soaring, the mean effective strength of the harmonic gust is $2/\pi$ of its maximum. The mathematical proof, as regards feeble gusts, consists in noting that $NH = (a_m/g)$ of $(V.T/2)$, which is $\pi/2$ times NF as given in formula (17). Alternatively, the ratio between formulæ (1) and (18) may serve as a proof.

For a given harmonic gust with maximum wind velocity v_m, and maximum displacement r feet of the air each side of its mean position,[1] we may substitute for a_m in formula (18) either v_m^2/r or $r(2\pi/T)^2$. In the first case, we have :—

$$\frac{v_m^2}{r} \not< \frac{\pi g}{2n}$$

giving us

$$r \not> \frac{2nv_m^2}{\pi g} \quad . \quad . \quad . \quad (19)$$

and

$$v_m \not< \sqrt{\frac{\pi r g}{2n}} \quad . \quad . \quad . \quad . \quad (20)$$

In the second case, we have :—

$$r\left(\frac{2\pi}{T}\right)^2 \not< \frac{\pi g}{2n}$$

giving us

$$r \not< \frac{g}{8\pi n} T^2 \quad . \quad . \quad . \quad . \quad (21)$$

and

$$T \not> \sqrt{\frac{8\pi n r}{g}} \quad . \quad . \quad . \quad . \quad (22)$$

[1] A harmonically varying acceleration of a body is only consistent with the body having the projected displacements of a particle revolving in a circle. The full projected centripetal acceleration of such generating

Assuming the 1 in 10 birds are again under consideration, and limiting the maximum wind velocity v_m to 15 m.p.h. (notice this is only ***half the total fluctuation***), formula (19) gives $r \not> 96$ feet.

Formula (21) is no use till T is known, and, as a matter of fact, it is no practical use at all, because, when T is small, as it must be to find the minimum r, the bird has no time for straight runs, as assumed, between the wheelings at the ends.

Putting the above found 96 feet for r in formula (22), we get :—$T \not> 27{\cdot}4$ seconds.

Thus, according to the above showing, the superior limit to $2r$, in to-and-fro wheeling soaring, or the maximum total displacement of the soarable gusts, is unlikely to exceed about 192 feet, while the total time T of the same soarable gusts is unlikely to exceed about 27 seconds.

The missing inferior limits to r and T, which formulæ (19) to (22) failed to discover, will be found in the limits of the next class of soaring.[1]

To-and-fro Circular Wheeling Soaring

In practice, even the slowest existing bird cannot proceed in two straight paths joined by an insignificant wheeling path at each end, not even if it be allowed a total T of 27 seconds. The wheeling takes up so much time that we may as well calculate for the

particle is then the a_m of the body; the full projected velocity of the particle the v_m of the body; and the full projected radius of rotation of the particle the full displacement of the body.

[1] It may be mentioned here, that, although the absolute path (easily determined) is of different shape from the relative path, yet it has the same terminal points E and F, or E and N; because, whenever the bird is at these points the air has its mean position.

more probable circular orbit, and we practically must do this for the faster birds, seeing that they at least cannot execute sharp turns. The soaring to be considered then becomes to-and-fro *circular* wheeling soaring, the soaring paths for which, in the gust of fig. 9, are shown in fig. 11. The paths up the virtual levels being now foreshortened according to an obvious enough sine law, formula (15), for feeble gusts, takes the form:—

$$\frac{dh}{dt} = V \cdot \beta \sin \frac{2\pi t}{T} \quad . \quad . \quad . \quad . \quad (23)$$

Putting in this the value of β in formula (16), it becomes:—

$$\frac{dh}{dt} = V \cdot \frac{a_m}{g} \sin^2 \frac{2\pi t}{T} \quad . \quad . \quad . \quad . \quad (24)$$

This, integrated between the limits $t=0$ and $t=T/2$, determines the rise to half the gust cycle, in the form:—

$$NF = \frac{1}{4}\frac{a_m}{g} \cdot V \cdot T \quad . \quad . \quad . \quad . \quad (25)$$

The mean angle of rise in the *developed* path EF_1 is then N_1F_1 in EN_1, or

$$a_m V \cdot T/(4g) \text{ in } V \cdot T/2$$

or

$$a_m/(2g) \text{ in } 1$$

or

$$a_m n/(2g) \text{ in } n$$

so that, for a 1 in n bird to be kept afloat in such soaring:—

$$a_m n/(2g) \nless 1$$

or

$$a_m \nless 2g/n \quad \text{(see footnote 1)}$$

[1] A comparison of this expression and formula (1) shows that the mean effective strength of a harmonic gust, for this class of soaring, is half its maximum strength.

or

$$r(2\pi/T)^2 \nless 2g/n$$

or

$$r \nless gT^2/(2\pi^2 n)$$

or

$$\frac{1}{2}r \nless \frac{g}{4\pi^2} \cdot \frac{T^2}{n} \quad . \quad . \quad . \quad . \quad (26)$$

But the bird is pursuing a circular orbit, so n must be, not the common n, but n_e, the effective n while circling, and, of course, while banked. Therefore, formula (26) becomes:—

$$\frac{1}{2}r \nless \frac{g}{4\pi^2} \cdot \frac{T^2}{n_e} \quad . \quad . \quad . \quad . \quad (27)$$

On comparing the above with formula (4), and reflecting that formulæ (5), (6), (7), (8), (9), and the soaring chart itself of fig. 8, were, in reality, nothing but means of solving formula (4) with n_e expressed in terms of the constants of the bird in connection with its relative orbit, it is evident that the soaring chart of fig. 8 solves formula (27) for the $r/2$ of the present form of soaring in feeble gusts.

Accordingly, trouble is saved in fig. 12 by simply redrawing the chart of fig. 8, but with the old figures of the r scale crossed out, and double values substituted, and with the figures of the v radial-line scale also doubled to suit this change in the r scale.

Though the argument has been developed on the assumption of feeble gusts, carefully made large-scale graphical constructions, like figs. 9 and 11, will always be found to confirm the practical absence of error for the gusts actually required by the soaring birds.

With V, on fig. 12, limited to not less than 15 m.p.h.; the banking limited to not greater than 45°; and v

limited to not greater than 15 m.p.h.; the circumstances of this soaring, for 1 in 10 birds, are expressed by the shaded triangular area of the chart, and the following approximate limits of the soaring may be written down from inspection:—

Time T to fly round orbit, about . .	6 to 21 seconds.
Total displacement of the to-and-fro gust, or $2r$	20 to 150 feet.
Maximum velocity of gust wind, or v_m . .	6 to 15 m.p.h.
Total range of gust velocity, or $2v_m$ . .	12 to 30 m.p.h.
Headways of the birds, or V . . .	15 to 45 m.p.h.
Diameters of the orbits, or 2R, about . .	50 to 380 feet.[1]

It is instructive to compare these with the chart and limits of uniform wheeling soaring (fig. 8). The air movements necessary are much more vigorous, and everything is on a larger scale. Though light slow birds again have the advantage, this kind of soaring is occasionally practicable for a bird having a V as great as 45 m.p.h.

In straight to-and-fro soaring the limit of T was made 27 seconds; in this circular case it is only 21 seconds. Now simple, straight, to-and-fro soaring is really impossible, because the bird must always mix a good deal of the circular case with its soaring during the wheeling at the ends. Hence, the real limit of T in general to-and-fro soaring is probably about 24 seconds. Similarly, the superior limit of $2r$ is between 192 feet and 150 feet, or probably about 175 feet.

The other limits for the circular case may be regarded as the limits for the straight case, so far as the latter is practicable to the light slow birds. The

[1] Points E and F, or E and N, are also terminal points of the absolute path, for reasons similar to those given in footnote No. 1, page 27.

missing limits of the straight case have therefore now been discovered.

The Non-soaring Condition

If the bird in fig. 10 did not reverse its direction by wheeling at F, the return gust would be a rear gust, and the bird would descend by a path of the same shape as the ascending path (fig. 13, I.). The net soaring effect during the gust cycle would then be zero. In the atmosphere the gusts are not symmetrical as shown, that is to say, they are not *immediately* symmetrical, but they are usually so on the average, and if a bird, using its "elevator" to preserve constant headway, but refusing to wheel about selectively, finds a little gust element at this moment that gives it a rise of, say, one foot, it is certain, sooner or later, to find the corresponding gust element that gives it the same amount of fall.

Thus, assuming the gusts are random phenomena, *the non-soaring condition is that the bird shall use its "elevator" to preserve constant headway, but refuse to wheel about selectively in the gusts.*

The non-soaring path of fig. 13, corresponding to a harmonic gust cycle, may be represented, approximately, by four straight lines of equal length, suggesting that a good substitute for the gust itself, for purposes of general exposition, is one consisting of a steady head gust for quarter of the gust cycle, followed by no gust (*i.e. no acceleration but steady wind*) for another quarter of the cycle, then a return gust similar to the first gust, and a second no-gust period to complete the cycle. With such a gust cycle the constant-headway non-soaring path is similar to the full line of fig. 13, II.

ASYMMETRIC SOARING

In fig. 14 a gust cycle of the above-mentioned variety has been assumed, with the following attendant conditions:—Strength of each gust = 20 ft. p.s. p.s.; duration of each gust = 3 seconds, or one-quarter of T seconds, where T is the whole time, 12 seconds, of the gust cycle. The headway V of the bird is assumed to be 35 ft. p.s. (about 24 m.p.h.). The thick full line represents the constant-headway non-soaring path, each of the straight sections being, of course, 3×35 or 105 ft. long, to scale. The sloping parts are at an angle of 20 in 32·2, or 1 in 1·6, as they should be in accordance with the relative gravity diagrams used in determining them, though not shown.

If the bird, while maintaining constant headway, is to obtain any soaring effect, some means must be found of increasing the rise to the head gust, or decreasing the fall to the rear gust, or doing both. That is, *some kind of asymmetry must be introduced into the gust.*

Regarding the gust as the average gust about the time of observation, we must assume the displacement of air due to the head gust is equal and opposite to that due to the rear gust, for, otherwise, we should be confusing the *wind* with the gust. Now, the displacement of air, s feet, due to a gust of acceleration a acting for t seconds, is given by:—

$$s = \frac{at^2}{2} \qquad . \quad . \quad . \quad . \quad . \quad (28)$$

from which

$$a = \frac{2s}{t^2} \qquad . \quad . \quad . \quad . \quad . \quad (29)$$

When $a = 20$ and $t = 3$, as in our example, s is 90 feet according to formula (28), and putting this for s in formula (29) we find the accelerations a of all other gusts with the same displacement are given by $a = 180/t^2$.

With $t = 6$ seconds, a is 5·0, and the soaring path for that gust is at a slope of 5 in g, or 5 in 32·2, or 1 in 6·44, as found by a relative gravity diagram. The dotted path No. 6, drawn to A at that slope, is accordingly the soaring path of the bird during the 6-second head gust *having the same air displacement as the original 3-second gust.* The length of this dotted path, to scale, is, of course, 6×35 or 210 feet. Similar paths are drawn for 5, 4, 3, 2, and 1 second gusts, disclosing, by the numbered dotted curve passing through their extremities, that the best head gust from the point of view of rise is the one having a duration of about 2½ seconds and making a soaring path at 45°, and, therefore, corresponding to a gust of strength 32·2 ft. p.s. p.s.

The slope of the best path is *always* 45°, and the time is merely incidental. When the gust is of strength a the soaring path slopes at an angle α having $\tan \alpha = a/g$, or $\sin \alpha = a/\sqrt{a^2+g^2}$. Now, the vertical ascent in the gust of duration t is $V.t \sin \alpha$, and therefore $V.t.a/\sqrt{a^2+g^2}$. From formula (29), $t = \sqrt{(2s/a)}$. Hence, the ascent is $V.a\sqrt{(2s/a)}/\sqrt{a^2+g^2}$. This, being proportional to $\sqrt{a/(a^2+g^2)}$, is greatest when $a = g$, that is, when the horizontal gust is of the same strength as gravity and, as a consequence, of the strength that makes the soaring path slope at 45°.

The descending paths for the rear gust, drawn from point B, on the assumption that it also keeps to the same displacement of 90 feet but has various durations, are exact copies of those for the head gust, and show that to *minimise* the descent *the rear gust should be of either very short or very long duration.*

We can now generalise from fig. 14 as to the asymmetry of the gust that will give the constant-headway bird some soaring effect.

If the head gust is a very weak one, the nearest asymmetry for soaring consists in a rear gust of longer duration and weaker. As the head gust is made stronger and stronger the above rule becomes less definite, till, with a head gust about equal to gravity, or 32·2 ft. p.s. p.s., the nearest soarable asymmetry consists in a rear gust that is of less duration and stronger than the head gust. When the head gust is very much stronger than 32·2 ft. p.s. p.s., the nearest soarable asymmetry consists, decidedly, in a rear gust of still shorter duration and still greater strength than the head gust.

It will be easily seen that the asymmetry giving the bird positive soaring when it flies from right to left gives it just as much negative soaring, or beats it down, when it flies from left to right.

This kind of soaring appears to demand so much asymmetry in the gusts that it is surprising to find it may be of more than academic interest. It is notorious that an aeroplane, *long after it has left the ground,* climbs to higher levels more readily when flying against the wind than when flying with it. Seeing that the man and the machine are the same for both directions, and the wind, as a mere bodily movement of the atmosphere, does not enter into the question, *the phenomenon is inexplicable on any other* *assumption than that the gusts are asymmetrical.* Since aeroplanes do not usually fly when the gusts are as strong as gravity, or able to raise winds of 30 m.p.h. in $1\frac{1}{3}$ seconds, we may infer, from fig. 14, that the gust accelerations in the direction of a wind are usually stronger than those returning in the opposite direction. It is probable good pilots have the instinct for seeking steady headway in preference to steady pose, but the above inference does not rest entirely on that assumption, because the pilot has the same habits in both directions of flight.

Delay Soaring

Many birds soar in practically straight courses, as viewed from above, and with such indifference as to the direction of their course at a given time that both wheeling soaring and asymmetric soaring are ruled out of court. Yet, they rise and fall to the gusts, and, without doubt, to the head gusts and rear gusts respectively. Hence, we must assume each of these birds finds some means of enhancing its rises to the head gusts relative to its falls to the rear gusts, so that, *in itself, it acts asymmetrically* to gusts that may themselves be symmetrical. This most important kind of soaring is called delay soaring, for reasons that will soon be made apparent. For birds, it is probably less in favour than wheeling soaring, but aeroplanes have such high speed and inferior capacity for wheeling about, to say nothing of their desire to progress from place to place, that delay soaring is perhaps the only kind they are likely to cultivate to any degree.

Assuming the gusts are symmetrical, it has already been laid down that the non-wheeling but soaring bird must increase its rise to the head gust, or decrease its fall to the rear gust, or do both, and that it cannot do these by keeping to the virtual levels or constant-headway non-soaring paths.

In fig. 15 the relative gravity diagram and virtual level are shown for the 3-second gust of 20 ft. p.s. p.s. Since the bird flying at A, with headway V, must not keep to the virtual level, let it take any path such as AP, and arrive at the point P, at the end of 3 seconds, with an increased headway due to the relative gravity AD. Since, during the gust, the relative gravity and virtual level stand to the bird in precisely the same relationship that common gravity and the true level do when the air is calm, the frictionless bird at P can steer back to the virtual level perpendicularly along PY, or along any other path, and arrive at the virtual level with the same headway it had at A. In particular, it may choose to steer up the truly vertical path PQ, and so arrive at Q with its common headway V.

But, in rising up PQ it is only doing work against the AB component of the relative gravity, that is, against common gravity; and so, at the end of the 3 seconds, it may turn up PQ and rise the height PQ, or ZQ above A, with complete indifference as to whether the relative gravity AD and gust DB exist or not. Hence, *if during the head gust the bird, starting with headway V, arrives at any point P in the air, it may rise, after the gust ceases, to a height corresponding to that of a point, directly above P, on what was the virtual level, and arrive there with its original headway V.* The height of rise may consequently be determined by a simple graphical construction.

To make Q as high as possible, P must be as much to the left as possible, a fact which can be discovered or confirmed by another process of reasoning. When the bird arrives at P, its greater headway denotes that it has been given kinetic energy *relative* to the air at the expense of a fall in the direction of common gravity AB, and also at the expense of a *horizontal fall* in the direction of the pure gust "gravity" BD. Now the former has to be given back to common gravity, foot by foot, as the bird steers up PQ after the gust, but the latter is a surplus gift of energy available to do extra work against common gravity. To make the rise as *great* as possible that surplus energy must be made as great as possible by making the "fall," in direction BD, as *great* as possible while the gust DB is in action.[1]

Starting the bird to the right at A, so as to develop the similar argument for the rear gust, we see that to *minimise* the loss of height, Z_1Q_1, the horizontal travel of the bird from A must be made as *small* as possible. The bird ought to wheel round to obtain ZQ again, but that would only bring us back to the case of wheeling soaring in combination with delay soaring. Discussion of soaring necessarily resolves itself into discussion of the standard cases, and it may

[1] If gravity did not exist, a bird would be able to keep up a considerable average speed of progression, in the manner of delay soaring, by heading horizontally straight into the head gust, turning at right angles (up, down, or across) during the succeeding rear gust, heading into the next head gust again, and so on. If the bird had no friction it could, in this way, build up an *infinite* headway and average absolute speed, for each head gust would add a definite increment of headway, $(t \times a)$, which would be retained during the succeeding rear gust owing to the bird turning at right angles to that gust. If it wheeled right round it could develop infinite headway at double the rate corresponding to the above process, but that would be wheeling soaring.

be left to be understood how they may be combined by a bird, in various degrees at different times. Pure soaring of any one type is the exception, not the rule.

The problem now is to find the path AP, assumed straight in the first instance, that gives the *greatest* travel to the left.

In fig. 16, easily recognisable parts of fig. 15 are again drawn. Now the strength of the relative gravity AD, in any direction from AD, is—just as it would be for common gravity—proportional to the cosine of the angle the direction makes with AD. Hence, the polar cosine curve represented by the circle ABD, drawn on AD as diameter, gives the vector from A representing the strength, a_1, of AD in any direction.

When the bird at A, of headway V, falls in any direction from A under the influence of any acceleration a_1, the distance s it moves from A is given by the usual formula:—

$$s = Vt + a_1 t^2/2$$

which, with $t = 3$ seconds and $V = 35$ ft. p.s., becomes:—

$$s = 105 + 4\tfrac{1}{2}a_1$$

The 105 feet part of s is represented in fig. 16 by the circle F, of radius 105 feet, to scale, drawn round A; and putting 32·2 for a_1 we get 145 feet for the second part of s in the particular direction AB, a distance that is set off in the length AC. Now, the $4\tfrac{1}{2}a_1$ part of s is, in any direction, proportional to the acceleration a_1 in that direction, and, therefore, proportional to the corresponding vector from A to the circumference of the circle ABD. Hence, the circle ACE, passing through the two *certain* points A and C, and centred on the line AD, so as to be a copy, on the proper scale, of the circle on AD, represents, by the distance of its circumference from A, the $4\frac{1}{2}a_1$ part of *s* in any given direction.

Adding the distance vectors, from A, of circle F and circle ACE we get the value of *s* in any direction shown by the distance from A to the circumference of the thick-line cam-shaped figure. The farthest point of this to the left is P, so AP is the straight path giving the greatest rise above A, after the gust, and Q—the point in the virtual level immediately above P—is at the height to which the bird attains in regaining its normal headway.

If the bird is made with a less and less V, the circle F shrinks, and the cam-shaped figure shrinks till it coincides with the circle ACE. The best path is then AG instead of AP, so *the greater the headway of a bird the less steeply it has to dip down to the head gust to pursue its best delay soaring path.* Great headway, at last, appears to advantage.

If the gust were to be tried weaker and weaker, after the reduction of V to zero, AD would close up to AB, and the circle ACE would finally agree with the dotted circle passing through A and C, and centred on AB. Though, owing to the virtual level being almost coincident with the true level, the amount of soaring is, in this case, microscopic, what there is of it is still at its best when the path AH, which dips down at 45°, is taken by the bird. Thus, *the less the V of the bird, and the feebler the gust, the more steeply the bird should dip down to the gust.* This only confirms that *the birds of greater headway are more suited for this soaring*, and it is a significant fact that the heavier birds do prefer straight-ahead soaring to wheeling soaring, and when a bird suitable for both kinds is executing the former it often shrinks its wings to set itself for a greater headway.

It is probable the shrinkage of the wings during the head gust (to facilitate the advance into the gust) and expansion during the rear gust (to facilitate support without advance) are general methods adopted by delay soaring birds to get the utmost soaring effect, but the possibilities in the bird's alterations of its constants as a glider, during the gusts, are beyond the scope of this work.

The point J is interesting, because, although AJ is not the best soaring path, yet, it represents the simple delay policy of merely steering level during the gust, and the rise JK, at the end, is not much inferior to ZQ. The point L is interesting in being at the height attained when the bird simply pursues the virtual level path AL, 105 feet long, as it was at first assumed to do. The height of Q above L, therefore, represents the advantage to the bird of dipping down the delay path AP during the gust instead of keeping constant headway in the virtual level.

It is just as well to mention, that, if AP be made to curve towards P in the direction of the horizontal the point P may be pushed a little more to the left, but so little that it is usually not worth the trouble of finding out how much.

Everything, therefore, goes to show that dipping down a little to the head gust (so as to delay rising) is the best policy of the bird.

In fig. 14 the path AP is drawn parallel, and (to greater scale) equal, to AP of fig. 16. At P the bird attains a headway of about 124 ft. p.s., and the point

Q, vertically above P and on A_1A produced, is at the height attained after the head gust, on regaining the original headway V. The bird then has time to travel a very short distance horizontally till the rear gust commences, when it turns down the virtual level RS to avoid losing headway. From the soaring point of view the bird would do better not to do this, but to reduce its headway so as to stand still in the air and avoid forward movement as much as possible. But, *for reasons of stability*, we must assume the bird does not willingly reduce its headway much below normal.

As a matter of fact, many delay soaring birds do apparently risk this loss of headway to the rear gust, for the sake of the gain in soaring effect, and they are often being embarrassed by the rear gust being longer or stronger than they anticipated. At such moments they have to flap to maintain their headway. *The flapping energy they thus willingly expend per minute is probably far less than the soaring energy they obtain by continually risking the loss of headway*, and aeroplanes may possibly find ways of expending an average of, say, 5 horse-power, intermittently at the rate of 40 or 50 horse-power, at such well-judged moments as to obtain from the gust energy an average of perhaps 10 to 20 horse-power. Swallows flutter very frequently in their soaring in a way suggesting they are regularly having to extricate themselves from the lost headway condition, as part of their soaring policy.[1] Delay soaring, in its limit, is thus seen to be somewhat of a compromise with stability.

[1] There is, of course, another and prosaic explanation of a deal of this fluttering,—the bird is catching an insect.

In fig. 14 the rise in the gust cycle, obtained by the delay soaring, is the height of S above A_1, but a bird cannot pursue the sharp-cornered path. The actual path may be somewhat like the thick dotted line, which, repeated, gives a path resembling fig. 16, I.

When the bird has friction the path is tilted nearer the true level, like fig. 16, II., *but, more than in any other soaring, the shape of the path is greatly altered*, the waves being made lower in amplitude. In fact; friction makes this class of soaring so difficult that it is doubtful if there is any of it worth the mental effort of obtaining by a bird or aeroplane that has not a better gliding angle than 1 in 5. The general reason is that the head resistance prevents the bird or machine "falling" into the head gust gravity to acquire the store of kinetic energy to subsequently carry it up against common gravity. On the other hand, there is reason for believing that this soaring may utilise the short sharp gusts, or minor irregularities of the atmosphere, with T less than 6 seconds, that the other kinds of soaring cannot utilise. The aggregate energy ready to hand in these numerous little irregularities, and obtainable, probably, by frequent delayed jerks in the angle of incidence of the wings, may be of very considerable amount.

Since the author knows that a damped aeroplane which dips down momentarily to head gusts can already be easily constructed and, with care, be put in tune with the prevailing average gust character of a given wind, the realisation of sufficient soaring to *aid* flying is a proximate possibility full of practical interest. (See Chapter XII.)

Combined Soaring

Delay soaring may be profitably combined with every other class of soaring except uniform wheeling soaring, which is a pure form quite unique in admitting of no improvement when the bird has the usual friction.[1] In fig. 10 and fig. 11 the rises are greatly increased if the bird dips down in each half gust cycle, before ascending. Delay soaring may also be combined with the structure gust soaring soon to be described.

[1] If the bird had no friction it could refrain from rising for an hour, while continually gathering a headway capable of giving it an enormous rise at the end of that time, and a greater final elevation than if it had soared uniformly for the whole time. Notice, for example, in fig. 14, that the 6-second path A_1PQR gives a greater rise at R than twice A_1A,—which would also be a 6-second path, but for steady soaring.

Note.—Nothing has been explained with reference to soaring by upward and downward acceleration of the air. A bird that had no friction would be able to obtain a great deal of soaring effect from such accelerations, but, with the friction birds actually possess, it can be shown that the soaring obtainable of this kind is practically negligeable. It can also be shown, however, that some of the best soaring birds, that is those having the best gliding angles, do obtain what is possible of this soaring effect when they are pursuing the policy defined on page 88.

CHAPTER IV

STRUCTURE GUSTS

WHILE, in all cases, the gust is measured by the acceleration of headway it impresses upon the flying object, the acceleration may be caused in other ways than by an absolute acceleration of the air at the point where the flying object is placed.

Referring to fig. 17, let us suppose the machine is flying in some direction which need not be specified, at a point in the air where the velocity v of the *air* is represented by the vector AG. And let us suppose that, owing to the machine moving across the air, it finds itself, one second later, at a place where the air has a velocity represented by the vector AE. Now, the vector change in velocity between AG and AE is GE, and this change has occurred in one second. Hence, EG is the acceleration of headway impressed upon the machine as a consequence of its moving across what is called the "velocity structure" of the air.

Drawing AC equal and parallel to EG, and AB downwards 32·2 units in length, the relative gravity is found to be AD, and the machine, if ordinarily self-righting, *commences* to right itself with respect to this gravity, in the manner that has already been explained in Chapter II. Since the structure gust

CA alters in magnitude and direction with every change in the magnitude and direction of the headway of the machine, as well as with every change of place, the word "*commences*" must be included in the above statement, the complexity it suggests being, unfortunately, inherent in the case. If the machine had been flying in the opposite direction (still unspecified), so as to change vector AE to AG, the dotted construction finding the relative gravity AD_1 would have been employed. It will be remembered, the relative gravity of a pure acceleration gust did *not* depend on the direction of flight.

Compression Structure

One simple example of velocity structure in the atmosphere consists in the air farther and farther to the right of a given particle having a greater and greater velocity to the left, the alteration in velocity being, say, a_d ft. p.s. *per foot distance* to the right. It is evident the air particles of this stream are closing together very much as the particles of a stretched length of elastic close together when we allow it to contract, on which account it is called "compression structure." The term is not necessarily meant to imply the air is really being compressed in volume, because the particles may be being extruded transversely of the axis of the stream, just as in the case of the elastic. If we select one particle in the stream and refer velocities to that, the particles to left and right are moving inwards to right and left, respectively, towards that selected particle, and at a velocity $V.a_d$ ft. p.s., where V is a distance in feet from the selected particle. It follows that a flying machine, of headway V, flying either left or right in the stream, will have a *positive* acceleration of headway or head gust $V.a_d$ ft. p.s. p.s. impressed upon it, and, therefore, be able to soar in *either* direction.

This is illustrated for a compression structure in fig. 18, where $a_d = 0{\cdot}13$ ft. p.s. per foot distance left and right from A. The bird is supposed to have a headway V of 50 ft. p.s., so that $V.a_d$, or the strength of head gust created by the bird in flying *either* left or right from A, is 6·50 ft. p.s. p.s. The relative gravities, and virtual levels AF and AF_1 (*both* pointing upwards) for left and right flights respectively, are found in the usual way.

But there may also be, and usually will be, a true acceleration of the air at A (such as that in fig. 5), in addition to the structure gust. This will add its vector on to the vector of the structure gust (fig. 18), and so tilt the virtual levels AF and AF_1 to the positions AF_2 and AF_3, respectively, and to an extent depending on the strength of the acceleration gust. It will be seen, therefore, that it is characteristic of compression structure to make the virtual level surface of the trough-like or concave form FAF_1 or F_2AF_3, *encouraging soarability in both directions from A.*

Expansion Structure

If the air right and left of A is moving away from A, just as it was in the last case assumed to be moving towards A, we have what is called "expansion structure" (fig. 19). If a_d, the increase in velocity *away from* A per foot increase in distance left or right from A, is again 0·13 ft. p.s., the bird of headway V of 50 ft. p.s. will obviously create a rear gust for itself of strength $V.a_{d}$, or $50 \times 0{\cdot}13$, or 6·50 ft. p.s. p.s., in flying *either* left or right from A. The virtual levels are then found to be AF and AF_1, for left and right flying respectively, so that soaring is made *negative*, or *downward*, for flight in *either* direction. An additional acceleration gust at A tilts the pair of levels AF and AF_1 into the dotted positions AF_2 and AF_3, and if it is stronger than the structure gust it may produce positive soarability in one direction while making the negative soarability *worse* in the other direction; but it is evident that expansion structure always bends the virtual level surface at A into the roof-like or convex form FAF_1 or F_2AF_3, *detrimental to the soaring in either direction from A.*

If it were not for these expansion structures it would be possible to say that some degree of soaring is perpetually possible in the atmosphere, for, apart from them, the air is always accelerating more or less in some direction at every point, and so creating a flat virtual level plane at each point, one side of which (up which the bird may choose to steer) always points upwards. But, since expansion structure often bends down both sides of this virtual level, so as to bend down even the higher side below the true level, *it often happens that, for several moments, soaring is impossible in every direction of flight from a point.*

Structure Gust Soaring

A Standard Example

Fig. 20 illustrates a standard example of structure gust soaring. In the middle view is shown, in plan, a funnel-shaped chasm or cañon out of which issues a wind. The wind velocity v is over 50 ft. p.s. at the extreme right, but the chasm is so widened that the velocity is 6·44 ft. p.s. less, per hundred feet to the left, travelling out of the chasm. The slowing down is, of course, due to substantially the same volume of air passing successively through each section in one second of time, while having wider and wider sections to pass through. The chart at the top of fig. 20 is drawn to show the velocity v at each section of the chasm.

A bird of headway $V = 50$ ft. p.s. is supposed to glide into the chasm, from the left. Since it is rushing from nearly calm air into a head wind of nearly 35 m.p.h. at the narrow end of the chasm, it scarcely needs formal argument to show the bird will rise in preventing increase of headway, and when it wheels round in the narrow part and goes back, formal argument is again hardly necessary to show it may *still rise* in keeping constant headway, seeing that it is starting the return with an absolute velocity of nearly 100 ft. p.s. (*i.e.*, $V + v$), and charging down upon air which is at rest at the extreme left.

The *absolute* soaring path is shown in the elevation view, and the way it is derived is indicated in fig. 21, in a relative gravity diagram that refers to the 200-foot ordinate or section of the chasm.

As the bird proceeds into the chasm, while preserving its constant headway V of 50 ft. p.s., it crosses the 200-foot ordinate with an *absolute velocity relative to the cliff side* of $(V - v)$ ft. p.s., where v is the right to left speed of the wind at that point. Now v is there about 19 ft. p.s., so $(V - v)$—which may alternatively be read off the top chart—is about 31 ft. p.s.

But the v curve of the chart shows that the slowing down air is compressing from each side upon the air particles at the 200-foot ordinate, and with a difference of velocity of 6·44 ft. p.s. per 100-foot run left or right. Hence, the bird of headway 50 ft. p.s. is creating, by reason of its headway, ***a structure head gust*** of $\frac{50}{100} \times 6{\cdot}44$ or 3·22 ft. p.s. p.s. That determines, in fig. 21, BE and the relative gravity AE; AB being, of course, common gravity. But the air at the 200-foot ordinate is also accelerating to the right in slowing down its movement to the left. It is slowing down 6·44 ft. p.s. per 100 feet it travels; but, as its v is there only 19 ft. p.s., it is really accelerating to the right at only $\frac{19}{100} \times 6{\cdot}44$, or 1·22 ft. p.s. p.s. This *acceleration gust*, for such it is, determines EE_1 of fig. 21, and so the final relative gravity[1] AE_1. The line AF, 50 feet long, to scale, and at right angles to AE_1, is therefore the soaring path and velocity vector *relative* to the air,[2] that results, and setting off FG 19 feet long to represent v, we find AG, the *absolute* velocity vector of the bird in the direction it pursues *relative to the cliff wall.* This direction determines the *direction* of the length of path AB in the elevation view

[1] If we wish to obtain the result straight away, without troubling to build it up synthetically, we may notice, that, the air per hundred feet to the right along the chasm has 6·44 ft. p.s. greater velocity to the left, so that, if the bird could be instantaneously reduced to a hard, smooth, concentrated mass, its $(V - v)$, or 31 ft. p.s., absolute velocity, would give it an acceleration of headway of $\frac{31}{100} \times 6{\cdot}44$, or 2·00 ft. p.s. p.s. This 2·00 ft. p.s. p.s. is *at once* BE_1, or $(BE - EE_1)$, or $(3{\cdot}22 - 1{\cdot}22)$ of the synthetic process of fig. 21. This simple method lumps the component gusts together into a kind of composite structure gust relative to *absolute* co-ordinates, still giving, however, an acceleration of *relative* headway.

[2] Seeing that the path is slightly upward, the velocity structure gust is slightly weakened; but as the change depends on the cosine of a small angle, the necessary correction is quite beneath notice.

of fig. 20. It slopes upwards at 1 in 10, and, it happens, the absolute path has everywhere else the same slope, because it has been so arranged, for simplicity, in this particular example. Fig. 21 also shows, on its left-hand side, how the slope of the path on the return journey (again 1 in 10) is determined, and it is expected the construction will be understood without a full description.

It is by no means unlikely that the soaring of Professor Langley's famous buzzard, at "one spot," in the "aerial torrent" between the banks of the Potomac River, was of this variety. Nature cannot often arrange things so conveniently, and birds have a deal of curiosity; it is therefore possible that, in its constant repetition of its soaring, the bird was revealing an inquiring mind of its own kind somewhat in sympathy with that of its distinguished observer.

It will be noticed that there is an acceleration gust associated with the structure gust all along the chasm, and it is very difficult to see how there can be an example of a *pure* horizontal structure gust, for more than a single instant of time, for a flying machine.

When the wind is blowing into the chasm it must be avoided by the soaring bird, because the air is then expanding. The bird will suffer just as much negative soaring, or loss of height, as it before obtained of positive soaring, or gain of height. Expanding structures are probably the *principal* sources of those *remous* which aviators find associated with *certain spots of land*, as over certain parts of aerodromes, and which seem to take away the support from machines flying *rapidly* through them.[1] Structure gust is found in great variety of form, and the chasm example is only one of the simplest forms. Delay soaring may, as usual, be combined with fig. 20, and considerably increase the rise obtainable.

[1] *Model* aeroplanes are little disturbed by structure gusts, because of their inferior speeds. Balloons, having no headway, do not feel them at all, but only feel the pure acceleration gusts. A balloon, drifting through the chasm of fig. 20, will tilt at each point solely in accordance with the acceleration gust at the point.

CHAPTER V

THE AMOUNT OF SOARABILITY IN THE WIND

PASSING over fig. 22, we have, in fig. 23, I., a diagram showing, radially, the magnitude and direction of the velocity of a wind during 12 seconds. This wind is constant in magnitude, for all the radii represent, to scale, $v = 10$ ft. p.s., but it steadily boxes the compass. It is, of course, one of the winds permitting uniform wheeling soaring, but, at the moment, attention is not being drawn to that fact.

Consider, now, the first second of time. The velocity changes from the radius vector between the figures 12 and 1 to the radius vector between the figures 1 and 2. Hence, according to the resolution of velocity vectors by triangles, or parallelograms, the velocity added—in vector sense,—during the first second, is represented in magnitude and direction by the line forming section 1 of the circumference of the circle. Similarly, section 2 represents the acceleration during the next second, and so on; and it follows that the whole circumference of the circle divided by the whole time, or $2\pi v/T$, is the average acceleration a of the wind. In other words, $a = (2\pi v/T)$ or the average length of the circumference of the wind velocity-vector diagram traced per second, as measured on the velocity scale.

In fig. 23, II., is shown a less regular wind velocity-vector diagram, but just the same reasoning applies, so the average acceleration of the wind is again the total length of the traced line divided by the total time. The total length is 58 on the velocity scale, and, the time being 12 seconds, the mean acceleration is $58 \div 12$, or 4·8 ft. p.s. p.s. Now, this is (4·8/32·2) of 32.2, or $\frac{1}{7}$th of *g*, so the wind of this diagram is able to raise a frictionless bird up an average slope of 1 in 7, or keep level a bird having an effective gliding angle of 1 in 7, —assuming the bird utilises all the constant-headway wheeling soaring effect the wind is *proved* to contain (It may contain much *more* soaring effect.)

We thus have the following rule :—

> Having obtained a velocity-vector diagram for the wind, for a time T seconds, find the total length, according to the *v* scale, of the path traced by the pen, and divide by T to find the mean gust acceleration. On dividing *g*, or 32·2, by this mean acceleration, the result will be the *n* of the gradient, 1 in *n*, representing the minimum degree to which any perfect wheeling soaring bird may obtain soaring assistance from the wind gusts of the particular wind.

Fig. 25 is a copy of a velocity-vector diagram actually taken during 60 seconds of a N.E. wind that was blowing at Pyrton Hill, on 13th October, 1910. The original was published in the Government Advisory Committee's Report for 1910–11, in connection with Memorandum No. 35 by Mr J. S. Dines, M.A. The total length of the path traced by the pen is about 440 ft. p.s., according to the radial velocity scale, and, the time T being 60 seconds, the mean gust acceleration is 440 ÷ 60, or 7·3 ft. p.s. p.s. Then, 32·2 ÷ 7·3 being 4·4, the given wind was able to help a wheeling soaring bird to the extent of a gradient of 1 in 4·4. That is to say, it would have kept a frictionless bird soaring up a gradient of 1 in 4·4, or have kept level a bird with an effective gliding angle of 1 in 4·4. This helps to dispose of doubts as to whether there is sufficient gust energy available in winds, especially when it is seen later that the velocity-vector diagram only shows with certainty the soarability available by the pure acceleration gusts, and leaves out of account structure gust soarability of two kinds (horizontal and vertical), each of which may yield as much again in soaring effect. Delay soaring is also left out of account.

Referring again to the more open diagram of fig. 23, II., we know that each section, 1, 2, 3, etc., of the path represents the magnitude and direction of the gust acceleration during its particular second of time. But the wheeling soaring bird has to fly *against* the gust acceleration, and at a constant headway of, say, 30 feet per second. Now, on drawing twelve equal short lines, each 30 feet long, to scale, and in succession drawn in the opposite directions to the sections of fig. 23, II., and each one commencing at the end of the last one, we shall find that we only reproduce, to some scale, the shape of the velocity-vector diagram, but turned round 180°. Therefore, *the best wheeling soaring path of the bird, relative to the air, as viewed from above, is of the same shape as the velocity-vector diagram.* (As a matter of fact this is not strictly true, the resemblance is only a close one. There is a difference in shape owing to the sections of the vector diagram not all being equal, but the difference is not marked enough to affect the present argument.) For similar reasons, the wind vector diagram of fig. 25 represents, substantially, the best path of the wheeling soaring bird, relative to the air, to obtain all the proved soarability in that wind. But it is beyond belief that even the quick-manœuvring swallows could thread such a path in only 60 seconds. Hence, a good deal of the 1 in 4·4 soarability of that wind must be unavailable. However, the exploring point was only 36 feet above the ground, and there is room for hope that, if it had been, say, 200 feet high, where birds really do start soaring, the diagram might have been less tortuous, without necessarily being of less total length. The 96-foot tracings of the Government Blue-book do not support this hope very much, but the soaring would be less difficult if some of the extreme jerkiness of direction could be traced to the instrument, in accordance with the suggestion in the Memorandum.

To compensate, there are, as has been suggested, several reasons why the air may have been *more* soarable than is expressed by the gradient 1 in 4·4. In the first place, the bird may combine delay soaring with the wheeling soaring; that is to say, it may delay rising and falling to the fluctuations of the gust. In the second place, the diagram takes no systematic account of structure gust. For example, in fig. 23, II., section 1 may be as shown because it is either lengthened or shortened by a structure gust created by the exploring point having velocity structure passing over it.[1] The next section may also be lengthened or shortened in like manner, but the probability of random selection shows that a number of such sections are

[1] The exploring point is virtually *flying relative to the air.*

unlikely to have their average made either longer or shorter by the structure gust effect. This is equivalent to saying *the wind velocity-vector diagram gives the mean acceleration gust only.* But the unrevealed structure gust is there in the atmosphere, making something considerably better than the 1 in 4·4 gradient express the real soarability of the air. There is room here for a deal of investigation. What we appear to require knowledge of is the average difference of velocity of air particles one foot apart in various directions from the direction of the acceleration gust. Probably, to determine average structure gust, a number of exploring points, say seven, ranged in a circle of about five feet radius round a central one, and each determining at the same time its own velocity-vector diagram, will have to be used. The diagrams will almost certainly have to be dotted with time-spots.

Some instruments that have been used for measuring wind gusts only show the fluctuations of wind velocity in the same direction as the wind, and the charts, instead of being radial vector diagrams, are of the ordinary rectangular variety with wind velocity ordinates against time abscissæ. All the soaring definitely *proved* by such a diagram is evaluated by adding together the heights of all its mountains, and depths of all its valleys (at *right angles* to the abscissæ), as measured by the velocity scale, and dividing by the total time T seconds. This gives the average acceleration in the line of the wind, and it is probably only about half that which would be disclosed by the full radial vector diagram.

It may be gathered from the above remarks that *the gustiness of a wind cannot be properly expressed by* *velocity, or even by the width of fluctuation of velocity.* For *aeronautical* purposes *the mean gustiness is measured and expressed by the mean acceleration, and the maximum gustiness is measured and expressed by the maximum acceleration.*[1] A wind may vary from 20 to 60 miles an hour, but if it takes ten minutes to do so, no aviator will experience a gust. Acceleration bears just the same significance for the aviator that wind velocity bears for the constructor of factory chimneys, bridges, ships, and earth-bound structures liable to wind pressure.

[1] It is an interesting pursuit to devise an instrument to give a direct reading of the mean (or maximum) gust since first being exposed to the wind.

CHAPTER VI

THE PATH OF THE WIND

IN fig. 23, I., the radius between 1 and 2 is the mean velocity of the wind for the one second between $\frac{1}{2}$ and $1\frac{1}{2}$ seconds from the start; therefore, the radius represents the displacement of the air, in both magnitude and direction, during that one second. The same is true all round the circle. Hence, starting at a point 1 in fig. 22, and drawing lines equal and parallel to the successive radii of fig. 23, I., the *path* of the wind is determined. It is circular, in this case, as might have been anticipated. Figs. 22 and 23 I. being of similar shape, and related as described, it is evident that v/r in one is equal to a/v in the other, and therefore that $a = v^2/r$. This is the familiar expression for centripetal acceleration, used in connection with centrifugal force and in connection with uniform wheeling soaring.

In a corresponding manner the irregular wind path may be drawn for fig. 23, II., or even fig. 25—after it has been provided with time-spots; but wind paths so derived, other than the circular one, are not very reliable, because structure gust perturbations of the instrumental record, and certain other effects, are not allowed for.[1]

[1] Actually, "the path of the wind" means little; every particle moves differently. The velocity-vector diagram only gives the path on the assumption the wind moves in one mass.

Just as the circumference sections of the wind displacement-vector diagram of fig. 22 give, in magnitude and direction, the radii vectores of the wind velocity-vector diagram of fig. 23, so also do the sections of the latter give, in magnitude and direction, the radii vectores of the wind acceleration-vector diagrams of fig. 24. The sections of these diagrams, again, give the ***rate of change of acceleration*** in ft. p.s. p.s. ***per second***, for which the author proposes the term "suddenness" of the gust. "Suddenness" measures the liability of a gust to produce oscillations in a flying machine, just in the same way that acceleration of the wind measures the liability of the wind to produce oscillations in ships, factory chimneys, bridges, or other earth-bound bodies. Colloquially, one may say that all the derivatives of the wind, in their relationships to earth-bound bodies, are "moved one up" for flying machines.

In figs. 22 to 24 whole seconds of time have, of course, only been used for simplicity for the time intervals in the arguments. In cases where the diagrams are very much curved the reader may use shorter intervals, say tenths of a second, afterwards using the factor 10 at obvious points in the reasoning. The limit of this method, with infinitely short intervals of time, is the completely satisfying mathematical proof of each proposition.

CHAPTER VII

MECHANICAL ANALOGIES TO SOARING

IN fig. 26, I., is shown a light wooden track, and a ball or marble rolling upon the track. To make the experiments instructive, an appreciable amount of friction should be introduced into the rolling of the marble, as by covering the track with deep plush, the pile of which the marble has to crush as it rolls. The track is placed on a polished table and pulled to and fro, and in order to eliminate friction the underside is covered with felt, baize, or velvet.

To make the ball roll it is necessary to tilt the track at an angle called the angle of repose, or angle of friction, usually designated by ϕ; that is, to tilt it until the component of gravity down the track is just greater than the opposing friction. It is evident, therefore, the ball rolls when gravity makes an angle ϕ with the perpendicular to the track surface.[1] After measuring the angle ϕ to be 1 in n, say 1 in 5, assume we place the track level again, and the ball near the right-hand end. If we now accelerate the track to the right with an acceleration of $\frac{1}{5}$th gravity, or 6·44 ft. p.s. p.s.,

[1] For solids, the ratio of the frictional resistance along the track to the force pressing the object upon the track is constant, independently of the magnitude of the latter force. Angle ϕ, therefore, in no way depends upon the *strength* of gravity.

this impresses upon the ball an equal and opposite acceleration *relative* to the track, that, combining with gravity, produces a resultant acceleration tendency, or resultant *relative* gravity, AB, at the critical angle ϕ with the track. This, of course, entirely supersedes common gravity *so far as the track and ball are concerned*, and the ball, accordingly, rolls "downhill" to the left, *relative* to the track.

In plain language;—by hurrying the track (air) to the right, we can make the ball (bird) travel to the left, relative to the track (air), at steady velocity relatively to the track (headway), in spite of friction (head resistance). This is clearly analogous to the frictional soaring along AF in fig. 5.

In fig. 26, II., the experimenter is in a tramcar, with a pendulum, a large aquarium bowl of water, and a 1 in 5 light model glider. When the car is at rest, or even in *steady* motion (wind only), these pieces of apparatus act in the familiar manner; but if the motorman *accelerates* the car to the right at 6·44 ft. p.s. p.s.[1] (a gust of that strength), the pendulum will tilt itself as shown; also, the surface of the water will tilt; the experimenter will have to lean back to keep his balance; and, lastly,—assuming the rear door of the car is closed to confine the air—the model glider,

[1] Acceleration to the right, of course, includes the case of *slowing* down of the tramcar's movement when it is running to the left. Acceleration throughout this work is used in its vector sense in which it is independent of the velocity at a given moment. A body may have *any* vector velocity and *any* vector acceleration at one instant of time, and when it moves in a circle the two are at right angles. The popular obsession that a slowing-down wind is not an accelerating wind, from such points of view as soaring, must be discarded by students of soaring, and the fact that the *increment* of velocity may come from the left, or right, or any other direction, must be thoroughly understood.

launched from front to rear, will glide or *soar* parallel with the floor of the car. The whole car, in fact, will be found to have become a little world with a gravity of its own tilted at an angle of 1 in 5 to that outside.[1] If the driver switches on suddenly, so as to alter the acceleration suddenly (say in one-tenth second) from 0 to 6·44 ft. p.s. p.s., everything will be found to start oscillating—pendulum, water, and *glider*. That is because everything is left momentarily "out of place" as regards the new gravity, and in swinging to its new position of equilibrium overruns that position in a way easy to understand in the case of the pendulum. The passenger, moreover, will complain of "jerk," and the glider will have reason to complain of the 64·4 ft. p.s. p.s. *per second* "*suddenness*" of the gust.

When the car is stopping, the glider will soar in the opposite direction, but if the glider is launched in the wrong direction for soaring it will descend sharply, as if the supporting power of the air had vanished. It will then be, in effect, travelling down AG of fig. 5, instead of up AE, with the further loss of gradient due to friction, of course, added.

In fig. 27 is shown a round tea-tray, with a hollow rim, mounted on a square board, though this board is not really necessary. Everyone knows that a marble placed in the rim of such a tray may be made to career wildly round by merely shaking the tray round in a surprisingly *small* circle; even when the tray is kept flat upon a table, to eliminate accidental tilting. At

[1] Gliding fish in the aquarium may also soar, ***but only if the water is roofed in so as to have no free surface.*** If this is not done, the water simply tilts parallel to the virtual level, so that the fish, swimming parallel thereto, can get no nearer to the water-surface.

a pinch, this experiment may be performed with so simple apparatus as a pill in a round pill-box.

In fig. 27 the tray's centre is moved round the circle of radius r, centred at Q, and every other part of the tray is moved round a circle of the same size and in the same direction at any given moment. At the instant shown the tray is moving east with a velocity v, so every part of the tray, including the place A where the ball stands, is, at the moment, being accelerated south with acceleration v^2/r, or, alternatively, $r(2\pi/T)^2$, where T is the time, in seconds, of the circling. The ball (bird), therefore, has an equal and opposite acceleration tendency *relative* to the track (air), that has the component AC_1 in the flight path. This just equals the negative acceleration tendency due to friction (head resistance), and so the ball (bird) moves at steady headway.

If the ball lags behind at K, the component AC_1 becomes as strong as AC, and therefore *greater* than friction, and *hurries the ball forward to catch up with its revolving equilibrium position* as at A. If the ball, by chance, lags behind L, the AC_1 component is *weaker* than friction, and the ball, as a consequence, lags yet further behind, the defect gets worse, the experimenter loses touch with the ball, and the "soaring" is apt to end itself. The arc AL represents the "working zone" of the model, and it is easy to acquire the knack of keeping the ball included within that zone; just in the same way that the soaring bird keeps itself in similar relationship to the circularly moving air.

The model has many points of interest, but some of them have little connection with soaring, and will not be mentioned here. The dot-and-dash circle through

O is the polar sine curve showing, by its distance from O, the AC_1 momentary acceleration component in different directions from O; and the arc round O, of radius equal to friction, cuts the polar sine curve in two points defining the working zone. The working zone narrows if the speed of the tray is reduced with r constant, or if its circle of movement is reduced with T constant, showing that, as in the case of the bird, there is a certain $r(2\pi/T)^2$ below which "soaring" cannot be maintained. In starting, the headway is necessarily small, and therefore T large. The tray has then to be moved round in a large circle to make $r(2\pi/T)^2$ equal to friction. As the headway increases and T gets less, r may be reduced to minute dimensions, till the experimenter's skill is overtaxed, or confused, by the furious pace. He then increases r and reduces T to widen the working zone and make it move round more slowly, and the slowing-down ball soon drops behind into step again.

When the edge of the tray is pressed against a wall, M, it can only be reciprocated in a straight east-and-west line, but with very little more vigorous movement the "soaring" may still be maintained. This illustrates to-and-fro circular soaring, and if a long narrow tray with circular ends is used, or even a long oval tray, simple to-and-fro soaring may be illustrated.

Those who wish to make these models more impressive may use a track that spirals upwards, and, if they are skilful in operation, they may even employ one that spirals irregularly, crossing and recrossing itself like a scenic railway. These forms are of no more scientific value than the simple flat tray except, perhaps, so far as the skill required to operate the "scenic railway" form suggests the amount and kind of skill the *irregularly* soaring birds themselves have to exercise.

One lesson these models teach:—It is far more important to *feel* the relationship between the ball (bird) and the track (air) than to see it. If the tray is of very light wood, and the ball is heavy in comparison, *the circular soaring can be conducted quite as well with the eyes shut, and without conscious control*, as it was with the eyes open, because *the reaction of the ball can be felt* On the other hand, if the track is very heavy and the ball very light, the model must be *looked at closely* in order to maintain the soaring. Birds, no doubt, *feel* their soaring relationship to the air as well as see it, and the reputed dozing of the albatross, when soaring, is not altogether incredible.

In fig. 28, I., a simple undulatory track is shown, and by suitably *pulling* such a track the ball upon it may be worked from one end to the other. Now, *this does not necessarily prove anything more than fig.* 26, for it is perfectly obvious that the operator may be pulling the track to the right with little greater acceleration than he did in fig. 26, but taking care to start the ball with sufficient headway to surmount the waves. The model, in fact, only begins to demonstrate something fresh when, *in consequence of the waves, the "soaring" is effected with a reduced displacement of the track*, while, when the "soaring" is effected with no final displacement at all, the model illustrates what it is generally supposed to do,—straight-ahead soaring by means of a reciprocating gust. The model, accordingly, to be convincing, *ought to be anchored to a mean position*, by rubber bands or by steel springs, as shown in fig. 28, I., permitting an emergency displacement of about one wave-length each way. The best plan of all is to make the wavy track an endless circular one of about 10 feet circumference, *pivoted, like a wheel,* at its centre. The experimenter then undertakes to maintain the ball in *continuous* "soaring" *without making one complete rotation of the track round its pivot.* The circular shape is, of course, merely an artifice to make the straight-ahead "soaring" endless, and the model must not be supposed to illustrate any kind of circular soaring worth mentioning.

The necessary reciprocating movement when such a model has symmetrical waves will be found to be *asymmetrical,* and to a very noticeable degree if the track (being covered with plush having a deep pile) is made to offer considerable frictional resistance to the ball's movement. The reasons are similar to those under which the bird is unable to soar when the gusts are symmetrical and it itself keeps to the constant-headway symmetrical path, as it did in fig. 13.

Experiment will usually determine an asymmetrical wavy track, like fig. 28, II., which will allow the ball to be kept in steady movement, one way, by a steady *symmetrical* oscillation of the track, though, for the reverse direction of flight, the jerkiness, and difficulty of keeping the ball "soaring," are likely to be increased.

When the model of fig. 28, I., is used to keep the ball "soaring" by asymmetrical jerks, *it illustrates asymmetrical soaring*; but when its track is shaped as in fig. 28, II., to allow of soaring by symmetrical jerks, *it illustrates delay soaring.*

It is practically impossible to construct any simple mechanical representation of structure gust soaring.

As has been pointed out by Mr Lanchester, mechanical models fail to resemble soaring in one respect,—they act on the principle of the gust (movement of the track) suiting the bird (ball), instead of on the reverse principle. For this, and other reasons, they are not very reliable guides to knowledge in the *details* of the phenomenon of soaring.[1]

[1] It is perhaps a mistake to lay so much stress on the models illustrating soaring that the student thinks of the models to the exclusion of the soaring. They illustrate certain mechanical principles underlying soaring, and as soon as these are understood attention should be withdrawn to the soaring itself.

CHAPTER VIII

VELOCITY SOARING

In connection with acceleration soaring it was remarked that the up and down accelerations only contributed to the soaring so far as they resulted in an upward displacement or velocity of the air. The soaring thus suggested consists simply in the air as a whole moving upwards, with or without a horizontal component of velocity, as fast as the gliding bird is compelled to lose height *relative* to the air.

For example :—A bird having a best gliding angle of 1 in 5, and a gliding headway of 25½ ft. p.s., loses 5 ft. of its height relative to the air, every second. It is obvious, therefore, that if the air rises at 5 ft. p.s., the bird will remain at constant height above the ground. In the very popular view this is held to explain *all* soaring, and to see a soaring bird is, mentally, to see a rising column of air, and be intolerant of any evidence or argument tending to unsettle this rather too simple explanation.[1] The question will be returned to later.

[1] At least, this was so up to the end of 1911. After that, the present author began to read and hear the usual distorted popular expositions of the views he had then published, rendered appropriatively in the first person singular. Such lectures and writings, mutually destructive of inaccuracies, are a useful part of the interesting natural process of the dissemination of new truths or points of view.

Stationary Soaring

Let us suppose we have a glider for which the best gliding angle and headway are 1 in 5 and 20 m.p.h., respectively. In a chart (fig. 29) having radial lines at various slopes, and arcs furnishing a scale of miles per hour for the lengths of the radii, put a spot on the 1 in 5 sloping line, at a distance, from the corner O, of 20 m.p.h., on the radial scale. Then, the radial line from O to that spot represents the best headway *velocity* vector of our glider.

In future, for brevity, such a point and vector on the chart will be expressed, in an obvious notation, as being the machine vector (5, 20), and, as a machine vector, it is always measured *downwards* from the right-hand top corner O.

The pilot now steers the glider steadily down a 1 in 4 gradient, and finding the headway is 25 m.p.h., he sets off the machine vector (4, 25), and so on for other gradients, to obtain for the glider the full characteristic headway curve shown. Theoretically, the curve continues within the best gliding point, as shown dotted; but no pilot can balance the machine in these glides, so the curve must be regarded as ceasing at the point (5, 20). Again, the curve goes far down in the other direction, but cannot be used because of the steep pose. The curve may be assumed to cease, at that end, at the point (2, 36); that is, at the gradient of 1 in 2.

Now, seeing that stationary soaring must consist in equilibrating or matching the machine's vertical and horizontal velocity components, or its whole vector headway, by the velocity of the wind, it is evident a site is wanted where the wind offers a great range of gradients to select from, and nothing better for this can be thought of than the side of a hill, such as that shown in fig. 30, the gradient of which varies from 1 in 2 at the centre to level at the top and bottom, as marked by the small figures along its profile. The stream-lines of the wind passing up the hill are shown in *a*, *b*, *c*, *d*, etc., and the loci of equal gradients on the stream-lines are shown by the arched curves marked 1 in 3, 1 in 4, 1 in 5, etc. Each arched curve twice crosses its contained stream-lines, and points in the soaring space above the hill will be referred to, in an obvious notation, as point (4½, *d*, lower), or (4½, *d*, higher), according to whether the point lower or higher up the hill, on stream-line *d*, where the gradient is 1 in 4½, is being referred to.

It is no use trying for *complete* stationary soaring on the hill, with our glider, unless the wind velocity is 20 m.p.h. up the hill, because that is the *least* head-way vector of the glider. With less wind velocity the glider must *inevitably* advance. On the other hand, it is no use trying stationary soaring when the wind exceeds 36 m.p.h., for if it is 37 m.p.h. the only machine vector that can equilibrate it is one for a steeper pose than is permissible in the machine, or steeper gradient than is to be found in the wind. The glider will *inevitably* be carried back over the hill.

We will assume the pilot likes his machine to fly down a 1 in 4 gradient *relative* to the air in order to have the slight margin of control, in the 1 in 5 direction of working his elevator, that he will be seen to stand in need of. He will then have to wait till the wind rises to 25 m.p.h., as seen by the machine vector (4, 25) of fig. 29.

Suppose, now, he takes his stand on the hill at the point (5, *a*, higher) in the 25 m.p.h. wind. The wind vector—measured radially upwards—is then (5, 25) of fig. 29; but there is not a single machine vector available that will not give him a resultant absolute velocity into the ground, except machine vector (5, 20), which gives the resultant velocity of 5 m.p.h. shown by the line (5, 25) to (5, 20). This velocity, unfortunately, causes the glider to vanish over the top of the hill. The rule under which the resultant absolute velocities are determined, is as follows:—

> Knowing, in fig. 29, the downward headway vector of the machine, as its elevator is set at a given moment, and knowing the upward vector for the wind around the machine, join the lower ends of the vectors to complete the triangle of velocities. Then, the length of this closing vector and its direction *from the end of the wind vector to the end of the machine vector*, represent, respectively, the magnitude and direction of the resultant absolute velocity of the centre of mass of the machine. *The direction of this velocity must not be expected to bear any essential relationship with the direction of pose.*[1]

The glider will be carried over the hill, in like manner, until the start is made from a point as low down the hill as (4, *a*, higher), where equilibrium

[1] The direction of pose is approximately that of the machine vector.

between the two vectors, and therefore stationary soaring, just becomes practicable.[1]

Notice, therefore, by similar reasoning, that the very highest point on the hill where soaring is at all possible is *where* the hill's gradient is equal to the very best of the machine, or 1 in 5, at the point (5, *a*, higher), and (see fig. 29) *when* the wind velocity is 20 m.p.h. As the wind increases, the highest soarable point travels down the hill, to vanish at the point (2, *a*) when the wind is 36 m.p.h.

We have seen that, with the wind velocity 25 m.p.h., stationary soaring can occur at the point (4, *a*, higher); but suppose the pilot now chooses a lower point, say (3, *a*, higher), and also chooses to keep close to the ground, although this is not quite his wisest policy. The wind vector for the machine is, at the start, (3, 25), and the machine vector giving a resultant velocity in the direction of the ground slope, in order to keep from rising, is (3, 30). The resultant itself is (3, 25) to (3, 30), or 5 m.p.h. just above the grass, and the pilot *cannot prevent the 5 m.p.h. forward movement if he refuses to rise.* Even with liberty to move as he likes the pilot cannot move away from (3, *a*, higher) with less absolute velocity than 2 m.p.h., directed about 50° upwards, for that is the *shortest* resultant that can be drawn, in fig. 29, from the wind vector (3, 25) to the machine's vector curve.

We are assuming, however, the glider keeps close to the ground, so that, as it goes forward, it is soon at the point (2½, *a*, higher) with wind vector (2½, 25) and

[1] In this marching down the hill the wind vector has obviously been changed from (5, 25), through (4½, 25), to (4, 25), where its extremity first intersects the characteristic headway curve.

machine vector ($2\frac{1}{2}$, $32\frac{1}{2}$), giving resultant ($2\frac{1}{2}$, 25) to ($2\frac{1}{2}$, $32\frac{1}{2}$), or $7\frac{1}{2}$ m.p.h. parallel with the ground. Similarly, at the point (2, *a*) the velocity over the ground is 11 m.p.h. After that point the velocity decreases till *it becomes zero at the point* (4, *a*, *lower*). Thus, once the glider gets at all within the stationary soaring point (4, *a*, higher) and insists on skimming the ground, it *cannot be prevented* from advancing to the point (4, *a*, lower), where it finds it can again accomplish stationary soaring. But inertia will carry it past (4, *a*, lower), say to ($4\frac{1}{2}$, *a*, lower). Now the resultant, parallel to the ground, of ($4\frac{1}{2}$, 25) of the wind and ($4\frac{1}{2}$, 23) of the machine, is 2 m.p.h. up the hill, so the glider, having overrun (4, *a*, lower), *will commence to return to settle to its stationary soaring at that point*. That is a very beautiful automatic arrangement, but great numbers of experimenters, finding the machine beginning to go back over the ground, take fright, and desperately put an end to the soaring, usually by digging the nose into the ground in the instinctive but mistaken view that they have to gather speed. They do not realise that coming to rest and the backward movement over the ground are perfectly safe, seeing that the pose and headway are both in order. Of course, it is hard to steer with confidence when travelling backwards up the hill, but that merely reveals the initial unwisdom of clinging so closely to the ground.

Since the attainment of stationary soaring in the 25 m.p.h. wind necessitates the machine being set as for a 1 in 4 glide in still air, we will assume the pilot, content to forgo his liking for the ground surface, takes his stand at point (2, *a*) with his machine set for an ordinary 1 in 4 glide. The wind vector being then (2, 25), and the machine vector being (4, 25), the resultant velocity is line (2, 25) to (4, 25), or 6 m.p.h. at 70° upwards. When this velocity has carried the machine to the 1 in 2½ arched curve, the resultant has become changed a little to the line between (2½, 25) and (4, 25), and so on, causing the upward path of the machine to curve slightly through the points near where the stream-lines and arched curves are osculatory to each other. If the machine, through inertia, goes too far, say to the 1 in 5 arched curve, the resultant becomes the *downward* velocity of the line (5, 25) to (4, 25), and ***the machine returns to settle at the* 1 *in* 4 *arched curve.*** That is to say, the machine, set for a 1 in 4 glide, ***always*** finds itself in equilibrium, as regards inward and outward movement, at the 1 in 4 arched curve, and consequently ***tends to hover of itself on that curve in a kite-like manner.*** Here again, numbers of experimenters, finding themselves leaving the ground at the point (2, *a*), lose confidence, and steer down, and finding they must steer down very much to keep from going aloft (about 1 in 2), resolve to terminate the experiment in any violent manner that suggests itself, and blame the wind for "upsetting" them. On fixing the elevator of the glider as for a 1 in 3 glide, and putting on a light ***artificial*** load, they are surprised to find the glider starts an excellent slow glide on its *own* account,—it has no nerves.[1] The experimenter, when himself controlling the machine, should collectedly allow himself to float up at the normal pose, or, if he prefers

[1] Sometimes, the experimenter will find it floats gently enough, on its *own* account, at the end of a couple of ropes.

it, keep low, but without being alarmed at the steep pose necessarily accompanying this action at the commencement.

If he starts at other points on the hill, with the machine set for a 1 in 4 gradient, he will also move nearly straight up in the air till he reaches the 1 in 4 arched curve. The paths are approximately parallel to the middle one, and are easily determined in similar manner.

Now, in rising as described, the experimenter may fear being blown back over the hill. Suppose, therefore, he starts from the middle point (2, *a*) with the deliberate intention of moving back as much as possible. With wind vector (2, 25), the machine vector giving the most backward resultant is (5, 20), so, in the direction (2, 25) to (5, 20) the machine commences to move. The path, after the next arched curve, is seen to change to the one ($2\frac{1}{2}$, 25) to (5, 20), and so on, giving, as a result, the path from (2, *a*) curving over the top of the hill. The *optional* paths from (2, *a*) are thus seen to range from forwards along the ground, to the backward curved path just mentioned—a most satisfactory range. These backward paths are also drawn for many other points, and those near (4, *a*, higher) are naturally the ones to which the interest of danger attaches, as will be shown.

Suppose the experimenter happens to be at point *e* over the top of the hill. This corresponds to the wind vector (∞, 25), and the most forward resultant velocity he can obtain is about 20 m.p.h., from (∞, 25) to (2, 36), at about 65° downwards. The path is indicated by arrows in fig. 30, and will be seen to just take him safely within the 1 in 4 arched curve, after which he may steer as he likes. But, *if the experimenter once gets into the black space over the top of the hill, his soaring is at an end*, for he cannot possibly dive into the 1 in 4 arched space before reaching the ground. He must at once dive to the ground and land his machine, accepting the steep pose and high speed, accompanying such action, as the least evil that can befall him. If he once gets behind the hill he will have to land *moving tail first over the ground.*[1] Though the black space is the positively dangerous space, the whole of the rear part of the arched curve should be avoided on account of the inconveniently vigorous movements of the elevator required to correct for trifling deviations from the stationary soaring condition.

With the aid of fig. 29 and fig. 30 it is, accordingly, easy to obtain indications of the best policy to pursue to be successful in this class of soaring. First choose a long, smooth, sloping hill, with a profile roughly as shown in fig. 30, and with a steepest gradient of about 1 in $2\frac{1}{2}$, or a little steeper. On a day when the wind is blowing up the hill at a speed about 25 per cent. in excess of the least gliding headway of the glider being used, take up position at the steepest point of the hill, and float off the ground. Do not prevent yourself floating up under a vain hope of staying afloat where you are and at natural pose,—that is impossible, as has been shown. Therefore, allow yourself to float upwards; but you will find you have practically complete control over the direction in which you move, and the safest plan to adopt is to steer

[1] Unless he prefers the alternative of landing with the wind, at a dangerously great absolute speed over the ground.

upwards at about 30° from the point you started from, and keep to that line. Acting on these instructions in the example of fig. 30, the machine will at first point steeply down, as for a 1 in 3¼ glide.[1] But it will have a headway of about 29 m.p.h., and an absolute velocity of about 5½ m.p.h., and as it rises to stop at the 1 in 4 arched curve its pose will reduce to that for a 1 in 4 glide in still air. So long as the experimenter has steered up the 30° path, and kept to it even when coming to rest, he may have confidence the flattening out of pose and coming to rest relative to the ground do not arise from the upturning of pose and loss of headway he properly holds in dread. Yet, winds will die down, and he cannot then ignore headway and keep in the 30° path. He must, therefore, resolve to keep to the 30° path only so long as this is consistent with proper headway; but whenever he feels his headway become reduced below about 20 to 25 m.p.h. he must steer below the 30° path, and forwards, even if his doing so terminates the glide—as will inevitably be the case when the wind sinks below 20 m.p.h.

As the wind dies down, the arched soaring curve extends *outwards* to the 1 in 5 curve by the time the wind has sunk to 20 m.p.h. For a little less wind velocity the 1 in 5 arched curve is merely distinguished by being the locus of the smallest absolute velocity in the machine, where the machine seems as if it is on the point of becoming stationary, but just fails to do so, and then proceeds

[1] Reason:—In fig. 29, a resultant line from the point (2, 25), and parallel to the 30° path in fig. 30, cuts the headway curve in point (3¼, 29) and is of length corresponding to 5½ m.p.h.

onwards and downwards with increasing speed. With strengthening of the wind, on the other hand, the pilot will find that keeping to the 30° path involves moving backwards and downwards, till, when the wind velocity has risen to 36 m.p.h., he will find himself deposited on the ground at the point (2, *a*) from which he started. This will be accomplished quite safely, provided he expects it, and does not confuse the backward movement with loss of headway. It is a curious fact, to be noted, that the increase of the wind *shrinks* the soaring space, and *the maximum dimensions of the soaring space occur with the weakest wind that will just make the soaring possible.*

The above advice presumes the experimenter knows how to balance a glider, but if he does not, he had better take up position near the point (4, *a*, lower). Stationary soaring on a 30° path is there practicable just above the ground, but usually only for a few moments at a time, because the variations in the strength of the wind cause the stationary point to advance and recede along the surface of the hill. The inexperienced pilot will not be prepared to follow these movements, and the absence of air-space below him will make the following of the movements actually require *more* skill than high up in the 30° path. As skill in balancing is acquired the start may be made further and further back, till, at last, the 30° path from the centre can be taken.

Since the machine tends of itself to remain at the proper arched curve, it might be thought the pilot need not touch the controls beyond keeping the machine facing the wind. Theoretically, in a steady 25 m.p.h. wind, if the machine could be set *exactly* as for a 1 in 4 glide, that would be true, but the elevator cannot be set exactly as for a 1 in 4 glide. If set even as near as 1 in 3·99, a study of the vectors in fig. 29 shows the machine will gradually creep round the 1 in 4 arched curve till the ground is reached at (4, *a*, lower). If the machine be set at 1 in 4·01, it slowly creeps round the arched curve in the opposite direction, till the dangerous black space is reached at the back. Though the pilot is necessary to keep these movements in check, his doing so requires less conscious effort than, say, the keeping of a cylindrical bottle in the centre of a tea-tray held in the hands, the bottle being rolling on its side. It is also easy to deduce that, in the 25 m.p.h. wind, the pilot can never execute a closed path either wholly inside, or wholly outside, the 1 in 4 arched curve, but he can always execute a closed path intersected by that arched curve. The semi-automatic character of the soaring is due to these peculiarities.

As a means of remaining poised in the air, in a strong wind, stationary soaring cannot compete with a man-lifting kite, because the latter is not confined to a small locality. It cannot compete at all with the captive balloon when the air is calm. It can, accordingly, only be of interest to sportsmen, and those who have reasons for making experiments with motor-less aeroplanes.

Birds do not practise stationary soaring to any noticeable degree, and probably for two principal reasons:—(1) The places *where* it is most easily executed are long bleak hills where the bird has no wish to hover. (2) The times *when* it is practicable coincide with the existence of strong winds, when a bird can find all the soarability it wants anywhere it likes to fly.[1]

In fig. 30, several streams of arrows are drawn passing from the right downwards. These are useful in indicating, approximately, the *most downward* optional paths for the machine at any point *within* the 1 in 4 arched curve, and the *most forward* optional paths *outside* the 1 in 4 arched curve. The other streams of arrows, passing from left to right, indicate the *most rearward* paths possible *within* the 1 in 4 arched curve, and the *most upward* paths *outside* the 1 in 4 arched curve. The wind is supposed to have a velocity of 25 m.p.h. The wind has not, in reality, the same velocity everywhere above the hill, but the modifications of the general conclusions arrived at are not worth troubling about.

It hardly needs pointing out that the experimenter in this class of soaring has to fly in a strong wind, and, consequently, to have a machine designed for the utmost stability in disturbed air. This does not necessarily mean that power of "running all by itself" which represents stability in the popular view, but the power of making its own adjustments to defeat the disturbing influence of a sudden change in the wind. To distinguish what is meant, and give the poor word "stability" a rest, we may say the machine must be designed with the utmost "flyability"—a

[1] As will be pointed out later, birds may be presumed to *feel* the air in soaring, and a form of soaring which can be shown to depend entirely on sight, and not touch, is not likely to be recognised by their soaring instinct.

somewhat inelegant but, it is hoped, expressive enough term.[1] (See Chapter XIII.)

General Velocity Soaring

Though stationary soaring is not adopted by birds, there is, as has been mentioned before, a common impression that the general soaring of birds is *simply* due to each bird keeping in a homogeneous upward wind. Such a conclusion is only too easy to arrive at.—Here is a bird gliding but not getting any closer to the ground,—what more natural than to suppose the wind is just carrying it upwards as fast as it tends to sink? The simplicity of this explanation is more apparent than real, as will now be shown.

Suppose a homogeneous column of air, 100 yards in diameter, is moving steadily upwards at 7 ft. p.s., and there are two similar birds, one inside that column and one outside it. The bird inside the column, which bird we will assume has a common gliding descent of 5 ft. p.s., relative to the air, knows, as it starts from the ground, that it is inside the column, because it can *see* the ground receding at 2 ft. p.s. But the *sight test fails* at perhaps 200 feet height, and birds are seen to soar up to 2000 feet or so. The sight test fails for the same reason that a man slowly drifting at sea, in a row-boat, cannot tell immediately whether he is approaching to or receding from a quay wall a couple of hundred feet away. The bird is worse off than the man because its eyes are nearer together, and judgment of approach or recession of the ground necessarily depends on the binocular

[1] A weight carried in front, on outriggers, is one of the simplest additions that may be made to promote this "flyability," (Chapters XII. and XIII.).

parallax. *It is impossible for the bird to feel that it is in the column of air, for its flight relative to the air, and the magnitudes and directions of all the forces acting upon it, are identically the same as when it is outside the column of air.* The bird can no more be dynamically conscious of its soaring, as by its sense of touch, than can a fish be when its aquarium is carried steadily upwards in a lift. Fig. 31, I., illustrates a 1 in 5 bird of headway 25½ ft. p.s., and so of normal descent of 5 ft. p.s., gliding level in consequence of there being an upward wind velocity CD, though any of the dotted winds having the same upward component will also keep the bird level. Notice that the downward pointing of the bird, and the forces acting, are *precisely* the same as they are during gliding in still air. In fig. 31, III., the bird is seen soaring upwards by the aid of an upward wind of 10 ft. p.s., but it should again be noticed that the pointing of the bird, and the forces acting, are absolutely normal. The effects of winds of 10 ft. p.s., in other directions than the vertical, are also shown by dotted lines, but the pose of the bird, and the forces acting, never alter. For comparison, the same bird is shown in the corresponding acceleration soaring in fig. 31, II., and fig. 31, IV. It will be seen that the diagrams of forces —copies of the diagrams of accelerations—are, in *these* cases, tilted, and so also are the poses of the bird. These comparisons will again be referred to, later.

Since the bird, when higher up than 200 feet, cannot detect that it is in the upwardly moving column, either by means of sight or by means of touch, *pure* upward velocity soaring, or soaring by means of a ***homogeneous*** upwardly-moving column of air, must be regarded as impracticable, except close to the ground, where, as it happens, upward winds are not usual. But the bird can always detect, by a sudden jerk, the moment of passing out of the boundary of the column, and this fact gives us a clue to the true nature of the nearest possible soaring to that which has just been pronounced impracticable.

The assumption that there may be a column of air, 100 yards in diameter, with a sharp boundary, moving upwards, is not true to Nature. An upwardly-moving column of air will usually have a fast-moving central axis, and less and less upward velocity away from that axis, so that it will be hard to say where the boundary lies. Now, if a bird is in the vicinity and heads straight for the axis, it will find itself in an *upward structure gust*, for it is moving from a place where the air has one velocity upwards to a place where it has a greater velocity upwards. The conditions of fig. 2, therefore, obtain. There is no doubt the bird can sense the direction of flight, at each moment, that gives the maximum upward pressure, and therefore head directly for the centre of the upwardly-moving column of air. But, having reached the centre and crossed it, it will, for similar reasons, find itself moving in a *downward structure gust* (refer to fig. 3) with the support of the air seeming to fail. This it will instinctively evade by turning round, and, again sensing the direction of maximum upward gust, it will again charge the central axis of the column. Thus, *it will come to dwell near the centre of the upwardly-moving column, and therefore be carried upwards by the column.*

In general soaring of this character the bird keeps wheeling about to keep hunting after the directions of maximum upward gust, and this most natural action automatically causes it to dwell within the upwardly moving *patches* of air more than within the downwardly moving patches. The popular view that soaring may be obtained from up-currents is thus justified, but not so far as it claims that this soaring is *essentially* simpler, and more obvious, and universal, than horizontal acceleration soaring.

That the uniform wheeling soaring of the tropics is acceleration soaring, and not up-current soaring, is indicated by the fact that the bird usually *points horizontally*, or even *upwardly*, like fig. 31, II., or fig. 31, IV., as if drawn by an invisible tractor screw, and *not* downwardly as in fig. 31, I., and fig. 31, III. This observation, when made, is conclusive.[1] The uniformity of the soaring can also be shown to render the up-current explanation improbable, while the way all the circumstances of the soaring agree with charts like fig. 8 constitutes almost irresistible evidence against the up-current explanation. Finally, direct observations have often been made showing the absence of an up-current where the birds are soaring. It would add greatly to the knowledge of this subject if someone would send up amongst the soaring birds a small captive balloon (say about a yard in diameter), and observe its movements through a low-power telescope with cross-wires in the focus of its eyepiece;

[1] Mr Wilbur Wright, in his paper read many years ago (1903), explained careful observations he had made to show the wings of the soaring buzzards pointed upwards at about 5° angle of incidence. These did *not* support the up-current theory; they are the very observations required to support the horizontal gust theory.

or, alternatively, photograph the balloon once a second, with a fixed camera. The author believes the balloon would be found to be executing loops of about 20 feet diameter in about a dozen seconds or so. Observations of the spiral manner in which narrow chimneys deposit their smoke plumes in the atmosphere indicate, to some degree, the fact of the air having such circular movements in calm, hot weather; but chimneys are too near the ground to furnish evidence of great value.[1]

[1] It is rather curious that (at least so far as the author is aware) the uniform movement of clouds across the sky is taken for granted. Have no observations been made to determine fluctuations of velocity having a period of about a dozen seconds or so? Balloons have been observed in the manner suggested for clouds, but not at close enough intervals of time.

CHAPTER IX

THE POLICY OF THE SOARING BIRD

THE many varieties into which soaring may be analysed creates a desire to see general soaring reduced to some simple, comprehensive, straightforward policy on the part of the bird.

Referring to fig. 5, AE is the best soaring path in the virtual level, and to keep in that path, from instant to instant, the bird has simply to use its "elevator," at all times, to keep constant headway (that keeps it in the virtual level), while using its "rudder" to find the steepest upward pose (that finds the path AE). In adopting this policy the bird is using its sense of *sight*, and in the continuous unidirectional gust (unknown to Nature), only the apparent direction of the ground can distinguish the path AE from the path AG or any other path in the virtual level. But, as regards each *fresh* gust, the sense of *touch* will always *commence* the soaring, for the bird has simply to steer to the side from which it *feels* the gust pressure come, and use its "elevator" to keep constant the headway. As fresh gusts are always commencing, or adding themselves to the existing one, the bird keeps itself in a perpetual state of commencing fresh soaring, and so obtains a good *average* soaring effect. This policy carries the bird through all the wheeling soaring up to fig. 12, and avoids the non-soaring condition of fig. 13.

Asymmetric soaring, positive and negative, usually surrenders itself, whether wanted or not, without any definite policy; but delay soaring requires the simple natural policy of charging as fast as possible into the head gust to obtain a good rise at the end. The combined policy of the bird to obtain both wheeling soaring and delay soaring is thus seen to consist in wheeling about to keep heading the gusts, and charging as fast as possible into each head gust when it is at its strongest, and steering up with more or less of a jerk when it is at its weakest. *Nothing could be imagined more natural and in accordance with the instincts of either man or bird in connection with obtaining the utmost lift from the gusts.*

It is easy to see that the same policy captures the available structure gust soaring in combination with the pure acceleration soaring. When the bird seeks out the direction of the head gust from instant to instant, and delays rising, it is solely concerned with the head gust as a head gust, *without reference to its causes.* For example, in fig. 20, the bird is simply flying, each moment, in the direction of the maximum head gust.

The above simple policy will not secure the stationary soaring of fig. 30, but we have the significant fact, mentioned before, that birds are rarely, if ever, noticed practising stationary soaring. Since soaring birds probably act by the sense of touch, a soaring in which the force reactions are absolutely the same as in still air must remain unrecognised by them.

General velocity soaring, or that soaring effect obtainable by dwelling nearer the centres of the upwardly-moving patches of air than away from them, is accessible to the bird by a simple policy depending on the sense of touch. The bird has only to wheel about to hunt after the direction which, at each instant, gives it the maximum sense of upward gust or pressure from below.

Therefore, the grand policy of the soaring bird, that, in proportion to the bird's manœuvring capacity, obtains all the available soarability in the air, consists in **wheeling about to seek, at each instant, the direction of the maximum upward head gust, and at the same time delaying rising and falling to the increases and decreases in the strength of the head gust.**

CHAPTER X

COMPARISON OF SOARING AND NON-SOARING BIRDS

In the discussion of soaring flight it was shown that the bird can only obtain soaring effect in proportion to its allowing its path through the air to be dictated by the wind gusts instead of by its own wishes. Now birds may be divided, broadly, into two classes;—(1) those that employ their time flying short distances from place to place; and (2) those that live in the air on a grander scale, make flights of long duration, and have no particular wishes as to the direction of flight from moment to moment so long as they keep afloat. The first class naturally contains the non-soarers, and the second class the soarers.

A good representative of the first class is a wood-pigeon. Such a bird's average flight is one of a few hundred feet from one tree to another, and it cannot find it worth while waiting five minutes or so till a favourable gust will allow it to pass from one tree to the other without flapping. Then, when it is under way, it cannot trouble to execute loops and turns in a path that it cannot be sure will terminate at the tree to which it is wishing to fly. Finally, the short flights, with frequent rests, make it unnecessary for such a bird to economise its strength. There is, therefore, every reason for wood-pigeons having the habit of flying straight to their goals, without any noticeable attempt at soaring.[1]

A good representative of the second class is the albatross. This bird has been forced, by the struggle for existence, to seek its living cruising over the oceans, and practically living in the air. Economy of muscular energy is practically a necessity, and it is easy to realise how, in past ages, the first rudimentary development of an instinct for soaring would be cultivated, by natural selection, till it reached the present stage of development, at which it is maintained. Since, for obvious reasons, except at the moment of picking up food, the albatross is indifferent as to the exact path it takes through the air, it can, and no doubt usually does, take almost the best soaring path possible from moment to moment. Taking advantage of the opportunities around it, its speciality is soaring close to the surface of the sea, by the air disturbances due to the waves. This is, of course, a form of structure gust soaring; but the albatross by no means neglects the other varieties of soaring, which it demonstrates to great perfection when at a considerable height above the sea.[2]

Very perfect soaring is also practised by the birds which have to keep afloat over the great hot plains of the earth, that are, in a sense, solid oceans. The

[1] In past evolutionary times, during the millions of years that have formed the race of wood-pigeons, these birds, *far more than in present times*, have lived in perpetual fear of birds of prey. Only strong muscular flight in directions determined by their own necessities, without regard to soaring, has been serviceable to them.

[2] So seldom is the albatross reported to be seen flapping, that it may be suspected of a kind of wheeling soaring on a very grand scale, in which it avoids, from day to day, the regions (such as dead-calm regions) with meteorological conditions unfavourable to soaring.

evidence seems to show that the air over these hot plains is often in the jelly-like oscillatory state of movement referred to in Chapter III. of this work, and the speciality of the birds is uniform wheeling soaring merging into to-and-fro wheeling soaring, and aided by up-current velocity soaring. The birds, to suit the conditions of their existence, are of very light weight per square foot, and low headway, a type that would be unable to contend with the stronger winds of our English climate.

In Northern Europe, soaring birds are not conspicuous, because the strong winds, as has been suggested, make it necessary for the birds to be rather heavy per square foot, and of considerable headway. This makes them unable to capture a great deal of the wheeling soarability of the air, and, as a consequence, their speciality is delay soaring in boisterous weather, aided, to a moderate extent, by wheeling soaring and velocity soaring. To this class belong the gulls, and, to a lesser degree, the swifts and swallows. The reason for the swallows being soaring birds, though living locally for half their lives, is not far to seek. Great numbers that fall below a certain standard of soaring ability are, every year, killed by fatigue, or drowned in the seas, during their migration. It may be pointed out that delay soaring, involving a lagging reaction to the gusts, is precisely the kind likely to be discovered by, and perpetuated in, a race of birds subjected to the same fatigue test as the swallows.

Intermediate between the gulls and the wood-pigeons are the rooks, which seldom soar without flapping, but show considerable discretion, at times, in availing themselves of the more pronounced aerial disturbances.

It will be understood, that, because a bird, even a wood-pigeon, is flapping, it must not be assumed to be not soaring at all. The two modes of flight are supplementary, and it would prevent soaring being relegated too much to the background if *it* were to be regarded as the fundamental mode of bird flight (the air is never quite still), aided, according to necessity, by flapping.

CHAPTER XI

HUMAN SOARING

In the absence of anything like complete data as to the structure of the atmosphere, in any locality and at any particular time, it is difficult to predict how far human soaring may be developed. Wheeling soaring depends, as shown, on manœuvring power, and there is small hope of aeroplanes or gliders ever being manageable enough to secure as much wheeling soaring as the birds obtain from the gusts. The highest type of wheeling soaring is the uniform soaring of the chart of fig. 8, and few gliding pilots could undertake to turn circle after circle in about 12 to 15 seconds, such as the chart suggests is necessary in this soaring. The tortuous character of fig. 25 suggests even greater difficulties in the way of general wheeling soaring. However, it must be remembered that, in fig. 5, the path AE is only the *best* path in the virtual level; those several degrees to either side, into and out of the paper, being little inferior. It thus comes about that a glider steered on an average straight course, without making any loops, might obtain a fair amount of wheeling soaring aid from the gusts by simply swerving left and right to the side on which the virtual level happens to be tilted up from moment to moment. The expert pilot who does not trouble about formal science will be acting in the correct sense if he keeps steering to the side from which the wind gusts seem to attack him. What he calls the "wind," in this connection, will really be the *element of wind added (in vector sense) to the wind*, that is, *acceleration and not wind*; but, so long as the pilot acts correctly, terminology is a detail.

If he wheels about, not only to the side from which the wind seems to attack him, but, in addition, to the side from which the wind seems to attack him in an *upward* direction, he will secure a certain amount of upward-current soaring in his wheeling soaring.

If only a pilot could cultivate the habit of systematically delaying rising to the head gusts, he would, no doubt, obtain very considerable aid to flight of the delay soaring variety; but, with present-day machines, in weather in which soaring is possible, the pilot's attention is so much engaged in defeating the attempts of the sudden gusts to disturb his balance, that he has no time to cultivate the more refined art of soaring. That may be remedied in time.

Stationary soaring, of the kind described in connection with fig. 30, is already easily practicable with suitably constructed gliders, but, compared with general free soaring, it is of little interest. It is likely, however, to prove a convenient means of getting afloat and obtaining practice in the general free soaring.

CHAPTER XII

AUTOMATIC STABILITY AND SOARING

Practical Lines of Development

It will be seen, in fig. 1, that the first stabilising improvement suggested for the aeroplane is the conversion of the wavy path AH into the damped path AI. Now, the common way of damping the aeroplane is to add a large tail surface or empennage. This, however, only defines the path AH *more obstinately* than before, unless the empennage is made with considerable spread in the fore-and-aft direction (*e.g.* placed in apteroid aspect), when there is a resistance to making very sharp turns *relative* to the air.[1] It is often overlooked that the air itself is sometimes turning sharply, and then this damping becomes a *source of disturbance.* Seeing that AD (fig. 1) is, in effect, gravity, and AB a component which is balanced, at the moment, by the lift of the aeroplane,[2] it is evident that the straight line AC will not be left if the headway, as the cause of the lift, be kept constant. One way of doing this is

[1] The "washed-out" ends to an aeroplane's wings often co-operate with the tail empennage to produce a very effective *combined* empennage of the kind in which there is a surface near the body of the machine, *also* travelling edgewise through the air. The two have a considerable moment relative to each other, and some *power* to define a *straight* path *relative* to the air. (The improved flight of *battered* models is a related subject.)

[2] This is, of course, the familiar static or force point of view, but employing AD as gravity.

to provide a propeller D (fig. 32, I.) that will give a *backward* thrust to check the tendency to increase of headway.[1] This propeller is entirely wind-driven as a wind-driven fan, and it acts as a damper by the simple process of resisting, through its fly-wheelage, change in its speed of rotation. This resists the too rapid changes in the headway of the aeroplane, and so resists the decreases and increases of headway that determine the descents and ascents of the wavy path AH (fig. 1). The device absorbs very little power in steady flight, because it is then only running idly as a wind-motor specially designed to have as small a no-load loss as possible.[2] When the headway of the aeroplane is changing, the fan does dissipate energy, and there would be good reason to doubt its power of damping if this were not so.

A fan of somewhat less size, but equal damping effect, may be employed when it is mounted, as shown, at a height above the main plane, so as to have a leverage by which to *turn* the main plane gently as if it were a huge elevator. The designer of such appliances has to pay great regard to the principle of maximum advantage in design. That is to say, because *some* fly-wheelage, or inertia, or constancy of speed somewhere is a good thing to have, it does not follow that the rule of "the more, the better" applies. So also with

[1] At this point, the fan's up-turning action upon the machine is not referred to, but only its augmentation of the head resistance as the machine tries to gather speed. For the moment, consider the fan D *not* elevated.

[2] The fan has thin smooth blades of symmetrical section and constant pitch throughout. It is also journalled on ball bearings so that it shall normally run as near to zero-slip speed as possible. Fly-wheel masses, the addition of which should not be overdone, may be added near the blade tips.

the height of this fan. As regards combinations of things, it often happens that several combinations will give equally good results, but each best combination is exceedingly difficult to discover.

One advantage of the elevated fly-wheel fan is that it helps to extricate the aeroplane from the dangerous situation in the downward rear gust of fig. 4, by pulling forward the top of the aeroplane, for a few moments, as it tends to lose headway, until the violence of the gust has abated. These are just the moments when the common elevator controls are *powerless* to do likewise, owing to the decline of headway.[1]

When such elevated fan is fitted specially with a view to soaring, it has the singular property of causing the aeroplane to tend to keep in the constant-headway virtual level from moment to moment, and of doing so in a *damped dead-beat manner* as regards the changes of pose. For example; if the aeroplane, in fig. 5, is moving along AF when the gust attacks, the fan will quickly place the aeroplane in the path AE, and *without oscillation.* So far as this is done automatically, the pilot who is striving for wheeling soaring has no more left to do than to steer right and left to seek, from instant to instant, the steepest upward pose, or, alternatively, to head into the gusts.

Referring back to fig. 1, and again viewing it from the familiar statical point of view with AD as gravity, the turning up into AH depends on the lift growing greater than AB under the influence of the increase in speed,

[1] The elevation of the fan, though increasing the damping of the free oscillations, also gives rise to disturbances of pose in rear gusts and head gusts. These disturbances are *advantageous* in rear gusts jeopardising the headway; in head gusts they are easily *compensated* for by the down-dipping effect of pp. 98, 99, etc.

exactly as stated before. But, though the lift can be kept down by resisting the increase in headway, it can alternatively, or additionally, be kept down *by decreasing the angle of incidence of the lifting planes.* A way of arranging this was described by the author in an article on "Longitudinal Stability in Gusts," in *Aeronautics*[1] of February, 1912. Described here in a briefer and more general manner, the method consists in placing a centre of mass W (fig. 32) forward of the machine to make it front-heavy, and counteracting this by an up-steering effect due to a *springily-mounted* elevating plane,[2] T. Owing to the springy tail frame ensuring the up-steering plane T being pressed upon with a substantially *constant* force by the air, it becomes impossible for the centre of mass to be pulled away from the straight path AC (fig. 1). The least increase in lift on the main planes simply tilts the planes round the centre of mass, and reduces their angle of incidence; or, in an alternative view, it turns the main plane and the tail in a down-steering sense relative to each other, to just the degree necessary to prevent the centre of mass being pulled up from its level path.[3] *The action is, in kind and degree, that of an ideally vigilant aviator.*[4]

When the rigid portion of the machine has a *retreating* centre of pressure with decreasing angle of incidence, or a permanent *down-steering* tendency, or a

[1] Reprinted on page 117.

[2] In the drawings of fig. 32, the springy tail is supposed to be constructed of cane. A front elevating plane *can* be used, if preferred.

[3] Because, of course, the endeavour to pull up the centre of mass is the cause of the bending of the machine. (See Article III., pp. 123, 124.) The machine is supposed to have no moment of inertia.

[4] This may seem an extravagant statement, but, as a matter of fact, it is a compliment to an aviator to say he succeeds in flapping his elevator as correctly as this automatic appliance.

negative righting tendency,—these are various ways of saying the same thing,—the machine dips down to the head gust; and it is now possible to add a *slow-acting*, overtaking, righting tendency—indispensable even when disturbance is substantially eliminated—and so obtain a self-righting machine which, in gusts, takes paths like AL (fig. 1) instead of paths like AI. This machine, consequently, realises the improvement indicated on page 7. The necessary slow-acting righting tendency is easily provided by a small "slow-fan," F (fig. 32), arranged to wind up or let down an elevator, under the influence of excessive or defective headway, respectively. With such arrangements added in a somewhat exaggerated degree, the machine tends to pursue the delay soaring path like that shown dotted in fig. 14, and the author has found that, besides improved stability, a certain degree of automatic soaring, as an aid to flight, is already practicable when such devices are properly designed in accordance with the principles underlying their action.

Though the author refers to appliances of his own invention, they are only mentioned as simple examples of practical methods of satisfying the stabilising conditions revealed by fig. 1 to fig. 5, and some of the soaring conditions referred to later. Other simple appliances *functioning similarly*, if known, may be substituted as examples, but it would not do to discuss them in these pages.

Fig. 32, I., shows, diagrammatically, the general appearance of the more simple models employed by the author in connection with these studies. The fan F is a small piece of thin wood-veneer bent into the form of a fan of such exceedingly long pitch that the blades are nearly edgewise to the wind. The fan is mounted on a double cotton thread or cord which it twists and shortens under the influence of the relative wind, and so winds up, and keeps in adjustment, the springy rod carrying the tail plane.

For flying in still air the fans D and F may be removed, and the tail-rod be made rigid, for *the practical problem of stability vanishes in still air.* Many models will also run quite well in some gusty air, without the damping fan D, and some light models have even been made to run well with *only* the damping fan D, and no fan F, and no central tail.[1]

The chief principle underlying the model is that of having a *yielding* connection between the elevator and the main plane, and it is obvious the tail plane may be rigid and the main plane be made to yield. This is, no doubt, the underlying motive in those machines designed with flexible rear edges to the main planes, but it does not seem the principle can be carried to its logical conclusion when only *part* of the lifting surfaces yields. Moreover, whenever this principle is carried out thoroughly, so that the machine has the momentary negative righting tendency for gusts, a slow adjusting-fan F is practically indispensable to give the machine

[1] These models should not be launched from the hand, but from a proper launching device that allows them to run several feet, at proper headway and pose, before release. A common rigid model is put in proper relationship with the air immediately it is released at proper pose and proper headway, but the model of fig. 32, I., requires, in addition, that the fan D should be rotating at full speed, and the fan F be fully wound, but not over-wound. Hand launching may be resorted to if there is a good deal of air space, below the launching platform, in which the model can "set" itself, but if a model shows it requires, say, 100 feet travel and 20 feet drop in which to "set" itself, it is futile thinking to shorten these by darting it at high speed, or up at the sky. The result is merely an erratic path, which may be explained but is not at all satisfactory to view.

a slow, overtaking, positive righting tendency. (See pp. 127 and 153.)

In fig. 32, II., a standard monoplane is shown robbed of its neutral empennage, which is replaced by a springily-mounted tail T with adjusting fans[1] F, and a fixed supporting tail plane M_1. Each of these auxiliary planes may be about half the area of the original empennage, and, having equal and opposite steering effects in normal flight, they may be regarded as the equivalents of the removed empennage. If, however, this construction results in M and M_1, *considered together as one rigid, compound, main plane,* having a positive righting tendency, a weak negative righting tendency should be formed by tilting the plane M_1 to a greater angle of incidence, and at the same time cutting down its area. The area removed may be added to T. In general, the angle of incidence of M_1 must be *greater* than that of M. *The pilot is left with his original flap elevator* E for occasional use so far as the automatic arrangements do not always act as he wishes.

Now, planes M_1 and T are not only equivalent to the empennage, in ordinary flight, but are equivalent to the empennage and the pilot, in disturbed air. A head gust, for example, squeezes M_1 and T towards parallelism, and, therefore, turns the equivalent empennage in a down-steering sense. Seeing that the exciting cause is the refusal of the weight W to be suddenly raised when T is preserved constant by the springiness, it is clear the down-steering of the

[1] One or more at each side of the propeller's draught. They are very simple, and in three or four lies complete security in case of breakdown of any one.

equivalent empennage is an exact substitute for that down-steering of the elevator E, which the pilot would otherwise have had to execute. Since E is a flap, and the tail fuselage is raised by the automatic action, E will be tilted, by the wind, with respect to the machine, but without the pilot's intervention, and only on account of its moving to remain *inactive.* If the pilot keeps his hand passively on the control lever of E, he will find *his hand actuated by the elevator.*

The experimenter is not under the necessity of applying this control in full degree, at first, if he does not wish, to his standard machine, as may be seen by supposing M_1 to be turned slowly to zero angle of incidence, at the same time that the fan-cord F is gradually slackened till T flaps out uselessly in the wind. The aeroplane is then back in its original fixed-empennage condition, and, in disturbed air, the elevator E will again have to be vigorously operated by the pilot, much to his dissatisfaction.

The damping fan (like D) may not be a very necessary addition to this aeroplane if the propeller is large, and, as usual, driven by a heavy rotary-cylinder engine having a good deal of fly-wheelage. The existence of the special stabilising properties of these engines is partly accountable for their popularity for aeroplane work. Not only does the fly-wheelage help to steady the speed of the propeller, but the large amount of power required to whirl the cylinders against air-resistance also helps to steady the speed of rotation. The cylinders of some engines are said to take one-fifth of their horse-power to whirl them round, or about one-fifth of the full-load torque of the engine.

Since this torque sinks with the square of the speed of rotation, while the mean indicated engine torque keeps fairly constant, or even increases, a fall in speed of rotation automatically releases a torque available for driving the propeller to prevent the speed of rotation falling as much as it otherwise would have done. The speed of rotation is correspondingly steadied when it tends to increase,—the cylinders demand more torque to whirl them round.

Multiple-propeller schemes, with several engines, are at present coming into fashion with designers, and they certainly tend to promote propeller stability. It may plausibly appear, that, to have the second propeller positively driven by a heavy (and expensive) engine, must be better than only adding fly-wheel effect; but too powerful and sustained a thrust, and a too rapid and sustained increase of thrust with decrease of headway, are liable to promote a kind of instability referred to by the present author in an article, "Propellers as Disturbers of Stability," in *Aeronautics*[1] of September, 1911. Moreover, power-driven propellers cannot be appreciably elevated.

Fig. 32, III., shows a glider of a form which has been found very suitable for the stationary soaring[2] described in connection with fig. 30. The glider has an independent mass *w* (a 10-lb. bag of shot, for example) carried in front, on outriggers. This is compensated for by the yielding tail plane T, as already described. The flap elevator E is under the control of the pilot, but he has only *passively* to follow

[1] Reprinted on page 109.

[2] And, to some extent, delay soaring, in which stationary soaring provides opportunity for practice. That is one use of stationary soaring.

its movements with his hand, apart from the deliberate steering movements described in connection with fig. 30. As regards mere balancing movements of E, he will find E actuates his hand, and not *vice versâ.* The tail T is not absolutely necessary to a self-reliant pilot who is confident he can maintain a steady downward pressure, on E, and yield his control lever to changes in the pull of E. Alternatively, E may be maintained in position by springs adjusted now and then by hand, and also, if desired for safety, by a fan F. The stabilising action of the weight *w* exists, but to a very inferior degree, if it is otherwise compensated for than by an up-steering elevating plane.

An elevated, wind-driven, damping fly-wheel fan is not always indispensable in the glider shown.

In some cases, two front masses *w*, one towards each extremity of the wings, may be employed, so that, acting as before, each one tends to warp the wing on its own side in the event of a gust suddenly tending to disturb the lateral pose. The most valuable practical property of such side weights consists not only in their themselves warping the wings, but in their prompting the pilot to handle his lateral control correctly in sudden gusts. He literally *feels* sudden changes in lateral pose. When the tips of the wings are as shown dotted in fig. 32, I.—a construction of itself promoting lateral stability—the side weights may over-correct for each gust, or tend to dip the side of the aeroplane down momentarily into each side gust. This is advantageous from the point of view of delay soaring, as well as stability.[1]

[1] *Up-pulled* rear flaps, similar to those of some Austrian machines, were also adopted by the author, in 1909, as an aid to these arrangements.

Automatic Wheeling Soaring

It has been suggested that, with a fan D (fig. 32, I.) helping to keep the machine in the virtual level, left and right turning to head the gusts should be performed by the aviator when he desires to pursue wheeling soaring. But, whenever a fresh gust *commences*, a glider generally heads into that gust automatically. How far this may be relied on in developing entirely automatic wheeling soaring the author is not quite prepared to say. The question is one of considerable difficulty. Continuous automatic soaring up the path AE of the continuous unidirectional gust of fig. 5 is, at least, absolutely hopeless, because only the sense of sight, as a means of directly perceiving the upward pose, can distinguish AE from other paths in the virtual level, and keep the machine in the path AE. But the obtaining of an *average* wheeling soaring effect in *fluctuating* gusts is not necessarily an insoluble problem.

CHAPTER XII—*continued*

REPRINTED ARTICLES

I

Propellers as Stabilisers

Prefatory Remarks.—The following brief article, contributed by the present author to *Flight* of October 1st, 1910, was intended to call attention, very simply, to the stabilising effect of propellers, in disturbed air, so far as such propellers act to resist fluctuations of headway. The stabilising effect of a wind-driven fly-wheel fan, such as D of fig. 32, I., is of substantially the same nature as that of the power-driven propellers referred to in this article, but with additional advantages due to the *permissible elevation* of such wind-driven fan.

A large propeller is advised, and, from the point of view of the article, it is regarded as an irrelevant detail that a single power-driven propeller beyond a certain size is not actually employable because of the powerful lateral counter-torque upon the aeroplane. The trouble is easily overcome by using two oppositely rotating propellers, and then the advice as to size, etc., applies to each of these. There is never any counter-torque with a wind-driven fan, on a frictionless bearing, however large the fan may be.

It will not be overlooked that the rotary-cylinder engines, with their considerable fly-wheelage and air resistance to the whirling cylinders, already conform to some of the recommendations of this article; and, as has been said on p. 102, the stabilising effect of such engines is no doubt one of the causes of their superiority for aeroplane driving. These engines, however, being heavy, are apt to be credited with more fly-wheel effect than they really possess, for their radii of gyration are not very great, and fly-wheel effect is proportional to the *square* of the radius of gyration. A given weight of fly-wheel is more serviceable when applied to an independent wind-driven fly-wheel fan, because there is less restriction to its change of speed, and consequent output of energy, in emergency.

The disadvantages of making the thrust increase too fast, or in too sustained a manner, with loss of headway (as by using very large, or several engines), are indicated in the article "Propellers as Disturbers of Stability" (p. 109), following the one below.

The stabilising effect of the propeller upon an aeroplane seems to be somewhat neglected, but perhaps this is because in full-size aeroplanes, as at present constructed, the stabilising effect is not so great as it is in some of the lighter elastic-driven models.

An aeroplane is almost invariably given a certain degree of automatic stability by first forming it so that the centre of pressure moves forward with a diminution in the angle of incidence, and then placing the centre of gravity where the centre of pressure lies during the desired steady flight. It is well known how the centre of pressure then moves forward, and steers the aeroplane up if it tends to dive; and how the centre of pressure moves backwards, and steers the aeroplane down if it tends to sweep up. It is also well known that such an aeroplane sweeps up to a sudden head gust, and down to a sudden rear gust. Why the aeroplane does not merely rise to a sudden head gust, but also rotates in an up-steering sense, is, however, not always made clear, for the head gust does not primarily alter the angle of incidence to bring the centre of pressure forward. The primary effect of the head gust is to increase the lifting force upon the aeroplane without rotating it, but once the aeroplane begins to move upwards, without being rotated, it is moving more edgewise through the air, and the angle of incidence is reduced. The centre of pressure does *then* move forward, and the up-steering torque is produced as a secondary effect of the gust.

It is evident that the disturbing effects of the head gust and rear gust, upon the pose, are caused by the changes in velocity relative to the air, and will be prevented by anything which keeps the relative headway constant. Now this is exactly what the propeller tends to do, for it is essentially an appliance for driving the aeroplane at a certain speed through the air.

When the aeroplane is flying steadily, horizontally, it shows that the propeller's thrust is just equal to the head resistance. If the relative headway then tends to increase or decrease, in consequence of a head gust or rear gust, the head resistance is increased or decreased respectively, while the propeller's thrust is decreased or increased. The alteration in relative headway is therefore opposed.

The features favourable to this form of stability, and the reasons why, are :—

(1) *A Large Propeller.*—This will drive the aeroplane on very small slip, and therefore be likely to give large changes in thrust for small changes in slip or relative headway.

(2) *Means for Preserving the Rotation of the Propeller against Sudden Change.*—This may take the form of fly-wheel energy, especially in full-size aeroplanes. In elastic-driven models, friction in the propeller bearing, or certain forms of inefficiency in the propeller, will have the same effect. If, for instance, the torque of the elastic is overcoming much resisting torque independent of the slip of the propeller, the speed of rotation will not vary greatly with changes in the slip or relative headway.[1]

(3) *A Light Aeroplane.*—This enables a small thrust to drive it, and the large propeller will be working on still smaller slip than otherwise, and have its thrust most sensitive to changes in slip or relative headway. The light aeroplane is also rapidly accelerated, backward and forward, by the small thrusts which act to keep the relative headway constant.

These features are characteristic of most successful elastic-driven models, and are little in evidence in the heavy full-size aeroplanes, with their small propellers without added fly-wheel effect.

The propeller-induced stability is primarily longitudinal in nature, but, in most aeroplanes, lateral loss of balance depends so much on loss of headway, that the propeller indirectly aids the lateral stability also.

[1] The rotary-cylinder engines, as has been mentioned on page 102 of this book, comply, to some degree, with these conditions.

From one point of view, the aeroplane, stabilised in this manner, may be simply regarded as following the longitudinal movements of the air so closely as to be virtually always flying in calm air. The velocity relative to the ground, it will be noticed, is made variable to the degree the relative headway is made invariable.

II

Propellers as Disturbers of Stability

Prefatory Remarks.—This article, reprinted from *Aeronautics* of September, 1911, contains a standard type of diagram (fig. 34) of simple construction, but of great utility in the graphical theory of the aeroplane. One use it may be put to is that of explaining the self-righting property of a common rigid glider obeying the law of constant attitude to its trajectory. Thus:—After reading the article, it will be seen that the glider for which the diagram is constructed cannot glide more level than AF, its common gliding path, because, in the absence of the forward propeller thrust indicated by the appropriate point on the circle AEHC, the glider cannot maintain the speed and lift necessary to prevent its path (and pose) bending down. Similarly, it cannot remain in a steeper downward path, because, in the absence of the "*backward* total thrust required" (see circle), it will gather excessive speed and lift, and these will necessarily cause the path (and pose) to bend upwards.

The article contains an implied caution against over-engineing or over-flywheeling the propulsion of an aeroplane, and this caution should not be overlooked, now there is a tendency for new machines to be constructed with a view to obtaining a deal of the propeller stabilising effect referred to in Article I., preceding this article.

In the aeronautical journals there has lately been exhibited evidence that the influence of propeller thrust upon stability is attracting attention. The following graphical method of dealing with the subject has been employed by the writer, and seems to bring out the essentials in a broad and comprehensive manner, from the chosen point of view. Incidentally, it shows how the thrust required by an aeroplane depends on the inclination of its flight path.

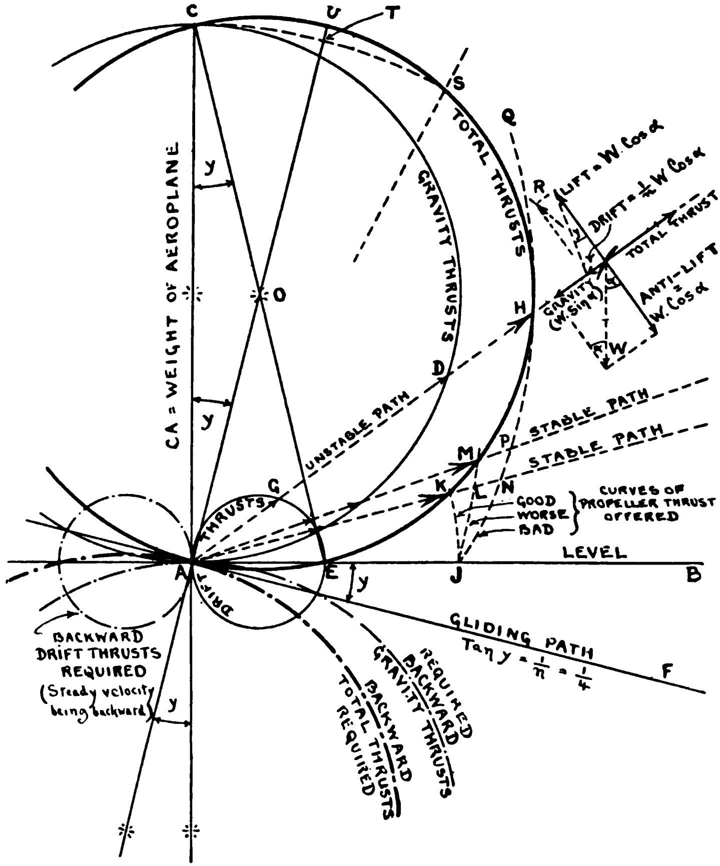


FIG. 34.—The Thrust Diagram.

In the diagram (fig. 34), take any point A as a pole, and draw the level line AB. From A set off the vertical line AC, equal, to scale, to the weight of the aeroplane, and on AC as diameter describe the circle ADC.

Then, any length like AD, measured from A to the circle ADC, represents the propeller thrust required to overcome gravity to keep the aeroplane flying steadily along AD, assuming the propeller to be fixed with its shaft in the direction of flight and passing through the centre of gravity of the aeroplane.

From A set off AE horizontally, equal to the thrust required for steady horizontal flight, and join CE. In the diagram, the gliding angle is supposed to be 1 in 4, so AE is made exactly one-fourth of AC, and the angle ACE exactly equal to γ, the normal gliding angle of the aeroplane, or to angle BAF obtained by drawing the gliding path AF. On AE as diameter draw the circle AGE. Then, any length like AG, measured from A to the circle AGE, represents the extra propeller thrust required to overcome the air resistance, or drift force, during steady flight along AG.

On CE as diameter draw the circle AEHC. Then, in any given direction AH, the length AH is equal to the sum of AD and AG, and therefore represents the total thrust required to drive the aeroplane steadily, against both gravity and drift force, in the given direction AH.

Let us suppose the aeroplane, while flying steadily along AB, with thrust AE, to have that thrust increased as much as possible, say, to AJ about twice AE, and yet be restrained from rising up steeper paths.[1] In consequence of the excessive thrust, the speed has now increased by about 40 per cent., and the lift about doubled, so, if we gradually remove the

[1] This restraint had better be imagined to be an inverted railway track pressing without friction upon the centre of gravity of the aeroplane. It is horizontal at first, but removal of the restraint consists in slowly tilting it up till the aeroplane ceases to press on its under surface.

restraint, the aeroplane will gradually swerve upwards, and the pose, under the law of constant attitude, will follow the trajectory.

As the steepness of the path increases, the backward pull of gravity increases, leaving a less surplus propeller thrust to overcome drift force and keep up the speed, which will consequently decline. So long as the path is less steep than AK, where AK equals AJ, and K is on the circle AEHC, the thrust, speed, and lift[1] are all in excess of the values required for steady flight, and the path becomes steeper; but, on the other hand, if the path is steeper than AK, the thrust, speed, and lift[1] are all insufficient for steady flight, and the path becomes less steep. The path AK is thus seen to be the stable, steady, flight path. But, in practice, the propeller of an aeroplane increases its thrust as the headway declines, so, in the above experiment, the propeller thrust is likely to be an amount KL in excess of AK by the time the path AK is reached, under which circumstances the path must become as steep as AM before steady flying becomes possible. In some cases (they actually occur in models only), the propeller thrust offered may follow such a curve as JNHQ, just making contact with the total thrust circle at H. The point H is then an unstable point, for directly the slope exceeds AH, ever so little, the propeller thrust finds itself *greater* than required, the aeroplane accordingly turns upwards towards the zenith, and, moreover, it is not able to remove the cause of its turning in an up-steering sense till it has turned a complete somersault, and approached AH again from below.

[1] Related as cause and effect in the order named.

It does not seem likely this kind of instability is of much consequence in full-size machines, for the maximum horizontal thrust AJ, obtained with the *present-day* engines and propellers, does not much exceed AE, and increases very little as the aeroplane loses headway. As a consequence, the propeller thrust curve sharply enters the total thrust circle at a stable point like K, and never emerges from the circle to form an unstable point like H; at least not within the quadrant BAC.

With very light elastic-driven models, on the other hand, AJ frequently exceeds AE, very much indeed at starting, and then, owing to the enormous propellers and vigorous maintenance of speed, the curve JHQ, in some cases, not only fails to enter the total thrust circle, but actually passes quite outside it. These models are, in consequence, compelled to turn one or more decided somersaults at starting, till the elastic has run down sufficiently.

There are indications this kind of instability may be reduced by placing the propeller at a height to give a down-steering effect at steep poses, but a power-driven propeller, so placed, is inadvisable on account of the vagaries of engines, and the question is one not easily decided.

In all the above, stability has been considered as if it consisted solely in the permanence of a straight path in still air. It so happens the properties making for instability of this statical variety, such as great size of propeller and constancy of its speed of rotation, are the properties making for stability of the higher dynamical variety in which damping of oscillations, and freedom from disturbance by gusts, are taken into account. The latter kind of stability may be cultivated without the former kind of instability, by maintaining the propeller speed, not positively, but by suitable fly-wheelage, which gets exhausted under the comparatively prolonged demand of an attempt to turn one of the somersaults described. This is beyond the scope of the present article, but is mentioned in fairness to the propeller, which is usually far more a stabiliser than the reverse.

To emphasise the simple construction of the diagram, free from distractions, assumptions were made, leaving their justification to the present stage.

When an aeroplane, of weight W, flies steadily upward at any angle like BAD, now called α, as indicated in the little diagram near H, the backward pull of gravity is easily seen to be $W \sin \alpha$. But, in the circle ADC, in which AC has been made equal to W, we know by simple geometry that polar ordinates like AD are equal to $W \sin \alpha$. Hence, any length like AD represents, as assumed, the propeller thrust in direction AD, required to overcome the pull of gravity down that flight path.

Again, when the aeroplane is flying steadily as just described, the pull of gravity at right angles to the flight path is clearly $W \cos \alpha$, and if the flight path is straight, the lifting force opposing this must be exactly equal. Now, for a rigid aeroplane, the ratio of drift to lift is well known to be constant, and therefore equal to one of its known values — the ratio of the normal horizontal flying thrust to the weight, or alternatively, the ratio of the vertical descent to the horizontal travel while gliding, as when the gliding slope is said to be "1 in *n*." We have seen the lift is $W \cos \alpha$, hence, the drift is $\frac{1}{n} W \cos \alpha$. Now, in the circle AGE of the diagram, AE has been made

$\frac{1}{n}$W (actually $\frac{1}{4}$W because of n having been taken equal to 4), and simple geometry tells us lengths like AG must then be $\frac{1}{n}W \cos \alpha$. Such lengths, accordingly, represent the thrusts required to overcome the drift forces for the corresponding steady flight paths, as was assumed.

Still further, while the aeroplane is flying steadily at the angle α, the total thrust required is the gravity thrust plus the drift thrust, or $(W \sin \alpha + \frac{1}{n} W \cos \alpha)$. Now, $\frac{1}{n}$ is easily seen to be $\tan \gamma$, where γ is the ordinary gliding angle, so the total thrust is $W(\sin \alpha + \tan \gamma, \cos \alpha)$, which is easily transformed to $\frac{W}{\cos \gamma} \sin (\alpha + \gamma)$, the formula given by Mr MacAllan in the August *Aeronautics*. But $\frac{W}{\cos \gamma}$ is a constant, so the total thrust is proportional to the sine of an angle measurable round A, and is therefore capable of representation by a circle through A, like the other thrusts. Since AC is the only thrust in that direction, C is evidently a second point on this total thrust circle, and since AE is the only thrust in that direction, E is evidently a third point on the total thrust circle. Hence, the circle is the circumscribed circle of the right-angled triangle CAE, which, as everyone knows, is the circle having CE as diameter, or the circle AEHC, as was assumed.

It seems relevant to comparisons of the helicopter and aeroplane to find the steady flight path at which the thrust equals the weight. Since AC is equal to the weight, drawing the dotted arc CTS, centred on A, and cutting the total thrust circle in S, plainly determines AS as the path required. Angle CAS is obviously twice angle CAU, or is 2γ, and, therefore, the angle BAS, or the "α" for AS, is $(90° - 2\gamma)$. In the diagram this angle is 62 degrees, and to make it 45 degrees the normal gliding slope would have to be made as bad as 1 in $2\frac{1}{2}$. It might as well be mentioned that the least possible flying thrusts, for straight paths, occur when the propeller is fixed at the upward angle γ to the trajectory.[1] The flying thrusts are then represented by a circle on AT as diameter, but the trifling economies in thrusts are outweighed by other little disadvantages.

The speed has been said to decrease with steepness of path, and the exact speed may be found as follows. When the path is straight it is an indication that the lift force and the opposing component of gravity are in equilibrium, and the latter has already been stated to be $W \cos \alpha$. Now, since the aeroplane obeys the law of constant attitude, the lift force is only proportional to V^2 where V is the velocity, so, conversely, V is proportional to the square root of the lift force. Hence, when the aeroplane flies steadily upward at angle α, the speed is the normal horizontal speed, in which α is zero, multiplied by $\sqrt{\cos \alpha}$.

In a complete discussion the paths would have to be traced into all the quadrants of the diagram, but outside the angle FAC the interest is more of an entertaining than practical nature.

[1] *One Way of seeing this to be True.*—Draw the triangle of forces for weight (direction and magnitude *both* definite), air reaction R (at angle $(\alpha+\gamma)$ to the weight), and for thrust T, at angle γ to the flight path, as directed above. It is evident this T is, for every triangle, at right angles to R, and so the *shortest* possible *for all flight paths*. It is also easily

III

Longitudinal Stability in Gusts

Prefatory Remarks.—In Chapter II., in connection with fig. 1, there was given an abstract explanation of the disturbing effects of longitudinal gusts, upon an aeroplane; and, on page 7, it was pointed out that the usual positive self-righting tendency should be abolished, or even reversed, at the onset of a gust. In this chapter, on page 98, in connection with fig. 32, means of effecting the required momentary reversal of the positive self-righting tendency were described in general terms, but a closely reasoned argument was not given in support. Such an argument is accordingly provided in the following article, reprinted from *Aeronautics* of February, 1912.

It will be seen this article deals with the aeroplane, not as an abstraction, but as actual aeroplane surfaces combined to form a tangible glider, and relative gravity is ignored. All points of view, however, lead to similar conclusions.

There is no doubt that a glider or aeroplane can be made stable in calm air, but several writers have now pointed out that the means commonly taken to stabilise the machine in calm air are the means whereby the stability is disturbed in gusty air.[1]

Natural Stability

What is generally known as "natural stability" depends on forming the planes of the machine with a longitudinal dihedral angle, or placing them in a permanent up-steering relationship, or, *in any case*, on forming the machine so that its centre of pressure moves forwards or backwards with a decrease or

seen to be, on that account, W sin $(\alpha+\gamma)$, and so represented by the circle on AT in the diagram, as stated. That reaction R is at constant angle $(90+\gamma)$ with the flight path is, of course, assumed in this.

[1] The *general abstract* explanation is contained in Chapter II. of the present work.

increase, respectively, in the angle of incidence. In itself, this only gives the machine a righting tendency, and the stabilising scheme usually owes its completeness to the damping effects of head resistance and resistance to rotation of pose.

Natural Stability in Gusts

In fig. 35 is shown an ordinary biplane machine having the usual longitudinal righting tendency obtained by means of a rigid neutral tail plane carried behind. The mass is supposed to be concentrated in the black

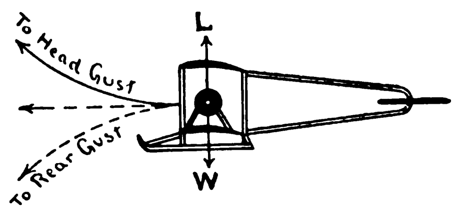


FIG. 35.

spot, so that the machine has no appreciable moment of inertia, as is most favourable to stability. When the machine is flying steadily, horizontally, the downward force W due to gravity, acting at the centre of mass,[1] is exactly equalled by the upward lift force L of the air, acting at the centre of pressure, which centre of pressure is vertically above and near the centre of mass. When a head gust attacks the machine the headway is increased and, with that, the force L is increased to a value greater than W. The machine then *commences to rise while keeping a level pose*, but as soon as it combines any upward movement with a forward movement, it finds itself moving more

[1] A better term than "centre of gravity," because all its properties do not depend on gravity.

edgewise through the air, and so has its angle of incidence reduced. The centre of pressure then —*and not before*—comes forward, and causes the pose to rotate in an up-steering sense, as the machine rises. The machine consequently sweeps upwards in a curved path and, if the gust is a severe one, the machine may even come to rest with its tail pointing downwards—a decidedly dangerous state for it to be in.

The upward sweep of the machine after the change of headway is thus seen to be primarily due to the increase in L, and on general mechanical principles it is evident, that :—

> No load W can be carried in an undisturbed level path unless L be kept constant, and equal and opposite to W, independently of variations of headway.

The problem of steadying the machine has thus been narrowed down to finding a means of keeping L constant independent of headway.

Solution by Wind-Tunnel Experiments

Let us now retire to a wind tunnel with a model of one of the main planes affixed to a central fuselage by which it may be held in experiments (see fig. 36). The main plane is supposed to be of the kind in which the centre of pressure does not move with changes in the angle of incidence, and the mass is supposed to be concentrated in the black spot at the centre of pressure. The problem of making L keep practically equal to W, for a great range of wind velocities, now suggests its own solution, which is simply to pivot the model forwardly as shown in fig. 36. The only effect of an increase in the wind speed is then to make the model tilt a little round the pivot, as it trails out flatter in the wind and so automatically reduces L to renewed equality with W.

But the solution is not complete, for, when the wind *suddenly* increases, the mass has to be accelerated upwards into its new position, and during this acceleration L must exceed W. Moreover, in the free air, a pivot can only be represented by a centre of mass. We are, therefore, prompted to make the changes shown in fig. 37, where the mass is moved to the pivot,

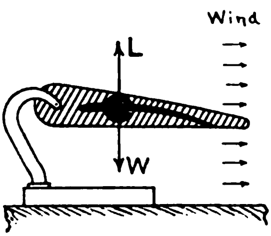


FIG. 36.

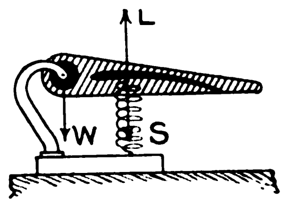


FIG. 37.

and the load is furnished by a massless spring force instead of a weight force. When the wind now suddenly increases in velocity the plane *at once* takes up its new position, for there is no mass to be accelerated, and L, accordingly, remains quite constant, even from instant to instant. It is true the pull of the spring increases with its extension, but the spring is to be taken so long that the increase in pull, for the small extension really occurring, is insensible. If the wind velocity is made very low the model slopes steeply downwards from the pivot, and the constancy of L can no longer be claimed; but the fact is not altered that there is a great range of velocity for which L is practically invariable, instead of varying, as usual, with the velocity *squared.* It would be unreasonable to expect the lift to persist with no wind at all.

The real defect of fig. 37, as an aeroplane, consists in its giving no lift force at the centre of mass to balance the weight W, for force S cancels all force L. An aeroplane, free in the air, insists on the resultant lift being above the centre of mass and equal to W; therefore, fig. 37 must be further modified. Since S and L have equal and opposite moments about the pivot, which pivot is now also the centre of mass, their resultant, even if it be zero, as in fig. 37, necessarily passes through the centre of mass, in accordance with well-known principles of mechanics. The next problem, therefore, is only to give the resultant some upward magnitude, seeing that its position and upward direction look after themselves.

Noting that the magnitude of the upward resultant is (L – S), it is evident that the resultant lift can be made nearly equal to L itself, merely by placing the spring S further and further from the pivot, because the force S, necessary to balance the *moment* of L about the pivot, becomes a less and less fraction of L as the spring is so altered in position. But the arrangement with a spring like that in fig. 37 is not very glider-like in form, and all the properties of a far-distant spring S, with the advantage of a more glider-like form, are obtainable by attaching a long springy tail rod,[1] as in fig. 38, pulled down, near its end, by a force T, by means of the cord wound on

[1] The tail rods used in experiments have generally consisted of thin strips of close-grained wood, so springy that a strip as long as the glider easily bends into a circle without breaking. The fuselage, in the drawing, is a little too short for the best results, and the cord C (referred to later) is also too short. (Fig. 32, I., of this work has better proportions.)

the clamped drum P. In fig. 38, T is less than one-tenth of L, because T is more than ten times as far as L from the pivot, and the resultant of L and T, or L_R, which equals (L – T) and acts upwards at the pivot, is very nearly equal to L itself.

It must be thoroughly understood, from this point onwards, that, with such a springy tail rod, the force T is made a practically invariable force for a very great range of wind velocity, because the change in bending of the tail rod, that such change in wind velocity occasions, is a very small fraction of the total bending of the tail rod from its relaxed position at B.

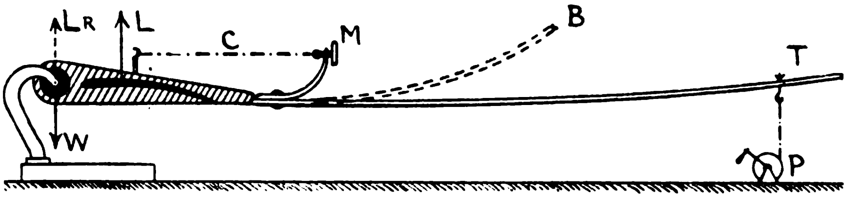


FIG. 38.

Above the model is shown a cord C, which may be twisted by a somewhat stiff milled head M, to adjust the initial bending of the tail rod and so adjust the constant force T, for purposes soon to be explained.

Let us now suppose the cord C is relaxed by means of the milled head M, and that the wind in the tunnel is set at 10 miles an hour. The model has no appreciable weight outside the centre of mass, and as it trails out in the wind, and tightens the cord at P, a force T, a force L about ten times T, and a resultant L_R about nine times T, all come into existence. Since C is relaxed, L_R will probably be decidedly less than W, so that the model will not lift at its pivot; but by tightening C, by means of M, the force T may be increased, and since T, *and nothing else*, determines L and L_R, the resultant L_R may be gradually brought to equality with W, so that the model does just lift or float at its pivot. Such lifting may be detected if the pivot holes are made short vertical slots.

The Constant Lift Property

A very extraordinary observation may now be made, which is as follows :—On increasing the wind velocity from 10 miles an hour to any practicable limit, say 50 miles an hour, no appreciable increase in lift will be observable at the pivot, as measured by a spring balance applied to the pivot. This is because the constancy of T, for the various headways, determines the constancy of L and therefore the constancy of (L – T), or resultant L_R, for all the headways.

Completion as a Glider

It will be noticed that fig. 38 is not yet a self-contained glider, but the final step is easy to take, consisting,

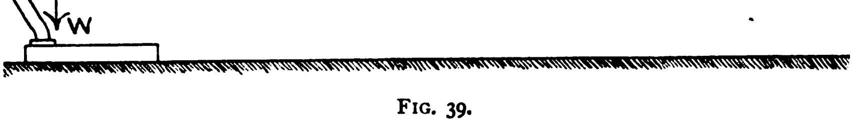


FIG. 39.

simply, in attaching a plane to the end of the tail rod, large enough to enable the force T to be derived *from the air itself* (fig. 39). The springiness of the tail rod will still look after the constancy of force T over a great range of headway.

Behaviour as a Free Glider

The model of fig. 39 is now adjusted to just float in the wind of 10 miles an hour, and keep floating without sensible increase in lift for all greater wind velocities, which it will do with no perceptible change beyond a slight deflection of the two planes, in a down-steering sense, relative to each other. If it is then gently lifted off its pivot and projected horizontally in the open air, at a *very high speed*, it will be observed to move almost perfectly *horizontally* until its speed has declined somewhat below 10 miles an hour. Moreover, if while moving at, say, 20 miles an hour it meets a considerable head gust, or rear gust, it will neither leap up nor descend to the gust, for L_R *keeps constant despite the change of headway.*[1] All the gusts do is to slightly tilt the body of the model about the centre of mass, which latter pursues a sensibly straight path, as indicated in fig. 40, path I. The centre of mass is thus seen to be what physicists sometimes call a "steady point."

Such models, of which type the writer made many in 1909, fly very much as a heavy-headed arrow might be expected to fly if gravity were annihilated in our atmosphere.

[1] Notice that the fan F (referred to later) is not in operation in this experiment. When fan F is in operation, the above property may only be looked for when the glider is attacked by a sudden transient gust *after* being launched. A hand-launched model is virtually attacked, *while at rest*, by a *most intense* head gust of about 300 ft. p.s. p.s. (say 40 m.p.h. headway given in $\frac{1}{5}$th second), *followed by no return gust.* These conditions, of course, represent nothing ever met with in actual flight, and therefore, nothing to provide against.

An Artificial Aviator

Though the model has the above satisfactory property, it has a drawback in having very little preference for a gliding path of one slope rather than another.[1] Also, the particular gliding angle it does settle down to is so sensitive to M as to be hardly adjustable thereby, and landing shocks nearly always derange the adjustment. The model, in fact, though

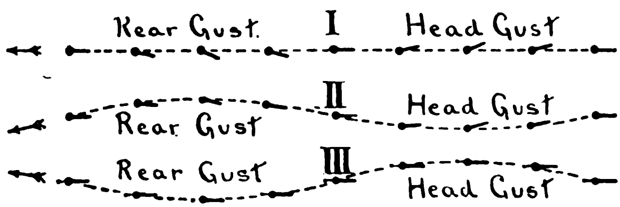


FIG. 40.

it is freed from momentary disturbance of pose, wants a small aviator to stand by M, and adjust the average flight path now and then. An artificial aviator, for models, is easily provided in the small fan F (a mere wisp of thin wood veneer, or even stiff paper in very small models) arranged to twist and shorten the cord C, which is made a double cotton thread or cord, according to the size of the model. When the average path becomes too steep and the model, as a consequence, moves too fast, fan F winds up the tail to steer

[1] The righting effect of a common glider, from a steep plunge, depends on two causes. (1) The gravitational component opposing the lift is reduced, so the machine would swerve upwards even if its speed remained constant. (2) The speed is accelerated as the machine points downwards and the lift force is increased with the square of the speed. The machine would therefore have swerved upwards even if the gravity component opposing the lift had remained constant. The first cause, which is very weak in the vicinity of the stable position, but is fortunately *not a cumulative cause provocative of oscillation*, is the only one operative in our constant lift model. (In fig. 44 draw a constant lift circle of radius P*c*.)

level, and it lets down the tail, in a corresponding manner, if the model travels up too steeply.

Fan F re-introduces Gust Disturbance

Now fan F has only brought back the old righting tendency, fortunately too sluggish to be much abused by sudden gusts, but still able to make the model mount up, to some head gusts, to a degree that might as well be abolished. So far, the centre of pressure, where the lift force acts, has been assumed to be constant in position for all angles of incidence; but if the main plane is so cambered as to have its centre of pressure *retreating* with decrease in the angle of incidence,[1] the model has curious properties added to it, including a correction for the disturbing effect of fan F.

Dipping down to Head Gusts

Let the model with the new main plane be mounted in the wind tunnel, as in fig. 39, but without fan F in action, and let the model be arranged, as before, to just float at the pivot in a wind of 10 miles an hour, and with the lift force corresponding in position and magnitude to L_{10} in the figure. Now let the wind velocity be increased to, say, 15 miles an hour. As the flexible model straightens out, and the angles of incidence of both planes decrease, the centre of pressure of the new main plane retreats, say, to the position (exaggerated) at L_{15}. But the moment of L_{15} about the pivot will balance that of the constant force T; hence, L_{15} must be about two-thirds of L_{10} (it is about one and a half times as far from the centre of mass),

[1] Alternatively, a second fixed down-steering plane M_1 (fig. 32, II.) may be combined with the main plane.

and therefore, L_R at the pivot, which is $(L_{15} - T)$, must diminish to less than W, and the model will *descend* at its pivot. The greater the wind velocity, the more L moves to the right, the less it becomes, and the *more* the model tends to sink. On the other hand, if the wind be reduced below 10 miles an hour, L approaches the pivot, and increases in magnitude, and the model consequently tries to *rise* at its pivot.

This model will not fly stably without an aviator, for as soon as it commences to dive, and gathers headway, it tends to dive all the more; but with an aviator, or fan F, this tendency is easily counteracted, and the up-steering impulse fan F promotes to a sudden head gust, and the down-steering impulse of the model apart from fan F, may be arranged to cancel each other, and make a model which travels very well indeed.

Connection with Soaring

If the above anomalous behaviour to gusts be exaggerated, as by using a strongly cambered main plane, we have a model which, even with a fan F, dips down momentarily to head gusts and up momentarily to rear gusts (fig. 40, path II.). This action is of great interest in connection with attempts to produce automatic soaring of the kind called "delay soaring," but the reasons why belong to the subject of "soaring flight," and not to that of "stability" (Chapter III. page 35).

Application to a Common Glider

Let us suppose this stabilising principle is to be added to the already existing glider of fig. 35, with as little alteration as possible and with a view to making further discoveries. Since the tail plane of fig. 35 is neutral, its removal (weight assumed insignificant) does not effect the mere *equilibrium* of the central part of the machine when flying in calm air. The central part is re-drawn in fig. 41, where W = 300 lbs., is supported by L_W = 300 lbs. Now W is at the centre of pressure like W of fig. 36, so we must create an independent forward "steady point," as by carrying a 20 lbs. weight *w*, 10 feet in front, on outriggers. But this makes the machine front-heavy, so to balance *w* an elevating plane is fitted at the rear, which, in accord-

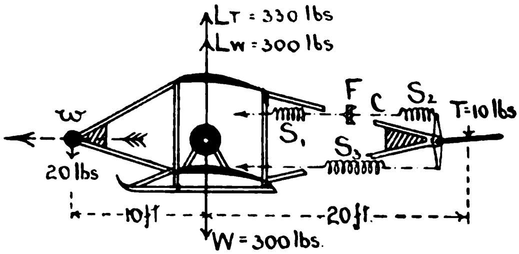


FIG. 41.

ance with the principles established, must be a yielding plane (such as a flap) furnishing only a *constant* downward force T = 10 lbs., just sufficient to balance *w* only. The total lift L_T of the main planes will now have to be $(w + W + T) = 330$ lbs.

With this machine the aviator may glide in still air provided he keeps a constant pull of 10 lbs. (or geared equivalent) on the control lever of the elevator, and corrects, if necessary, for slow undulations.

Stability in Gusts

Now let a head gust attack the machine. The lift L_T at once increases and lifts the central part upwards.

But *w* is left behind, downwardly, because its starting to move up obviously depends on T increasing, and that increase the aviator does not permit, for he yields his control lever directly he *feels* the extra pull. Hence, the machine only rocks about *w* as a "steady point" that travels horizontally, and with the slight tilting of the main planes the excess in L_T soon vanishes. The flight is then very much like fig. 40, path I., only that *w*, and not the main mass, is the horizontally moving steady point.

In keeping *w* steady, by responding to the changes he *feels* in the pull upon the elevator, the aviator will find his elevator control lever in constant movement in gusts, but it will practically be a case of the *elevator working the aviator*, and not the reverse, as it may *appear* to be.

An Artificial Aviator applied to the Glider

The necessity for following the elevator in all its movements may be done away with by putting springs S_1, S_2, S_3 in the cords actuating the elevator, so as to leave to the aviator only the adjustment of the average pull, now and then. Even this average pull may be made self-adjusting, to a great extent, by adding the small fan F, corresponding to fan F of fig. 39. The aviator is still left with the duty of maintaining the mean pull of 10 lbs., to avoid making a dreadful dive, but another spring, attached to his control lever, would relieve him of that duty also.

Effect of Moment of Inertia

In saying the machine of fig. 41 will rock about *w*, the principal mass W is assumed to have no moment of inertia round its own centre. If W has considerable moment of inertia, *w will* rise and fall, though its rising and falling may be minimized by using a main plane with a retreating centre of pressure, and by placing *w* further forward. On the other hand, there does appear to be a construction in which the reactions are so balanced that the two masses tend to rise and fall together, so as to give a flight path similar to path III. in fig. 40. In this case constancy of path is sacrificed to constancy of pose. Moment of inertia, however, generally complicates the problem, and tends to produce unsatisfactory performance in *unmanned* machines. Usually, it develops oscillations, which have to be damped out by the aviator or by special auxiliary appliances.

Conclusion

This article is written chiefly to create interest in simple methods of obtaining longitudinal stability by *elimination* of gust disturbance, instead of by actively fighting the gusts or by simply trusting to the fixed longitudinal dihedral, and it is not intended to discuss the matter in all details. For instance, all gusts other than those in the line of flight have been ignored.[1] Again, the means of obtaining sufficient lateral stability to enable the longitudinal stability to be studied have not been entered into.

Nevertheless, it has been sufficiently demonstrated that there are methods whereby an aeroplane may be made to traverse sudden head gusts and rear gusts without perceptible disturbance of path, and with practically no disturbance of pose.

[1] This particular piece of apparatus, without special inertia effects, is somewhat less serviceable in eliminating disturbance by the up and down gusts than by the longitudinal gusts.

CHAPTER XIII

"FLYABILITY" AND "STABILITY"

If we send forward a tricycle without a rider it will remain upright, but if we do likewise with a bicycle its remaining upright, even for a few moments, is very improbable. Consequently, according to this test, the tricycle is a stable vehicle and the bicycle is not. But, to most men, the bicycle is the more *rideable* and more pleasant vehicle, and its inability to travel by itself is not regarded as a proof of its inferiority as a *man-carrying* vehicle.

So, in the case of the aeroplane: If we take a suitably built aeroplane with practically no moment of inertia, and start its engine, it may fly and stabilise itself in still air, but it might not be liked by a practical aviator. The machines preferred by the practical aviators will usually be found to have appreciable moments of inertia, *and very often not be able to travel of themselves, even in still air*, without the controls being attended to. It appears, therefore, that while the conventional stability of an aeroplane consists in its power of flying without intervention by the pilot, yet, in practice, the pilot recognises something else in his machine to be of more importance, which, for want of a better word, may be called "flyability." This does not mean to say that stability is not an advantage, but that, when it is a case of one or the other, the pilot prefers this "flyability" in the same sense that the cyclist usually prefers the "rideability" of the bicycle to the stability of the tricycle.

The distinction between stability and flyability appears to depend on the fact, that, while moment of inertia beyond a certain small limit has the property of amplifying the free oscillations of an aeroplane, yet *it has the overlooked, or discounted, property of resisting sudden changes of pose by sudden transient gusts*, and so relieving the pilot of a deal of rapid and tiresome elevator flapping. It *does* impose upon him the duty of damping down the slow free oscillations, but that is a far less arduous duty than the one he has been relieved of.

It is exceedingly likely that, for an aeroplane, the elimination of sudden gust disturbance is a more important and immediately attainable improvement than any other, because it represents an improvement in the flyability by which the practical aviator naturally judges the machine, and requires little more than a proper placing of the masses. If conventional stability can be added at the same time, so much the better, but *the two things are so distinct that they must not be tested by each other*. The eliminatory trials for all proposed improvements, therefore, should not be confined to models; some assured improvements to full-size manned machines may quite spoil a given model.

Towards the end of 1911 the author gave some publicity to the improvement obtainable by placing the weight of an aeroplane somewhat forward, so as to bring a downward air pressure upon the rear flap elevator. He was rather startled to hear at once of a series of fatal accidents of that "mysterious" and "unaccountable" nature in which the aeroplanes had, while flying smoothly, turned nose downwards and travelled straight at the ground. Now, if a pilot possessing a standard machine makes such small and inconspicuous alterations in the distribution of weight relative to the wings as will bring a downward pressure on the elevator, and feels confident of keeping that pressure on the tail, by hand control, and yielding the elevator at the right moments, he will certainly find a great improvement in the flyability of his machine, but decidedly not in the pure stability, *and he takes upon himself a great risk.* The risk is, of course, that, in a moment of absent-mindedness, he may release his control lever.[1] The slow-fan F (fig. 32), with its spring connection with the tail plane, is, of course, to do away with this risk, and not only does the fan add the wanting stability, but, in addition to other advantages, it would rescue a machine from a vertical dive even if launched in that position.[2]

Whenever *multiple* masses are to be used in improving the flyability of a machine, and, in spite of objections, a test is ventured on in model form, hand-launching must not be employed. The reasons for this prohibition are simple:—The function of such masses is to *preserve* the steady flight of the machine, but, when the machine is hand-launched, it cannot be launched free from an initial rotation in one direction or another, and the masses then tend to preserve, if not augment, this rotation.

[1] The risk is only of the same kind as that confronting a bicyclist, but with the difference that the aviator cannot lose his balance with impunity.

[2] It is necessary to say "even if launched," because of the improbability of such machine being disturbed into the vertical position.

CHAPTER XIV

THE NATURE OF GRAVITY

WHEN the author first introduced the relative gravity point of view, regarding flight phenomena, its universal acceptance was delayed by its name and its apparently conflicting with the very proper belief in the substantial constancy of common gravity. Subsequently it was realised, more and more widely, that *common* gravity was not supposed to alter, but only that which dynamically stands for gravity in the relationship of the machine to disturbed air. To many, however, a difficulty still arose in an almost superstitious reverence for common gravity as something above the laws of cause and effect, and an inability to regard it in its dynamical aspect owing to never having had reason for regarding it as anything but the force of one pound which acts upon each one-pound weight. It seems advisable, therefore, to write a few words upon the nature of gravity, for the fact that even ordinary gravity is not quite immutable, but is itself a "relative gravity," may dissolve some belated prejudices.

To the average man, gravity, as regards a given object, is "the attraction of the earth upon the object," and the direction of gravity is the direction in which the object "weighs" when supported. He so far relies on its constancy of strength that he will buy and sell things for his living after weighing them on a spring balance, and so far on its constancy of direction that he will erect steeples and other costly structures that would collapse with a change of a few degrees in the direction they weigh upon the ground. It is only during a severe earthquake that man's trust in the apparent constancy of gravity is betrayed. During such an earthquake the ground has an acceleration represented by a rotating acceleration vector, and the *effective* direction of gravity varies very much like the variations in the directions of the connecting-rod of an inverted-type vertical steam engine. Many men then give up the attempt to "stabilise" themselves, and roll on the ground. The only thing that remains steady is the heavy mass of the seismologist's seismograph, or earthquake recorder, and it does so for the same reasons that the front masses of fig. 32 remain steady in gusts, or "earthquakes" of the air.[1]

It is not to be expected anyone can say whether gravity varies or not till it has been identified by some distinctive property of a quantitative nature, and when it is examined at London, with this end in view, it is found to have the distinctive property of adding 32·2 feet per second to the velocity of a falling body in every second it is falling. In other words, it impresses upon bodies at the earth's surface an acceleration of 32·2 ft. p.s. p.s. *relative* to the ground.

Though it is readily appreciated that gravity is the prevailing acceleration tendency of all bodies *relative* to the ground, the converse proposition—that the ac-

[1] In earthquake countries, buildings are built to yield in their foundations. To build them with the ordinary rigid stability we are familiar with in England is fatal to their security during an earthquake.

celeration tendency of bodies *relative* to the ground is gravity — is practically unrecognised, except by astronomers, and those who think of the phenomena around them on a cosmical scale. The proposition is true even when put more generally, thus :—

> The acceleration tendency of one body relative to another, or the impressed acceleration of the one body relative to the other, defines the effective gravity of the one body relative to the other.

This is, of course, the principle underlying all the phenomena in the tramcar of fig. 26, II. Use of the principle is usually avoided by clumsy statical methods.

Let us now deal with the general belief that common gravity does not vary, not to show the belief is unjustifiable,—for the variations can barely be detected by the finest instruments that can be made,—but to indicate the non-absolute nature of gravity, and show the variations are, even now, of some practical importance in the affairs of men who have dealings with the sea.

In fig. 33, I., E is the planet earth, assumed, for the present, to be a homogeneous sphere without any rotation. The fundamental gravity due to the earth alone is represented, for each point of the ground surface, by the vector AB, 32·2 units in length, directed to the centre of the earth. *That* is, at each place, absolutely constant in magnitude and direction. But, near the earth is a satellite M, and M accelerates E, as a whole, to the right with a certain acceleration CB, so that BC is the equal and opposite acceleration of object A, *relative* to the ground, due to the pull of M upon E. The vector BC is, accordingly, applied to the end of each AB vector to give, so far, the resultant relative gravity AC. But AC need not be drawn yet, because there is another vector to be taken account of. The satellite M not only pulls E, but it pulls the object at A towards the centre of M with an acceleration CD, expressed by :—

$$CD = \left(\frac{EM}{AM}\right)^2 \times CB.$$

The vector CD, therefore, represents the acceleration tendency of any object at A, due to the pull of M upon the object, and, when applied to the point C, it yields the *ordinary resultant relative gravity* AD. Notice that CD has to be drawn, in each case, not pointing at M, but parallel to AM. When the direction AD is thus found all round the planet E, and a continuous "virtual level" is drawn at right angles, or orthogonally to AD, we discover the shape that an ocean covering the whole earth would assume. The tides are, of course, nothing but the perpetual strivings of the sea to keep itself level with respect to the changing direction of gravity as the earth and planets move. The moon, when nearer and plastic, had tides raised upon it by the earth's interference with its own gravity, but these huge tides stopped the moon's rotation in the same way a thick or viscous syrup half filling a bottle will abruptly end the rolling of the bottle. That is why the moon keeps the same face to the earth, and the evidence indicates the now hardened moon is egg-shaped, with its longer axis pointing to the earth. Not only does the ocean tilt, but the earth's *surface* tilts. Refined observations have lately indicated that the land surface at the equator rises and falls nearly eight inches twice every day. In fig. 33, I., the moon produces the two acceleration vectors BC and CD, but the sun also produces two similar vectors, likewise every other planet, and the rotation of the earth adds a centripetal acceleration vector of some strength near the equator. Ordinary gravity, therefore, is not quite so constant as it seems, and *is itself a complex relative gravity*[1] *with the sea as its changing virtual level.*

If the moon were to come nearer and nearer to the earth, the variations of gravity would cease to be of only academic interest, the tides would submerge the continents, the earth and moon be disrupted, and few people would be left to doubt the underlying relativity of gravity and its essentially dynamical origin.[2]

The *cause* of the acceleration that constitutes the fundamental gravity is, of course, absolutely unknown, but it need not be known for purposes of physical calculation. *Mechanics is purely a science of relations, founded on experience.*

[1] Quantitatively, the effects are so small that the solar and lunar actions together do not vary the weights of bodies at the equator by more than one five-millionth part of their ordinary weight. This is about 20 lbs. in the weight of a liner like the *Olympic.* The centrifugal effect at the equator, though great (about 150 *tons* for the *Olympic*), is uninteresting because constant at each place.

[2] Corresponding changes in gravity are likely to have been the ruin of the moon. Parting from us 1,000,000,000 years ago, it commenced, being small, to cool four times as fast as the earth, while being driven away in accordance with the dynamics of our tidal friction. When only so far away as, say, 25,000 miles it commenced to harden, to a great depth, into the exceedingly egg-shaped, non-rotating, equilibrium figure corresponding to such nearness (see fig. 33, I.). On receding further, it tried to lose its extreme egg-shape, but the enormous, structural, *negative-tidal* stresses set up, cracked it, and maintained a frightful volcanic activity. The "cracks," where the light-coloured internal magma has welled up, are, no doubt, the volcanic dykes of the conspicuous bright ray systems of the craters Tycho, Kepler, and Copernicus, many of which pass right across the visible hemisphere, regardless of the most gigantic surface formations. The earth and moon fought each other for a stable home-made gravity and peaceful habitability, and the earth won by remaining plastic till it had driven the moon to a harmless distance.

CHAPTER XV

THE ANALOGY BETWEEN SHIP STABILITY AND AEROPLANE STABILITY

IN the last chapter (XIV.) the tides were seen to be due to the ocean, after the manner of liquids, tending to set its surface at right angles to the effective gravity. This proposition may be inverted, and when we see the surface of a fairly mobile frictionless liquid tilted, and in a state of free oscillation, we may assume that the relative gravity, or gravity of the tilted surface water in its relationship to the water immediately below, is at right angles to the surface.

In fig. 33, II., is shown a portion of the wave surface of the sea, and a ship is shown riding upon the surface in various positions relative to the waves. At B and D, midway down the slopes of the waves, the relative gravity is approximately as shown in the little relative gravity diagrams, in accordance with the proposition laid down in the last paragraph. Now, if the ship has, in a calm sea, a righting tendency with respect to common gravity, it will exercise the same righting tendency with respect to relative gravity in the disturbed sea, and will, consequently, tend to swing so as to keep at right angles to the local water surface. To minimize the tendency to tilt with the water surface, the righting tendency must be made as weak as possible consistent with sufficient strength to preserve the average or still-water upright pose of the ship, for it is obvious the ship cannot be allowed to have no righting tendency at all. So far, there is a strong analogy between the ship and the aeroplane in connection with fig. 1, and the analogy continues still further. It may be mentioned that shipbuilders are quite aware of the desirability of having only a moderate righting tendency, and do not strive to have the centre of gravity of a ship as low as possible, as popularly supposed, or "bottom-heavy," as it is called.[1] Aeroplane designers have been somewhat slow to learn the corresponding fact that they must not strive to make the automatic forward movement of the centre of pressure, or "veeing" of their planes, as great as possible.

If the ship, with its moderate righting tendency, has a smooth circular bottom, it will, in righting itself, swing past its proper position and continue oscillating, and if the waves only time themselves to accord with these oscillations, as they are *certain* to do sooner or later, the ship will have the oscillations augmented so as to heel past its critical angle and capsize.[2] The remedy is, of course, damping, and this is usually effected by employing a rectangular bottom, and adding large bilge-keels. It may be noted, however, that, like the empennage of an aeroplane, these bilge-keels do not damp the *absolute* oscillations of pose of the ship, but only the oscillations of pose *relative to*

[1] A fact to which Sir George Greenhill made reference in the Government Advisory Committee's Report, 1909–10, page 30.

[2] Such augmentation of the aeroplane's oscillations by a succession of gusts has not been discussed; the first thing is to understand and eradicate the disturbance by one gust. In the same way, discussions as to the recovery of pose after being upset should not be allowed to take precedence over discussions as to prevention of the initial upset.

the water surface, or virtual level. In one sense they are *disturbers* of pose, because *they bind the ship to the water*; but since sea waves do not often tilt more than 15°, and the bilge-keels resist the ship's tilting being *more*, they are a considerable advantage. In the case of the ship, dead surfaces may effect the damping, because it has no lateral velocity; but the aeroplane, having to move forward, should have a damper that *damps with respect to a mean velocity*—that is to say, it should have a fly-wheel fan or equivalent.

So far as the author is aware, no attempt has ever been made to stabilise a small ship by giving it a slight *negative* righting tendency kept in check by a gyroscopic control (such as Mr Brennan's) operating either directly or through balancing planes immersed in the water. The ship would have to have a smooth bottom, and the experiment would be very interesting. Such a ship might ride the waves like C, D, and E (fig. 33, II.), but it is not at all certain that it would be more comfortable than one riding the waves like A, B, and C, because the up and down accelerations are part of the discomfort of ocean passengers, and no one can suggest any means of eliminating their effects. It is also possible the horizontal accelerations might be found a greater source of discomfort in a non-tilting ship[1] than in one that tilts to the waves in a natural

[1] The usual view, no doubt, is that "fiddles" would not be required on such a ship, and personal stabilising problems would not exist. The contrary is probably the case, seeing the ship does not then swing to the "relative gravity" at the water surface. The ship in which fiddles could be dispensed with would be, theoretically, the one which kept itself at right angles to the water surface in a dead-beat manner, and the disagreeable rollers will be found to be those which are not content to do that, but add their *own* free oscillations to those of the water surface. They want more bilge surface or other destroyers of their own *free* oscilla-

dead-beat manner. For somewhat similar reasons it is likely that an aeroplane held quite unyieldingly to one pose would not be a success as regards comfort, and with that statement the analogy between the ship and the aeroplane has been taken as far as profitable.[1]

tions. Impeded rolling weights, or water *inside* the ship, will help, but these, again, do not damp the absolute oscillation, as too often assumed, but only the relative oscillation, as it is better they should do. Gyroscopes can be made to resist the absolute oscillation, but the advantage of so employing them is doubtful both on ships and aeroplanes, as suggested in the text.

[1] There is, however, one more analogy of some interest. A ship is usually lost when it gets amongst breakers, not only because it touches ground, but because its righting tendency is worse than useless when the water surface (virtual level) tilts suddenly and at a much steeper angle than the 15° of the open sea. A ship may complete a life of twenty years without ever being steered into breakers, but an aeroplane has to be *designed* for frequently encountering "breakers" which, being invisible, cannot be avoided. The "breakers" of the air are places where the relative gravity and virtual level are extraordinarily tilted more than 90°, and especially where they are tilted 180° or more (fig. 3).

CHAPTER XVI

THE SELF-RIGHTING PROPERTY IN STILL AIR

It has been taken for granted, throughout this book, that the reader is acquainted with the common self-righting property of a glider in still air, but a chapter dealing with the subject may be useful for reference, and make the book more self-complete.

The self-righting property is remarkable in being so easy to comprehend informally, or intuitively, that an explanation not based on intuitions suffers from the defect of appearing unnecessarily long and tedious.

An Informal Practical Explanation

The following is given as a frankly informal explanation that is not, however, believed to be in any way misleading.

In fig. 42 is shown a common glider, with a neutral tail, in three poses: (I.) steeply downwards, (II.) as for a normal glide, (III.) horizontal. When launched downwards, as at I., it is evident to anyone, by a legitimate enough intuition, that the up-steering relationship of the fixed planes must cause the glider, as it gathers headway, to turn towards a more level path and pose. When the glider is launched horizontally, as at III., it is just as evident, that, so far as it continues horizontally, without a tractive force, it must lose headway, and, consequently, permit the heavily-loaded main plane to sink down relatively to the unloaded tail plane, with the result that the glider turns downwards.

Seeing that there is an up-steering effect increasing with steepness of pose, and a down-turning effect increasing with the horizontality of pose, there is naturally an intermediate steady pose and glide, as at II., in

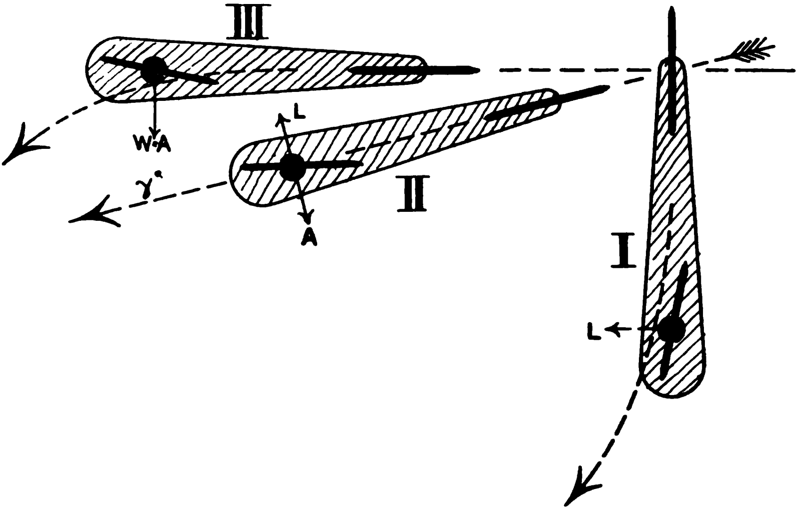


FIG. 42.

which the two effects are so balanced that one effect is ready to prevail over the other, to restore the balanced pose and glide, in the event of a deviation accidentally taking place.

This self-righting property, or "natural stability" as it is usually called, always depends on the planes, or parts of the planes, being arranged in an up-steering relationship, and on a forward weight being arranged to balance the up-steering effect in the desired normal pose and glide. The plain, flat, ballasted glider is no exception, for the better support accorded to the front part of such obliquely moving glider, as compared with the rear part, shows at once that the front and rear parts are already, without special construction, existing in an up-steering relationship. A few experiments with a note-paper glider are convincing enough as to the ordinary sufficiency of the above explanation.

A Formal Graphical Explanation

The following more thorough explanation will be found to differ from the last one in resting, not upon

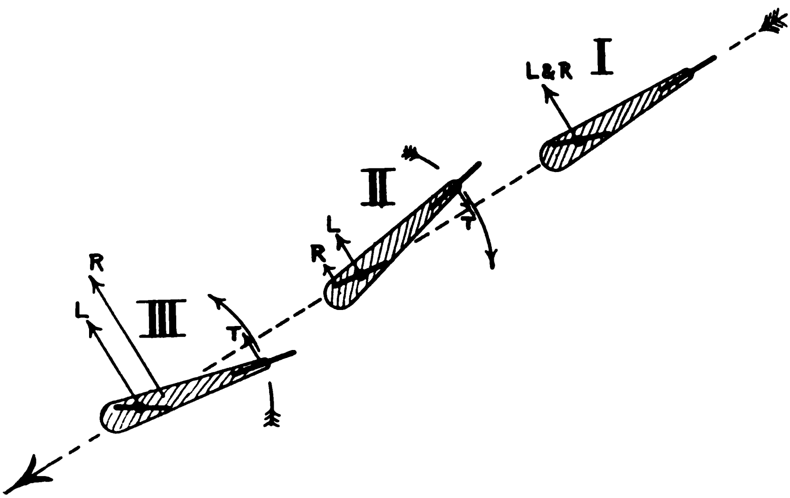


Fig. 43.

intuitions, even quite legitimate ones, but upon those principles of mechanics and geometry which are as far as we can or need get behind intuitions.

In fig. 43, the glider is shown with its centre of mass proceeding down a trajectory indicated by the great arrow. It is supposed to have its centre of mass coinciding with the centre of pressure of the main plane, so that, as will be seen, the tail will ordinarily be kept neutral, as at I. For, suppose the tail should tilt away from the trajectory, as at II. Then, while the tail is so tilted, the pressure which must come upon the top surface of the tail plane will press it back into the trajectory. The more general reason, however, is that, when the glider is tilted, as at II., the resultant of L and T is a force R, *forward* of the centre of mass, so that the moment of R about the centre of mass causes the axis of the glider to be turned into the trajectory. Similarly, when the glider tilts as at III., the resultant of T and L is a force R *behind* the centre of mass, and, therefore, again acting to turn the axis of the glider into the trajectory. It will be seen, therefore :—

> The glider tends to preserve constant attitude to its trajectory in consequence of the resultant air pressure upon the whole machine being prepared to move away from the centre of mass, in the right direction [1] to restore the constant attitude, in the event of a deviation taking place.

No reference has been made to gravity, and none is intended, for, contrary to the common opinion (even expressed in some text-books), *gravity is not concerned in the constancy of attitude with respect to the trajectory.* Gravity determines the trajectory, but that is another matter. When, in fig. 43, II. and III., the force R was said to turn the glider about its centre of mass, reference was implicitly being made to the principle in mechanics which may be stated in the following words :—

[1] A cautious form of wording, because up and down movements of the centre of pressure may be made to assist.

When a body in space is pressed upon by a force acting not through the centre of mass, but to one side of it, the force rotates the body with a torque or couple corresponding to the moment of the force about the centre of mass. (It also happens that the force accelerates the centre of mass as if directly applied thereto.)

Gravity acts through the centre of mass, and, consequently, can have no moment about it. Those who bring gravity into the law of constant attitude usually mislead themselves by drawing their figure, corresponding to fig. 43, horizontally only. The constant attitude to the trajectory, however, is just as well preserved when the glider is directed at the ground; more than that, it is just as well preserved when the glider is directed horizontally, at high speed, *upside down.* Gravity acting upon the centre of mass *affects its trajectory*, but that, as has been said before, is a different matter from the attitude with respect to the trajectory, and must not be confused therewith. If gravity disappeared, suddenly, constant attitude to the trajectory *would continue*, but the trajectory itself would become a perfect circle, such as has been referred to on pages 11 and 12, (*glider* assumed frictionless).

If the glider is now pivoted accurately at its centre of mass, and placed in a wind tunnel, not only may the constant attitude property be verified, but, with suitable measuring instruments, the following additional property may be established:—

For every headway of the glider there are produced two rectangular components of the wind pressure upon the glider;—a lift force L at right angles to the trajectory; and a drift force D, or head resistance, along the trajectory. These two forces *both* increase with the square of the headway, *so as to preserve a constant ratio, n.* (In the glider of fig. 44, *n* is supposed to be equal to 4, so that $D = \frac{1}{4}L$.)

Now that the properties of the glider have been ascertained, it is convenient to forget its shape, and, regarding it only as a heavy point possessed of the ascertained properties, proceed to construct the diagram of fig. 44.

In fig. 44 take a point or pole P, from which the glider may be imagined to be launched in any direction, and from which radial force ordinates may be measured. On a vertical diameter from P, equal, to scale, to W (the weight of the glider), draw the circle G_1. Then, the distance from P to the circle G_1, in any direction, represents the gravitational tractive force G down the flight path having the same direction. *Proof:*—Calling α the angle of the trajectory with the horizontal, the distance from P to the circle G_1 is, by a well-known and simple theorem, equal to $W \sin \alpha$, where W is the diameter of the circle G_1. But, in any of the little force diagrams, say diagram III. (fig. 44), it is evident the gravitational tractive force G is also equal to $W \sin \alpha$. Hence, the circle G_1 indicates, as stated, force G for any given trajectory.

On a horizontal diameter from P, also equal, to scale, to W, draw the circle A_1. Then, in any direction from P, the distance to this circle represents the gravitational anti-lift force A for the corresponding trajectory. *Proof:*—By the well-known simple theorem, the distance from P to this circle A_1 is, in any direction α, equal to W cos α. But, in any of the little force diagrams, say III., it is evident the anti-lift force A is also equal to

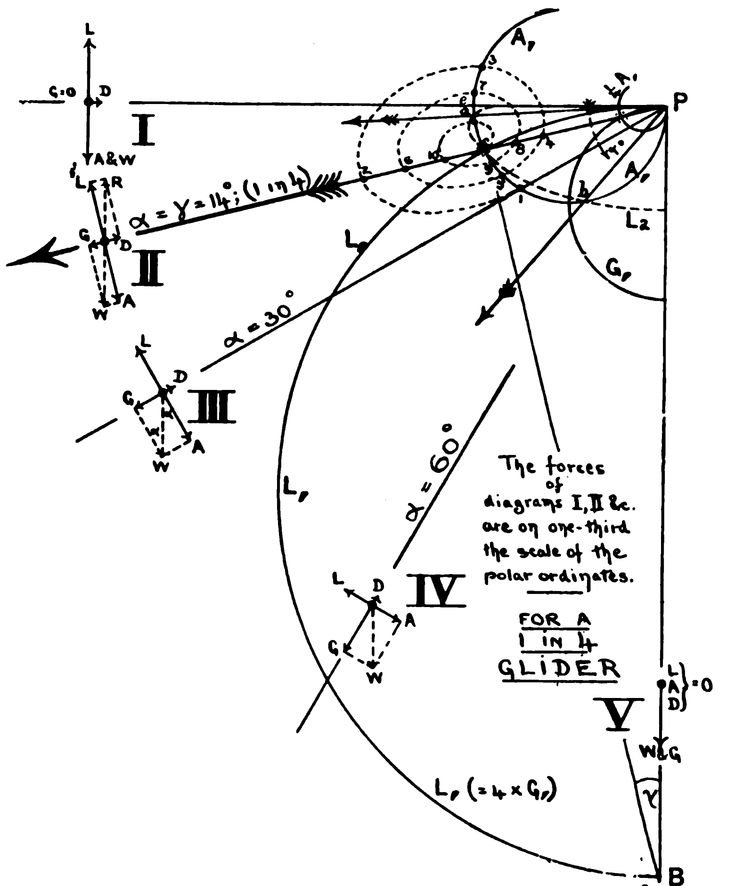


FIG. 44.—The Lift Diagram.

W cos α. Hence, the circle A_1 indicates, as stated, the anti-lift force A for any trajectory.

On a horizontal diameter from P, draw the circle marked "$\frac{1}{4}A_1$," exactly one-quarter the size of circle A_1, (n is equal to 4 in this glider). Then, any distance from P to this circle represents, for a trajectory having the same direction, the drift force D at the moment the glider—***with a view to keeping in the trajectory, if possible***—is launched, in the trajectory, at such speed that the lift force L exactly equals the anti-lift force A. *Proof*:—At the moment of such launching (*e.g.* see diagram III.), the force D, which, by the established property of the glider, is $\frac{1}{4}$L, must be $\frac{1}{4}$A, because L and A are then equal. Therefore, the circle marked $\frac{1}{4}A_1$, which indicates $\frac{1}{4}$A, necessarily indicates the *commencing* force D, as stated.

On a vertical diameter from P draw the circle L_1 exactly four times (*i.e.* *n* times) the size of the circle G_1.[1] Then, any distance from P to circle L_1, in the direction of any given trajectory, represents the value to which the lift force L tends, so far as the glider does not leave that trajectory. *Proof*:—If the glider be started in any trajectory, say the 30° trajectory, and, if necessary, be kept to that trajectory by a frictionless guide, it will accelerate its headway till the force D becomes equal to G. But, by the established property of this glider, force L is always equal to 4D, and, therefore, equal to 4G when D equals G. Hence, circle L_1, being four times circle G_1, indicates, as stated, the value to which the lift force L always tends to set itself in any trajectory.

It is now a simple matter to see why the glider is self-righting with respect to a gliding path about 14° downwards in this example, that is, with respect to the path P*c* passing through the intersections of the circles. For, suppose the glider is launched down a

[1] Notice, for it will be required later, that PB is now *n* times the diameter of circle G_1, or circle A_1, and so equal to *n*W.

steeper path than P*c*, and at the speed which makes the lift force L equal the anti-lift force A (or circle A_1)—with a view to the glider keeping in the steeper path, if possible. Under these circumstances the force G (or circle G_1) is greater than D, or $\frac{1}{4}$L, or $\frac{1}{4}$A (or circle $\frac{1}{4}A_1$), so that the glider must accelerate and commence increasing its lift force L from the present value equal to A (or circle A_1) to the value 4G shown by the circle L_1. Then, with L exceeding A, *the glider is compelled to turn towards the path Pc* in which L and A *may* remain in equilibrium. Similarly, if the glider is launched more horizontally than P*c*, G (or circle G_1) is less than the commencing D (or circle $\frac{1}{4}A_1$) ; the glider loses speed to bring its lift force to the value shown by the circle L_1, and this L_1 being less than A (or circle A_1), *the glider is compelled to turn downwards, again towards the path Pc.* Thus, the glider is self-righting with respect to the path P*c*.

Since L_1 is a semicircle upon PB, the angle P*c*B is a right angle; and since A_1 is a semicircle upon P*e*, the angle P*ce* is a right angle. Therefore, *e*, *c*, and B are in one straight line, and the figure has the following simple geometrical properties :—

(1) Triangles *ec*P, P*c*B, and *e*PB are similar triangles.

(2) The angles *e*P*c* and PB*e* are equal, so that, to find the slope of P*c* with respect to the horizontal, it is only necessary to find the slope of B*e* with respect to BP.

Now the slope of B*e* with respect to BP is P*e* in PB,[1] or W in *n*W (*n* is 4 in the figure), or 1 in *n*. Since, by (2) above, this is the slope of P*c*, it follows that

[1] See footnote, page 150.

the equilibrium gliding path, with respect to which the glider rights itself, is at a slope of 1 in *n* with the horizontal, where *n* is the L/D ratio of the glider. This is the familiar result which may be derived, alternatively, from the diagrams I., II., III., and in various other, but less comprehensive, ways.[1]

It will be seen that the glider owes its self-righting property to the lift curve L_1 passing *outside* the circle A_1 with steepening of the pose; that is to say, it owes its *stable equilibrium* in the path P*c* to the curve L_1 passing *outside* circle A_1, as stated. But its *mere* equilibrium it owes solely to the curve L_1 *crossing* the circle A_1 in point *c*. Now *all* rigid 1 in 4 gliders have the curve L_1 circular, precisely as shown, and there seems no possible exception; but the flexible glider of fig. 39 (page 123), of the type that *decreases* its lift with increasing headway (when the fan F is clamped so as neither to twist nor untwist), will, for reasons easy to discover, give a lift-force curve of the type of L_2 (fig. 44), crossing the A_1 circle in *three* points, *a*, *c*, and *b*, so that such a glider has *three* equilibrium gliding paths, P*a* (nearly level pose, with the machine practically "pancaking"), P*c* (normal pose), and P*b* (at a very steep pose). Now, though the mere equilibrium in path P*c* is the same as it was for the rigid glider (diagram II. is just the same), the *equilibrium* has been made *unstable* instead of stable. That is to say, if the glider deviates a little downwardly or upwardly from P*c*, it tends to deviate *more*, and, as will be seen, find for itself the stable path P*b*

[1] Be careful to distinguish demonstrations that P*c* is merely an equilibrium gliding path, from demonstrations that it is a *stable* equilibrium path, or path to which the glider tends to return after any deviation.

or P*a*, respectively. Suppose, for example, while flying steadily down P*c*, it deviates ever so little in the direction of P*b*. Then, lift force L (curve L_2) having, under the influence of the increased headway, *diminished* to less than the anti-lift A (circle A_1), the glider is compelled to turn more *downwardly* until path P*b*, where the L_2 curve passes outside the A_1 circle, is reached. If, on the other hand, the deviation from P*c* had been in the direction of P*a*, the *excess* of the lift (curve L_2) over the anti-lift (circle A_1) would have made the glider *deviate further*, till the direction P*a* had been reached, where the excess lift is seen to vanish. The crossing point *a* owes its existence, of course, to the fact that only to a limited (though as much as is desirable) extent can the flexible model be made to *increase* its lift with *diminishing* headway.

This flexible model can only be made a stable model with respect to the path P*c* by allowing the fan F (fig. 39) to operate and overtake the negative righting tendencies, for that fan determines an L_1 curve, in fig. 44, passing outside the A_1 circle at the point *c*, though, by way of improvement, not passing outside so rapidly as the L_1 circle passed outside. It will be seen the L_2 curve controls the glider in sudden gusts, and as that curve keeps the lift nearly independent of headway, the sudden gusts do not disturb the glider about the mean pose. The changes of mean pose, with the slower gravitational changes of headway they occasion, are controlled by the fan F.

When the flexible model, apart from its fan F, is said to be unstable in path P*c*, it should be clearly understood this refers to instability of direction of the trajectory, and not to instability of direction of pose with respect to the trajectory, (corresponding to the constant attitude property of the rigid model). In respect to keeping itself behind the centre of mass, the flexible model is far superior to the rigid model, because the latter has the centre of mass too much in the midst of the rigid portion. However, so far as absolutely *still air* is concerned, the flexible model constitutes an unnecessary improvement.

Explanations to Receive with Caution

An explanation of the self-righting property, that has become so common as to be almost the standard explanation, consists in first drawing a diagram corresponding to fig. 43 with a horizontal instead of a downward, or any other, trajectory. (Turn the page so as to bring the path of fig. 43 horizontal.) The next step is to say, that, if the glider pitches into the pose of II. or III., the coming forward or retreating, respectively, of the centre of pressure[1] (where R acts) causes the pose to be turned back to the horizontal trajectory. (Sometimes gravity is brought into the question of this turning of the pose, but that has already been criticised, so we will assume gravity is not mentioned in the above explanation.) The explanation as to why the glider maintains a substantially horizontal path is then *regarded as complete.* To an uncritical view it may appear so, but, actually, all that has been offered is the explanation of why the glider *keeps constant attitude to its trajectory*, and by drawing that trajectory horizontally the *suggestion*, and suggestion only, has been made that the complete

[1] Or, for the less general case of the neutral tail model, the existence of pressure on the upper or lower surface of the tail plane.

explanation has been given. The imperfection in such explanation is, therefore, nearly always revealed by re-reading the explanation with the diagram turned to point, say, 60° downwards, when it will be found to "prove," in the same sense it before proved anything, that the glider maintains *the* 60° *path*.

It is too often overlooked that the ordinary migration of the centre of pressure is only one means to an end. It exists to place the aeroplane in such relationship to its trajectory that it travels substantially head-first therein,—*not* necessarily at constant attitude, that is a particular and not altogether desirable attitude of the rigid machine,[1]—and so that the lift becomes excessive if the machine dives down and gathers headway due to gravity. It should also exist so that, if the headway is *rapidly* increased by a gust, the lift should *not* increase, and that is where the rigid machine is at fault. How a machine may be made to travel substantially head-first in its trajectory, *increase* its lift for the *slower* rates of increase of headway due to downward deviations of pose and path, and yet *decrease* its lift for the *rapid* rates of increase of headway due to violent head gusts, has been sufficiently indicated in Chapter XII.

Oscillations

As has been mentioned before, oscillations, particularly cumulative oscillations, though the bane of the theoretical student of the aeroplane, and of the

[1] Which pilots, happy in applying the term "natural stability" to the common righting tendency of their machines, spend most of their time in annulling, or over-annulling, in gusts. Over-annulment, having been *called* "*anticipation* of the gust" is *supposed* to be impossible to imitate by automatic arrangements.

man who wishes to make good self-flying models, are *not* sources of trouble to a practical aviator. With fig. 44, however, it is easy to trace the main causes of the oscillations, and in a rather interesting manner.

When the rigid glider is launched down the 30° path P1, at such speed that the lift force L equals the anti-lift A (circle A_1, point 1), it rights itself to the path P*c*, as already described. But, owing to its previous steep pose, it has by then acquired an excessive headway that makes the lift force equal, say, to P2 instead of P*c*, and, consequently, makes the path and pose *continue* to deviate upwardly. As the path points more upwardly, the glider loses headway and lift, till, at the pose and path represented by P3, the lift no longer exceeds the anti-lift A (circle A_1, point 3), and the pose commences to return to direction P*c*. But, when the pose and path are again correct, the glider has so lost headway, by reason of its recent upward pose, that the lift, instead of being P*c*, has only such a value as P4, and, as a consequence, the downward turning must continue. The glider then gathers headway and lift, and at some such pose and path as P5 the lift again equals the anti-lift A (circle A_1, point 5), and a return to the normal pose and path P*c* commences.

In fig. 44, point 5 is nearer to *c* than point 1, and, on the next round, point 9 than point 5, so that the dotted spiral indicates, by its converging on point *c*, that the oscillations *die down*. The spiral expressing the changing relationship between pose and lift force is usually of this converging type if the mass of the glider is concentrated, but, when the glider has a considerable longitudinal moment of inertia, the spiral is likely to be a diverging one, so that the oscillations not only refuse to die down, but tend to increase cumulatively, if once started.[1] The reasons are *roughly* as follows :—

On the glider being launched as before, in the circumstances of point 1, the angular inertia delays the turning of the pose, so that, when the pose is normal, the headway and lift are greater than before, and the point 2 further from *c*. The mere fact of point 2 being further from *c* would cause point 3 to be further from *c*, even if the glider could be reduced to its concentrated mass state; but, as it actually has considerable up-turning angular momentum at point 2, point 3 is carried still further from *c*. Now that point 3 is further from *c*, point 4 would be further from *c* even if the glider had no angular inertia; but, as it has considerable angular inertia acting to delay the return to normal pose and thereby to increase the loss of headway and lift, point 4 is still further removed from *c*. With point 4 further from *c*, point 5 would naturally be further from *c*, even if the glider had no angular inertia; but, since the glider has considerable down-turning angular momentum at point 4,

[1] For simple gliders, and *small* oscillations, the conditions for increase of such oscillations can be determined by analytical methods, but the conclusion must not be jumped to that they go on increasing in amplitude *without limit*, or that the spiral of fig. 44 *continues* diverging. There are indications that, for a glider with concentrated mass, the spiral is converging; and, as angular inertia (or moment of inertia) is added, the spiral becomes a *more slowly converging* one, till, with a certain amount of angular inertia, the spiral converges only to a small *closed figure round the point c*. The glider now shows the property of *increasing* very *small* oscillations from the equilibrium glide, and *decreasing* very *large* oscillations. Practically, these sensitive gliders cannot be made to glide, because sympathetic lateral oscillations confuse the flights. The closed figure round *c* enlarges with further increase of angular inertia.

point 5 is pushed still further from *c*. With the angular inertia operating as described, it is only to be expected that more than a certain amount will cause the point 5 to be further from *c* than point 1, and so prevent the spiral converging, and the oscillations from dying down.

The dampers of these oscillations—head resistance, empennage, and the fly-wheel fan D (fig. 32, I.)—have been mentioned in Chapter XII.

The flexible model of fig. 39, when it has the L_2 curve of fig. 44, but has not the slow fan F (fig. 39) in action, has no tendency to oscillate about the path P*c*, but it has such tendency about the paths P*a* and P*b*. Owing to such oscillations, the pose P*a* is rather difficult to obtain experimentally, the glider being disposed to oscillate so as to pass the path P*c* and find the path P*b*, which it prefers. The suitably proportioned slow-fan equipment (F of figs. 32 and 39), in giving a mean stability to the path P*c*, superimposed upon its momentary instability, adds so little tendency for the machine to oscillate after it is once "set" (see footnote, p. 100) that, in many cases, angular inertia may actually be added to steady the pose of the machine between the gusts.

CHAPTER XVII

FORMULÆ RELATING TO CIRCLING

WHEN the bird is circling in uniform wheeling soaring (fig. 6), all its impressed accelerations relative to the air are precisely the same as if the air were still and the bird were being pulled forward by a propeller (fig. 31, II.). In other words, the propeller and the air acceleration are merely alternative (or supplementary) modes of obtaining a flying thrust relative to the air. It follows that formulæ (1) to (14) are variously applicable to an aeroplane circling in still air, but since, for an aeroplane, the straight flight headway V_f is of more importance as a fundamental constant than the gliding headway V, and the banking angle ζ of more importance than T, *the formulæ include more than necessary, and may be simplified.*

For a circling aeroplane (see fig. 6) of gliding angle 1 in n, or γ degrees, we have :—

$$\left(1 + \frac{1}{n^2}\right) = (1 + \tan^2 \gamma) = \frac{1}{\cos^2 \gamma} \quad . \quad . \quad . \quad (30)$$

In formula (7) we used the fact that the velocity of an aeroplane is proportional to the square root of its weight upon the air, and we may again use that fact in the following formula :—

$$\frac{V_f^2}{V^2} = \frac{1}{\cos \gamma}, \quad \text{or} \quad V^4 = V_f^4 \cos^2 \gamma . \quad . \quad . \quad (31)$$

With (30) and (31) and (14), formula (8) may be reduced to[1]:—

$$R = \frac{V_f^2}{g \sin \zeta}. \quad . \quad . \quad . \quad . \quad . \quad (32)$$

The above, working backwards from the complex to the simple, is a little laborious, but *there is another way*: Anyone inspecting formula (8), or the detailed soaring chart[2] in *Aeronautics* of December, 1911, or the converging process for calculating R suggested in *Aeronautics* of November, 1911, will notice that R has a definite minimum when T = 0, *as marked on the soaring charts*, and certain values at other banking angles, *as marked on the soaring charts.* Now, when the propeller, instead of the motion of the air, furnishes 99·9 per cent. of the acceleration component AC that balances the drift force (as stated in the *Aeronautics* article referred to), the case is, from the point of view of equilibrium, that of a *frictionless* aeroplane, with *n* infinite, and V and V_f equal, circling in uniform wheeling soaring. The right-hand sides of formulæ (1) to (4) all vanish with *n* infinite, and formula (5) is indeterminate and of no account. Seeing that *r*—formula (4)—is now zero, and AC neglected, and putting V_a for the actual headway, formula (6) may be written (see fig. 6) in the modified form:—

$$AD_1 = V_a^2/(R \sin \zeta) \quad . \quad . \quad . \quad . \quad . \quad (33)$$

and, in the manner of the line preceding formula (13):—

$$V_a^2 = V_f^2 \frac{AD_1}{g} \quad . \quad . \quad . \quad . \quad . \quad (34)$$

---

[1] When the aeroplane has considerable size compared with V_f (the distance it ordinarily flies in one second), R is somewhat greater than the value given in formula (32).

[2] Reproduced in fig. 8 and the Plate facing p. 20.

From these two formulæ it follows, simply, that :—

$$R = \frac{V_f^2}{g \sin \zeta}. \quad . \quad . \quad . \text{ again (32)}$$

A yet simpler plan is to deal with the question on its own account, without regard to soaring. Thus :—

Noting in fig. 6 that $BL = V_a^2/R$, it is evident that $\tan \zeta$ or $(\sin\zeta / \cos\zeta) = V_a^2/(gR)$, from which, $R = V_a^2 \cos\zeta/(g \sin\zeta)$. But $V_f^2/V_a^2 = AB/AL = \cos\zeta$. Hence, as before :—

$$R = \frac{V_f^2}{g \sin \zeta}. \quad . \quad . \quad . \text{ again (32)}$$

When the result to be aimed at is seen, and put in the form $\sin\zeta = V_f^2/(Rg)$, it is evident that formula (32) may be written down if we can find a plausible-looking right-angled triangle with the angle ζ, a side x^2/R opposite ζ (where x is some velocity we choose to identify with V_f), and a hypotenuse called g. Such a triangle is readily obtained, on paper, by the simple process of ignoring that the pilot must increase the speed and thrust of the aeroplane when he travels round the level circle of radius R, with banking angle to correspond. It is evident, then, that the lift AL could be said to continue equal to AB or g, and the horizontal centripetal component equal to V_f^2/R, so that $\sin\zeta = V_f^2/(Rg)$. This is very seductive to one who might like to obtain formula (32) anyhow, by a short cut, but the process is grossly in error in reasoning about a circling aeroplane for which the upward component of the lift is only $W \cos\zeta$. In figures, this means that a 1000-lb. aeroplane banking at 60° is absurdly assumed to be circling with a vertical component of the lift equal only to 500 lbs. Yet, formula (32) is derived and it is correct! That is a geometrical accident of the kind that can occasionally be made use of when you know the result to aim at; but it is so ready to hand, in this case, that the reader is cautioned against any plausible derivation of formula (32) that does not pay regard to the physical necessity of the speed being increased.

Seeing that $W/\cos\zeta$ is the effective weight of the machine upon the air, when circling, (evident from AL of fig. 6), we have, if k be the mechanical strength factor of safety of the circling aeroplane :—

$$W/\cos\zeta \ngtr kW$$

or

$$\cos\zeta \nless \frac{1}{k} \quad . \quad . \quad . \quad . \quad . \quad (33)$$

As an example, this allows an aeroplane with factor of safety 6 to bank as steeply as 80°; but anything near that should be avoided, since only another 5° adds greatly to the stresses.

In order to give the increased lift of $W/\cos\zeta$, when banked at angle ζ, the machine must have its propeller thrust increased in the same proportion. Consequently, if an aeroplane engine is capable of giving no more than k_1 times its normal flying torque, we have :—

$$1/\cos\zeta \ngtr k_1$$

or

$$\cos\zeta \nless \frac{1}{k_1} \quad . \quad . \quad . \quad . \quad . \quad (34)$$

Usually, k of formula (33) is about 6, while k_1 of formula (34) is not often greater than about 2·0. Hence, (34) gives the *practical* limit of circling, as determined by limited engine torque, in the condition that $\cos\zeta \nless \frac{1}{2}$ or $\zeta \ngtr 60°$. However, 45° is a good limit for pilots to adopt, like the birds.

The thrust factor, for a given banking angle, is given by formula (34) in the form $k_1 = 1/\cos\zeta$. Now the normal thrust is W/*n*, so the thrust when banking in circular flying is $W/(n\cos\zeta)$. This is only another way of saying that the effective *n* of a circling banked aeroplane is, like that of the soaring birds, degraded from the normal *n* to $n\cos\zeta$.

Again, writing $V_f\sqrt{\cos\gamma}$ for the V of the line but one preceding formula (14), we get, where ζ is limited:—

$$T \nless \frac{2\pi}{g} V_f / \sqrt{\sin\zeta\tan\zeta} . \quad . \quad . \quad . \quad (35)$$

giving

$$T \nless \frac{V_f}{5 \cdot 12} \cdot \frac{1}{\sqrt{\sin\zeta\tan\zeta}}$$

Limiting ζ to 45° and 60°, T is limited to not less than $V_f/4{\cdot}3$ and $V_f/6{\cdot}3$, respectively; or, for a 50 ft. p.s. (34 m.p.h.) machine, T, the time of steering in a circle, must not be made less than 8 to 12 seconds,—preferably not less than the 12 seconds.

It will be seen, therefore, that a process of ringing the changes on the formulæ in this work, particularly those connected with uniform wheeling soaring, is capable of disclosing many interesting points of which the above are only examples. The same is also true of the methods of this work.

M 2

APPENDIX

AVIATION DISASTERS

SINCE the body of this book was sent to the press, the aviation disasters which have occurred have attracted an unusual amount of public attention. They have generally been characterised by the machine, while flying fairly steadily, commencing a dive that ends in a head-first collision with the ground, and the pilot, as might be expected, seldom survives. Such a disaster may, in some cases, be due to failure of a wire or bolt, or the bursting of a propeller or engine; but when, during the continuous repetition of such disasters, special causes are invoked almost every time, there must be a more fundamental cause which the designer cannot lightly undertake to remove from the next machine. The accidents will now be discussed as due to three principal causes, separately and in combination.

DISASTERS CAUSED BY FRONT-HEAVINESS

This cause has already been referred to on pages 132 and 133, and it is hardly necessary to add anything further. The pilot who privately improves his machine, in *one* respect, by flying with a down-pressed rear flap elevator (*i.e.* receiving the air on its upper surface) must be quite aware of the risk he is running, and also know how to avoid it.

DISASTERS CAUSED BY AN INVERSE STABLE ATTITUDE

This cause is of great interest and importance. It is that sometimes described, for rough purposes, as "getting the air on the top of the planes." The object of the following discussion is to indicate how it is that the recovery of pose is, in many cases, an *absolute impossibility* to the pilot.

When the machine is travelling steadily and horizontally at I. (fig. 45), the lift L and weight W are necessarily in equilibrium, as shown, assuming the propeller thrust and head resistance are, as usual, acting horizontally through the centre of mass of the machine. Now, when the aeroplane curves downwards, as at II., it is a *certain* indication that the lift

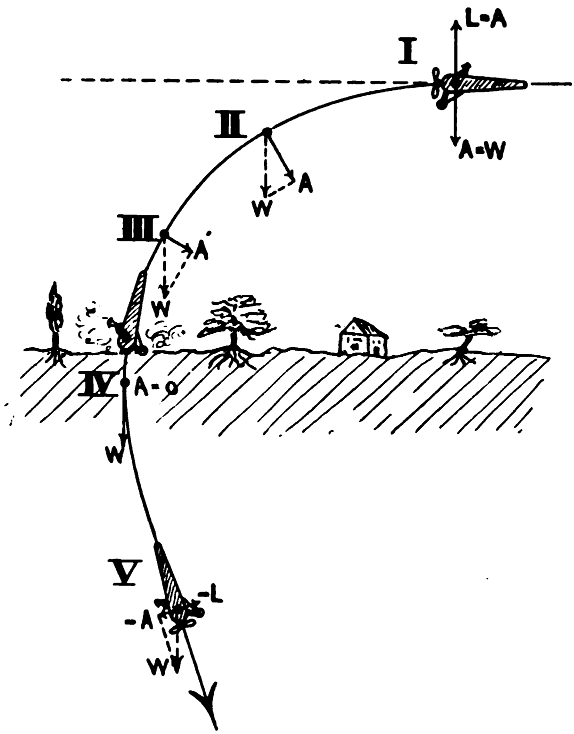


FIG. 45.

force has diminished to less than the weight ; and when the turning, as in these accidents, continues through III. and IV. to the straight path at V., it is *certain* that the lift has become not only less than W, but less than zero—in fact, *negative*. On no other condition can it be balancing the *negative* anti-lift in V. It remains, therefore, to be shown how an aeroplane, flying at I., may start flying with a negative lift impossible to change into a positive lift by any manipulation of the elevator.

Let us take as an example the simple, flat, ballasted glider of fig. 46, but without the elevator *e*, and pivot it accurately at its centre of mass, in a wind tunnel, as shown.[1] It will then be found that, besides having the usual property of flying in the normal or direct stable attitude, as at I., it will, if just forced past the unstable neutral attitude II., suddenly turn to the *inverse* stable attitude IV., and keep to that. In IV., it will have precisely the same lift as in I., but negative or downwards.

Let us now fit the small manually-operated flap elevator *e* to the rear of the glider, and proceed again with the wind-tunnel experiment of fig. 46. In I., with the elevator flapping loosely and so neutral, the glider is in the normal

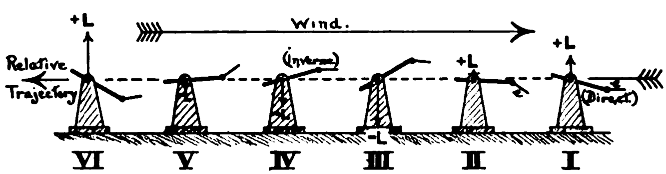


FIG. 46.

or direct stable attitude, as before; but, on turning the elevator, as in II., the attitude of the glider may be made to become nearly neutral with respect to the relative-to-air path of the centre of mass. We will assume the elevator—either through restricted size, or restricted movement, or both—is only powerful enough to bring the glider *nearly* neutral. The glider is now in a delicate state, and should the wind, as by a sudden tilting of the wind tunnel, be given a slight downward gust, the glider will swing from the attitude II. to the extreme *inverse* attitude III., passing through the stable inverse attitude IV. because the elevator is held in its extreme down-steering position instead of flapping freely. The elevator may now be moved to change attitude III., through attitude IV., to attitude V., *but no further*, for the same reason

[1] The wind tunnel need not be horizontal; it is only drawn so for convenience. The attitude effects described always take place with reference to the relative-to-air flight path of the centre of mass, whatever direction it may be in. That *must* be understood, as in Chapter XVI.

that it was powerless, without the aid of a gust, to change attitude II. to attitude III. or IV.

Suppose, now, that this machine is the one flying at I. in fig. 45, and suppose that, in the common act of balancing, the pilot has it near the critical condition of II. (fig. 46). If, as is *certain* to happen sooner or later, a slight downward gust chooses to attack at this moment, the inverse attitude of III. (fig. 46) is almost at once established, with great downward stress on the planes, and the machine will begin to take the downwardly curved path I., II., III., etc. of fig. 45, if not first broken by the downward stress (see −L in III. of fig. 46). The pilot now turns his elevator in an up-steering sense, but he can do no more than *reduce* the inverse attitude and lift of III. (fig. 46) to the attitude and lift, *still inverse and negative*, of V. (fig. 46). That is to say, he can do no more than straighten somewhat the downward path I., II., III., etc. (fig. 45) without being able to reverse its curvature.[1] He becomes, consequently, a helpless spectator of his own fate.

When the machine lands, and the pilot, who was perhaps under the false impression "the control jammed," is dead, there are those who may see in strained controls, broken wings, torn fabric, and deranged details the primary causes of the disaster, whereas they are probably merely secondary effects due to the desperate actions of the pilot, and to the extraordinary speed and stresses in the machine.

In some cases the pilot may be, and, apparently, sometimes *has been*, saved by a second, but fortunate, rear gust attacking while the machine is diving down in attitude V. (fig. 46). In other cases, the elevator has been just powerful enough to overcome the inverse attitude V. (fig. 46). In both these cases, however, the machine, travelling swiftly down in attitude V. (fig. 46), experiences a sudden jerk into attitude VI. (fig. 46),

[1] Assuming the pilot can do so well as make the negative lift negligible, the radius of path R *must* be V_f^2/g at I., and $V_a^2/(g \cos \alpha)$ at II., III., etc., where α is the angle of the trajectory. The path can easily be drawn, with all *essential* accuracy, for a specified machine, by a combined graphical and arithmetical step-by-step process that suggests itself when the attempt is made. The path is no parabola, such as it would be, of course, in a vacuum.

accompanied by a sudden turn on to a level and upward path, and this may break the wings, or produce the irregular disordered flight which the pilot finds so difficult to steady.

But, it may be objected, the pilots are not flying simple, flat, ballasted gliders. That is quite true, but a great number of the rigid machines now made on casual principles will, if tested in model form, in a wind tunnel, be found to have stable inverse attitudes as well as their direct ones, and of so marked a character that the elevator controls provided are barely powerful enough to change the inverse into the direct attitude, in emergency. In general, these machines are characterised by circularly cambered main planes, small elevators, and cambered, instead of flat, fixed tail planes, but they cannot be detected by inspection alone. The only detection possible is that furnished by the disaster which, sooner or later, may await such a machine, or, preferably, the detection furnished by a test of an accurate model placed in a wind tunnel.[1]

By modifying the camber of the planes, even at the loss, if necessary, of aerodynamic efficiency, designers may make a rigid machine have no actual inverse stable attitude, but they will find some difficulty in preventing such *near approach* to the condition that the machine is not involved, at times, in a deep downward dive with an unsatisfactory and dangerous recovery.

The flexible glider of fig. 39, in maintaining constant positive lift and allowing nothing to make the lift suddenly negative, is obviously as far removed as possible from the kind of disaster caused by a machine having an inverse stable attitude with negative lift.

Disasters caused by the Pilot's Weight on his Controls

If a pilot, flying in still air, chooses to steer in a quick up-and-down wavy path, he will discover that, whenever he points down or up, he has little perceptible tendency to slide forward

[1] Perhaps the submission of a test model to, say, the National Physical Laboratory will, after the decline of empiricism, be regarded as a matter-of-course procedure of the constructor of aeroplanes.

or backward, respectively, in his seat, though, if observant, he will notice he feels heavier when in the troughs of the waves than when on the peaks. Sometime, however, especially in more gusty weather than he has been accustomed to, he may find himself weighing very strongly forwardly on his seat, and, in some cases, disaster may follow the unusual circumstance.

In this case, we are concerned with a relative gravity, but the *internal* one; that is, the one of bodies within the machine relative to the machine, and not of the machine as a whole relative to the air.

In fig. 47, a machine flying steadily at I., in still air, chooses to steer down through angle a, into the position II., and, we

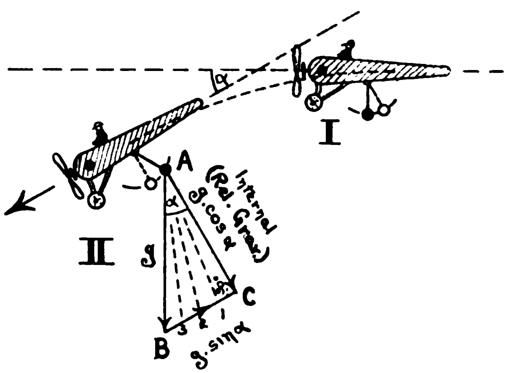


FIG. 47.

will assume, so quickly that the headway has not had sufficient time to increase appreciably. In position I. a pendulum, as an indicator of the direction in which things tend to weigh *relative* to the machine, tends to hang truly vertically, as shown, but in II. this is not the case.

Assuming—to avoid an appearance of begging the question—that the pendulum is in some non-central position A, common gravity impresses upon it an acceleration AB, or g, *relative* to the machine. But, on drawing AC at right angles to the trajectory, and CB parallel to the trajectory, we find CB, or $g \sin a$, to be the acceleration of the machine down its trajectory. Notice that no correction is yet required for head resistance, because the propeller thrust, in balancing the head resistance at the *present* headway, is making the machine virtually frictionless.

Now, in having the acceleration CB, the machine is impressing upon the pendulum bob an equal and opposite acceleration BC relative to the machine. (In ordinary language, it is tending to leave the pendulum bob behind to that degree.) The resultant of AB and BC, or the "gravity" of the pendulum bob *relative to the machine*, is AC, which is $g \cos a$, and, obviously, at *right angles to the machine.* Thus, since the pendulum bob, and, of course, the pilot too, weigh upon the machine in the ordinary direction *with respect to the floor*, tilting may seem of no moment; but suppose the pilot should dwell a little at the pose a. In this case, the machine increases its headway, and, through that, increases its head resistance and decreases its propeller thrust so that the rate of acceleration of the machine, or BC, shrinks first to B1, then to B2, and so on, while the direction of the resultant gravity relative to the machine changes from AC, through A1, A2, etc., to approach AB. That is to say, the pilot, if not strapped or otherwise anchored to his seat or the frame of the machine, but if at the same time gripping one of some types of control, may, before he realizes, find himself weighing forward upon the control with C1/AB, C2/AB, etc., of his ordinary weight, and so forcing the machine into a steeper and steeper pose of increasing danger. Disaster may follow.

The remedy consists in strapping the pilot in his seat, in giving him proper abutments in the frame to take his weight, and suitably altering the method of manual control.

Though the pilot has been assumed to start the weighing upon his controls by dwelling too long in a downward pose, those who have followed the earlier parts of this book, connected with Chapter II., will easily see that a prolonged head gust, in causing a horizontal machine to be *virtually* travelling downhill (fig. 1), may start the diving accident just as well as actual tilting.[1]

Since, in fig. 47, the pendulum's first tendency is to tilt with the machine into the direction AC, it will be seen that a great deal of the endeavour made to employ pendulums to

[1] See "Unpractical Lines of Development" (p. 172).

"hang *down*" and maintain pose by tilting elevators is waste of time. On "second thoughts," so to speak, the pendulum does begin to tend to hang down AB, but, so far as it is successful in that, it has the disturbing effect in gusts referred to on pages 7 and 8, when AB (fig. 47) is superseded by the machine-to-air, or external, relative gravity (figs. 1 to 4).

Combined Causes of Disaster

Seeing that a rigid machine having inverse stability of attitude is liable to dive at the ground, without hope of recovery, and that a front-heavy machine, held in check by manual control, is liable, on release of the control, to the same disaster, it might be thought that the inverse stable machine must be made doubly dangerous by putting its weight more forward; but, in point of fact, the forward placing of the weight, while contributing the risk of the pilot relinquishing his controls, actually reduces the risk of the air acting continuously on the upper surface of the machine, so long as the pilot handles the controls. This may be explained as due to the inverse centre of pressure being less able to get so far in front as, and further than, the centre of mass, and thereby automatically maintain a negative lift.

The pilot's weighing upon his controls necessarily always acts adversely, whether alone or in combination with other causes of the diving disaster.

Aviation disasters now occur with monotonous regularity, one serious injury for so many thousand miles flown, one death for so many more thousand miles flown (about a millionth of the distance one may travel on a tube railway or motor-car). These are probably the *final* constants of the rigid fluctuating-lift type of design in conjunction with the average human skill. The moral is obvious.

UNPRACTICAL LINES OF DEVELOPMENT

(Suggested by page 170. See its footnote.)

IN connection with the causes of aviation disasters, it will be seen that the pilot's weighing forward upon his controls, in a head gust, at once suggests itself as a plausible means of producing that momentary down-steer, at the onset of a head gust, which the author has advocated, for stability, when used in conjunction with a slow, overtaking, up-steering effect able to avert the diving disaster. So far as the mass effect is concerned, the corresponding invention suggests itself in four classes:—

(1) A *small* mass, either sliding or suspended pendulum-wise, and connected to the elevator in such sense that, on weighing forwards, it *down-steers* the elevator. This is in the contrary sense to that hitherto so popular with pendulums, the deliberate object being to give a quick-acting *negative* righting effect. The mass being small will have to set in action a compressed-air motor to operate the elevator, supplied with air from a well-stored receiver, fed by a compressor driven by an engine. Alternatively, hydraulic or electrical relay systems may be used, but the house-that-Jack-built kind of arrangement cannot be avoided when a small mass is employed.

(2) A large mass, such as the pilot or the engine, free to slide or swing and directly operate the elevator in a down-steering sense when it (the mass) weighs forward. This is a far more promising scheme to develop than No. 1.

(3) A concentrated mass carried at a height above the *main plane*, as, for instance, at a height above the main plane of the model of fig. 32, I. This has, in some forms, been tested by the author with varying, but not very noteworthy, success, as an auxiliary improvement. It has advantages over No. 2.

(4) Placing the centre of mass of the machine, as, for instance, the centre of mass of fig. 32, I., at a suitable height above the centre of resistance, as well as forwards. This has, in some tests, done very nicely on an otherwise defective machine, but it has never made a very good machine appreciably better.

Of the above, No. 4 is really the root-invention, in the same sense that the underhung load is the root-invention of all common pendulum schemes. The variant types, Nos. 3, 2, and 1, particularly the house-that-Jack-built No. 1, are, in the above order, less and less likely to improve on No. 4 in any detail without adding worse vices peculiar to themselves.

If we assume any one of the above is employed to copy the right degree of down-steering effect in a head gust (which it cannot actually do), it only provides for the "flyability" of the machine, and gives liability to the diving disaster of the weighing-upon-the-controls variety. Stability requires the addition of a supervising or overtaking control, such as that of the slow-fan equipment, to which there is no conceivable alternative other than the old pressure plate facing the relative wind, and up-steering the elevator with increase in the headway. This may be employed in four ways:—

(*a*) A small pressure plate may be used connected through powerful relays to the elevator (usual objections).

(*b*) A larger pressure plate may be used connected directly to the elevator.

(*c*) A large pressure plate may be used carried above the main plane of the machine, as at the top of the mast of fig. 32, I.

(*d*) The centre of mass of the machine may be lowered so that the centre of head resistance alone may constitute itself an equivalent of the pressure plate.

But, the reader may exclaim, to have the pressure plate scheme (*c*) or (*d*) nullifies the mass scheme, and obviously nullifies the mass scheme No. 4! That is perfectly true, and the root-inventions No. 4 and (*d*) bring to the surface an underlying law that is inherent in the obfuscating combinations:—You can have the mass effect, or you can have the pressure plate effect, but you cannot easily have both; that is, you cannot have the mass effect to act momentarily in the down-steering sense, and yet be overcome by the pressure plate acting in the opposite sense as necessary for stability.

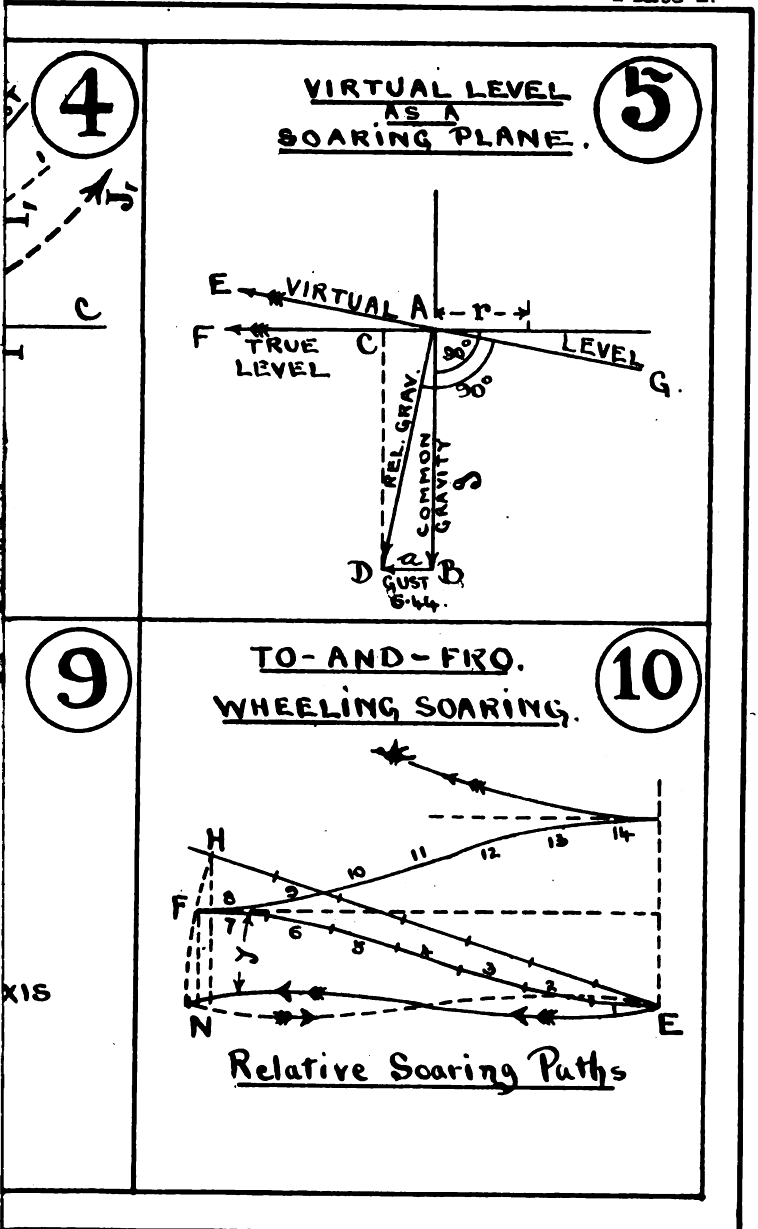
The facts are, that, the forward weight of the author's, as proposed in Article III., pages 117-130, is the *unique*, constant lift, constant path, solution by mass effects, and the slow-fan equipment is the *unique* simple solution of the essential overtaking, supervising effect.

However, nothing but educational good can come of attempts to develop inventions of the above class, and so far as they imitate the actions of the parent methods, and are simple and reliable, they *must* improve, to some degree, the stability of their aeroplanes, and so give rise, probably, to an epidemic of such schemes, rivalling that of the common pendulum schemes. There is now, in these matters, a smouldering fire of concealed effort and knowledge (positive and *negative*) within the aeroplane industry, particularly abroad.

INDEX

NOTE OF PAGES ON WHICH THE PLATE-FIGURES ARE REFERRED TO

Plate 1.



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E & F. N. SPON LTD. LONDON.

SUPPLEMENT

ON

LATERAL STABILITY

The Parent Principles and Types

SINCE an aeroplane always extends to the left and right of its longitudinal axis, it may be regarded as consisting, in principle, of at least two similar aeroplanes—a left one and a right one—flying side by side.

The following statement should then be allowable without proof, since its truth is obvious enough from first principles :—

> In order that the whole aeroplane, travelling steadily in straight, level flight, shall not be disturbed in its lateral pose, or rotate round its longitudinal axis, it is essential that the lifts (more accurately the lifting moments) of the left and right aeroplanes remain equal to each other.

Since the attacks of gusts are the cause of the left and right aeroplanes altering their lifts, and gusts are characterised by accelerations of headway, the problem of securing steady lateral pose is simply that of finding two similar constant-lift aeroplanes and attaching them side by side.

Now, in the type of aeroplane of fig. 39 (page 123), suitably made without the slow-fan F, we already possess a constant-lift type of machine, and in fig. 48 two such machines are shown coupled together by being quite freely hinged, at their forward edges, to a long bar. The figure therefore shows, diagrammatically, a machine that, once started in its steady flight, cannot be disturbed in its lateral pose, and it cannot be disturbed in its longitudinal pose because the left

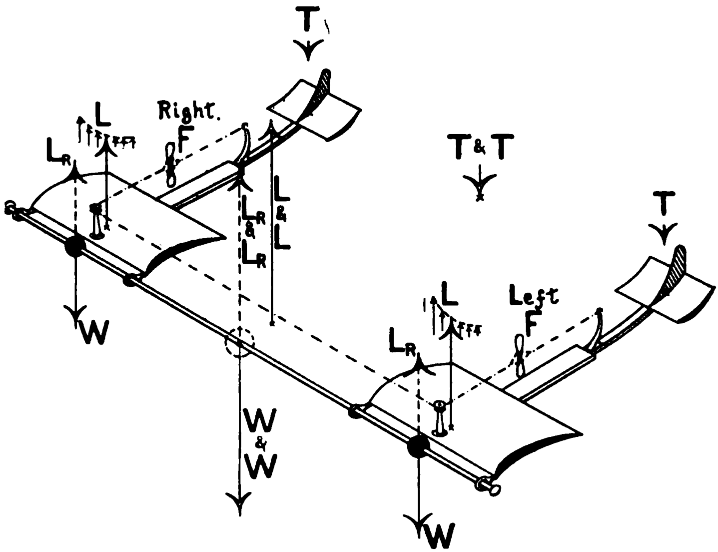

FIG. 48.

and right aeroplanes act in unison as a single constant-lift machine of the type shown in fig. 39.

But, although the machine of fig. 48 is free from *sudden* disturbance of lateral and longitudinal pose, it does not necessarily constitute itself a completely self-flying aeroplane. For one thing, it is not possible to obtain two aeroplanes that give exactly equal constant lifts, and if, for example, the left aeroplane is giving a little less lift than the right one, the whole machine will rotate left-handedly round its longitudinal axis, as viewed from the rear. This rotation, however, will obviously be prevented if, as a direct or indirect consequence of such rotation, the right aeroplane is caused to develop less lift than the left one, as in one of the ways now to be described.

When the machine tilts to the left, it commences to circle to the left; not so much in consequence of its sliding down to the left (it may not be doing that at all) as in consequence of the lift force having acquired a component to the left. This component of the lift first determines the curvature of the path,[1] and then the machine's proceeding head-first in that path, and not crab-like, is determined by the side-view centre of pressure having been designed, as usual, to the rear of the centre of mass.

As the machine so circles to the left, the outer and higher aeroplane, the lift of which we wish to have reduced, has a greater headway than the lift of the other aeroplane, the lift of which we wish to have increased. All we require, therefore, is that the lift of each of the two aeroplanes shall *decrease* with an increase in headway, and correspondingly *increase* with a decrease in headway.

Now the model of fig. 39, when it was designed with the retreating centre of pressure with decreasing angle of incidence of the main plane, had this very property of *decreasing* its lift with an increase in headway. The problem, therefore, of making the model of fig. 48 tend to preserve a level lateral pose even if

[1] If the vertical component of the lift is still equal to the weight W when the angle of lateral tilt is ζ, then the horizontal component is, of course, W tan ζ, and the radius of curvature of the path, being such that the centripetal acceleration corresponds to this force, is given by:—Radius $= V_a^2/(g \tan \zeta)$. Or formula (32) may be used:—Radius $= V_f^2/(g \sin \zeta)$.

the two aeroplanes are not an exact match to each other, and the practically identical problem of making the machine self-righting in its lateral pose when it happens to be disturbed laterally, are both easily solved by making each left and right aeroplane a *diminishing-lift* machine corresponding to the one described in connection with fig. 39.

The machine of fig. 48, therefore, is made to consist of two diminishing-lift aeroplanes, so that, when the whole machine tilts in its lateral pose, and circles as a consequence, the outer, higher, and faster aeroplane experiences *less* lift than the inner, lower, and slower aeroplane, and the machine returns to its level lateral pose. Incidentally, the converging spiral upsetting path, characteristic of most simple rigid machines, and due to the greater lift of the outer wing, is prevented in this model of fig. 48 by being converted into a *diverging* spiral *righting* path consequent on the level lateral pose being restored.

Consider, next, the longitudinal stability of this machine of fig. 48. Now that it consists of two diminishing-lift aeroplanes, it will be evident that it has been endowed with the permanent diving tendency that requires compensating for, either manually or by a slow-fan (see pages 127, 153). In fact, in discussing the lateral stability, and explaining the lateral self-righting, it was tacitly assumed that there was such a supervising longitudinal control.

Following the example of fig. 39, it might be thought that the addition of a *separate* up-steering slow-fan to *each* aeroplane of fig. 48 is all that is necessary to ensure longitudinal stability; but that way of securing longitudinal stability would spoil the lateral stability, because it would cause *each* aeroplane to have a slowly *increasing* lift with increasing headway. Such increasing-lift effect would, of course, annul and overpower the diminishing-lift effect essential to the recovery of lateral pose. We may, however (as alternatives to the pilot's supervision), put one or more slow-fans on the machine, arranged to wind up the two yielding tail planes *simultaneously*, with equal forces, as is the case with the connected fans, F, F, of fig. 48. Such an arrangement will be seen to control the average longitudinal pose of the whole machine, without interfering with the independent *differential* diminishing-lift effect of the outer wing, compared with the inner wing, that is required for the lateral self-righting effect.

Three-tailed Modification

Alternatively, a third aeroplane may be added at the

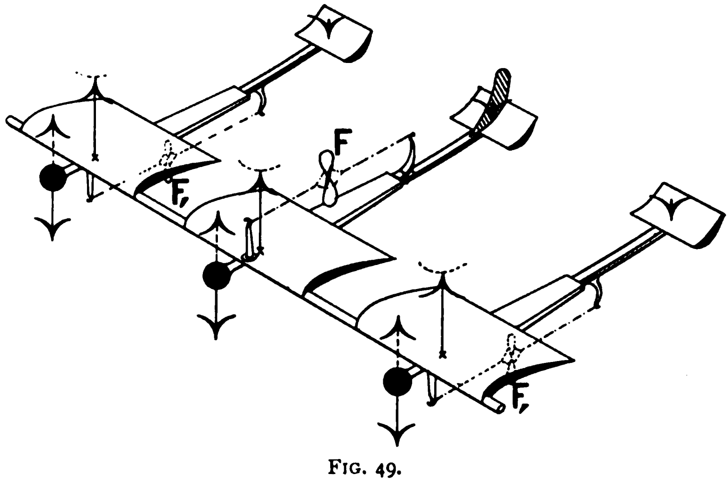

FIG. 49.

middle, between the other two, and this third aeroplane may carry a yieldingly mounted tail that, being operated by a slow-fan (or a pilot), may control the average longitudinal pose in the usual way (fig. 49).

If we wish to add separate slow-fans to the left and right aeroplanes to strengthen the lateral self-righting effect, we may do so, but each fan (F_1 in fig. 49) must be only small and arranged to let *down* or pull *down* its tail plane, instead of winding it up with *increasing* headway.

Other Modifications of Parent Type

Several types of machine may be constructed embodying the fundamental principles of those of figs. 48 and 49. In fig. 49 itself, the transverse bar to which the

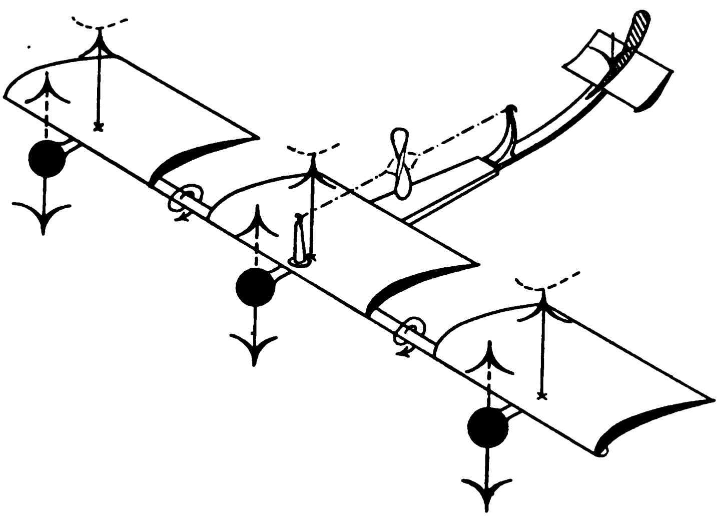

FIG. 50.

right and left aeroplanes are attached, instead of being infinitely yielding like a hinge, may have a slight degree of springy torsional stiffness that may assist the lateral tail planes in maintaining the loading or air pressure on the under surfaces of the lateral main planes.

In fig. 50, a more distinct type is formed by making the transverse bar still stronger in its torsional springiness, so that it may entirely supersede the lateral tail planes in keeping the main planes loaded with substantially constant or diminishing lifts. It is not easy, in practice, to get the best results with this mode of construction, even in entirely self-flying machines; while, for purposes of lateral control and adjustment, whether by pilot, gyroscopes, or other automatic means, it will be understood, later, that this type is at a considerable disadvantage in its absence of lateral auxiliary planes.

Intensified Warping Effects

In most well-constructed main planes, the warping of the extremities requires considerable force, and, in any case, a strongly determined warping effect, for a given gust, is always preferable to a weak, indecisive warping effect. In the modification of fig. 51, therefore, an intensified lateral control, of the same type as the other described figures, is obtained by the addition of auxiliary down-steering, up-pressed planes M_1, M_1, rigidly attached to the rear of the lateral main planes so as to have a leverage over the main planes. It will be noticed that, in fig. 51, the lateral masses have, by way of variety, been moved back to practical coincidence with the centres of pressure of the lateral main planes,[1] but they still function as before, by reason of being carried forwardly of the auxiliary lateral planes[2] (particularly forwardly of the down-steering ones) and forwardly of the centre of pressure, or transverse axis

[1] See page 266, claims 9 and 10; page 259, last two paragraphs, and page 260, lines 5 to 24.

[2] See page 253, last paragraph; and page 266, claim 11.

of movement relative to the air, of each lateral main

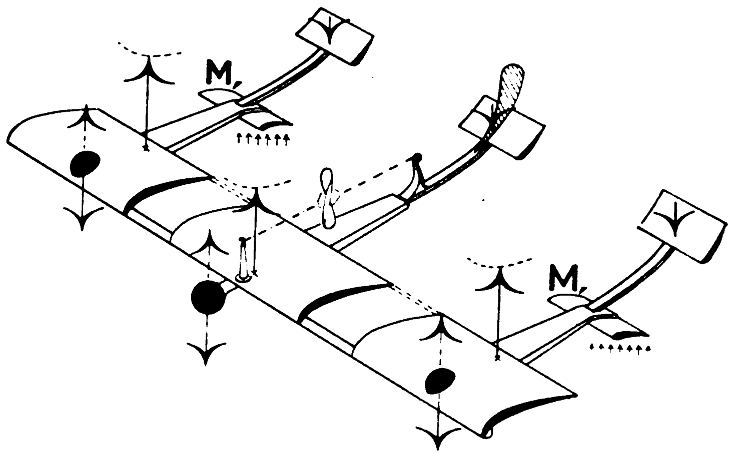

FIG. 51.

plane and its rigidly attached auxiliary plane considered together as one compound main plane.[1]

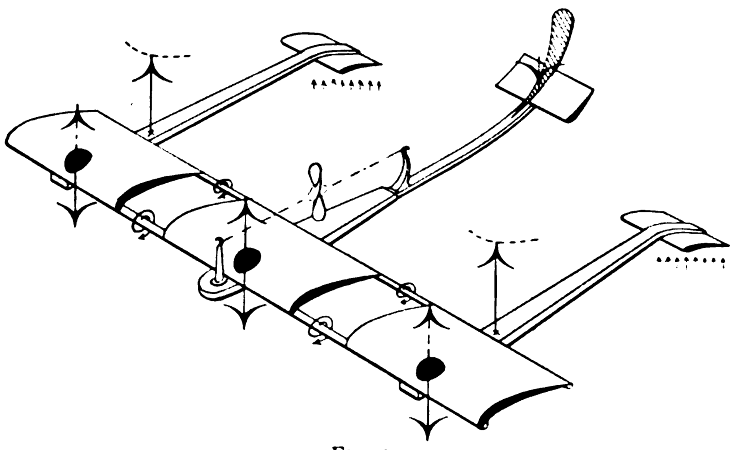

FIG. 52.

In fig. 51, the yieldingly attached tail planes may have only so much downward pressure upon them as may be necessary to aid the springy torsion of the

[1] See page 253, last paragraph ; page 266, claim 11.

whole main plane in keeping loaded the lateral extremities, and, therefore, when the springy torsion requires no such reinforcement, we discover the type of fig. 52, in which the lateral yielding tails are dispensed with. Though the springy torsion of the main planes has directly superseded the springy lateral tails, the reaction of the springy torsion has, of course, to be sustained by a correspondingly greater downward pressure on the central yielding tail plane. Instead of regarding fig. 52 as a development of fig. 51, we may, if preferred, regard it as a modification of fig. 50, necessitated by considerable stiffness in the torsion of its main plane.

Unpractical Ideal Types

In the illustrations, no more than three aeroplanes have been shown joined together and flying side by

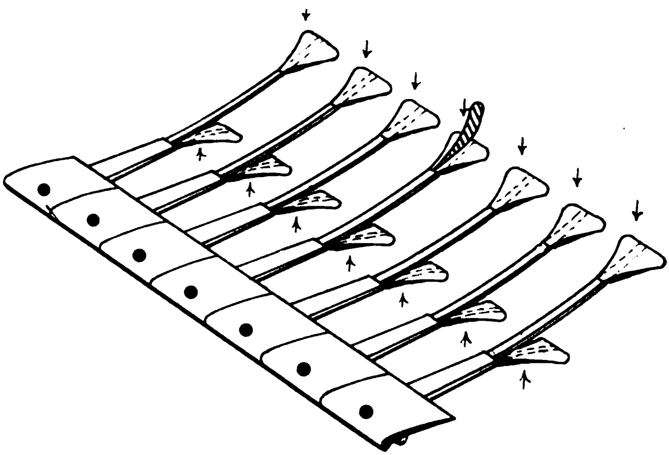

FIG. 53.

side, but it is easy to see that a real machine consists, in effect, of an infinite number of left and right aeroplanes flying side by side. Accordingly, in further carrying out the principles described, we should construct a machine of the type of fig. 53, having three constant-lift aeroplanes at each side of the central one. In the limit, we should have to go so far as fig. 54, in which there is a continuous main plane, a continuous up-steering yieldingly-held tail plane, and a continuous rigidly attached down-steering tail plane. Since, however, the parts of these planes cannot be made to

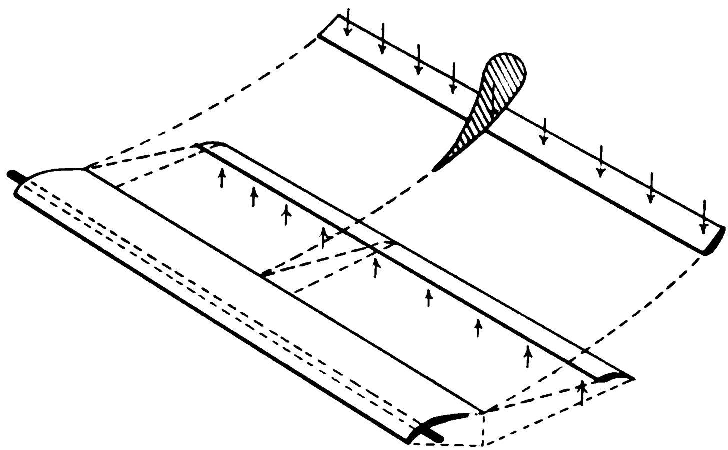

FIG. 54.

function properly with respect to their corresponding parts of the main plane without being infinitely flexible transversely of the machine, the type cannot actually be constructed.

Although not theoretically perfect, machines of the types of figs. 49 to 52, but with continuous main planes, can be made to satisfy all practical needs.

Non-disturbance round Vertical Axis

So far, steadiness of pose round the longitudinal and transverse axes has only been considered, so there remains the question of steadiness round the vertical axis.

When the type of model of fig. 48 (p. 190) is flying steadily, and its right aeroplane is attacked by a head gust, the head resistance of that right aeroplane tends to increase. Owing, however, to the planes of that aeroplane yielding, in conformity with its constant-lift property, to lesser angles of incidence, the change in head resistance may easily be very small compared with the corresponding increase in an ordinary rigid aeroplane for which the head resistance is proportional to the *square* of the headway. The centre of head resistance of the whole machine, therefore, has very little tendency to move away from the longitudinal axis, so the construction adopted to eliminate sudden disturbance of longitudinal and lateral pose has, in addition, practically eliminated sudden disturbance of the directional pose or head-first movement with respect to the vertical axis.

Practical Developments

Although some laboratory and test models may resemble them, the illustrations of figs. 48 to 54 are chiefly diagrammatic, and useful in explaining underlying principles.

In fig. 55 a more practical form is given to the proposals. A biplane is shown having warpable main planes, and in the rear of *each* lateral extremity of these main planes, and attached to it, is a tail frame[1] carrying a rear flap elevator, T, that has normally to be

[1] The *tapered* tail frames, convenient for the purpose of this illustration, are not recommended except in machines with narrow planes of very great aspect ratio. The parallel tails of the frontispiece and fig. 68 are usually better.

held, yieldingly, in an up-steering sense, with the air pressing down on its upper surface. There being no central elevator in this machine, and the centre of mass or gravity being substantially coincident with the centre of lift, the holding of the elevators, T, T, is made necessary by the lateral auxiliary lifting or down-steering surfaces, M_1, M_1, being rigidly attached to the tail frames, in the rear of the centre of mass so that the mass may be forwardly of them.[1]

Each of the elevators, T, T, may be controlled independently by hand, one by the pilot's left hand and the other by the pilot's right hand; but it is better that the control should be arranged in one of a variety of ways in which one hand and lever may simultaneously operate the elevators differentially for lateral control, and together for longitudinal control.

By way of example, one such simple control is shown, to avoid its concealment, on the top of the main plane of fig. 55, and it should be obvious how pulling the hand-lever sideways, or right and left, operates the planes T, T differentially for lateral control, and pulling the hand-lever fore-and-aft operates the same planes as ordinary elevators, for longitudinal control, without interfering with the simultaneous lateral control. Return wires from the elevators are advisable in this control, and in fig. 55 these wires may be supposed to proceed to reversed continuations of the control lever, and its gear, below the top plane.

Although the machine, as shown in fig. 55, is not self-flying, because of its permanent diving tendency, the pilot who flies it, and holds the elevators to

[1] See page 260, third paragraph; page 269, lines 9 to 13 and 22; page 270, lines 4 to 7; page 273, claim 5; and page 253, lines 13 to 16.

substantially constant reactions, will discover it has not only longitudinally, but laterally as well, that form of stability, or freedom from sudden gust disturbance, that is better called "flyability." (See Chapter XIII.)

It will be understood from the earlier pages of this book, that the reason the aviator finds this machine so steady in its longitudinal pose is that, in consequence of the too-far-forward weight, and the elevators being yieldingly held, every head gust forces up the main planes round the centre of mass, and forces down the yieldingly-held elevators about their hinges, so that the pilot, feeling the pull of the elevators, and yielding to it, is prompted to make, or rather allow, the exact movement of the elevators that will cause the mass to be practically undisturbed in its flight path. In that way is the pilot enabled to sense, or be made *tactually* aware of, every endeavour of the air to disturb the longitudinal pose, and of the correct movements to be made, or *permitted*, to avert the changes of longitudinal pose.

In a similar way, the machine enables the pilot to sense, or be made tactually aware of, the endeavours of the gusts to disturb the lateral pose, and of the correct control movements to be permitted to avert the changes of lateral pose. In detail, the lateral operation may be explained as follows:—

It will be seen that, so far as the main planes are freely warpable, each elevator T, through the downward pressure that is maintained upon it, determines the lift or loading of its own extremity of the main planes, including plane M_1 that may be regarded as an outlying part of the main planes. Now, by reason of the mechanical connection between the two planes T and T (such as the cord connections shown in the figure), the pressures on the two planes tend to equalise themselves. Therefore, the lifts of the extremities of the main planes, determined by the forces T, T, tend

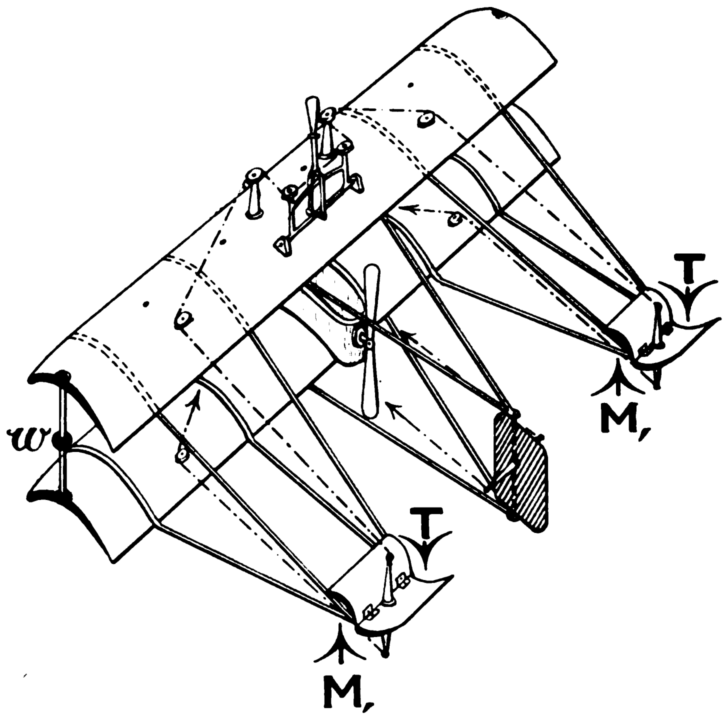

FIG. 55.

to remain equal, and the machine to be undisturbed in its lateral pose.

To take a particular example: in the event of a head gust attacking the right-hand extremity of the machine, it presses down the right-hand elevator T, and so pulls up the left-hand elevator T, and moves the pilot's control lever, and his hand upon the control lever, to the right, to the degree necessary to equalise the pressures on the planes T, and also, through them, the lifts of the two extremities of the machine. The pilot, therefore, is *prompted* to make, or rather *allow*, the correct movement of his lever necessary to prevent change of lateral pose.

In practice, this self-warping is aided, and the pilot's

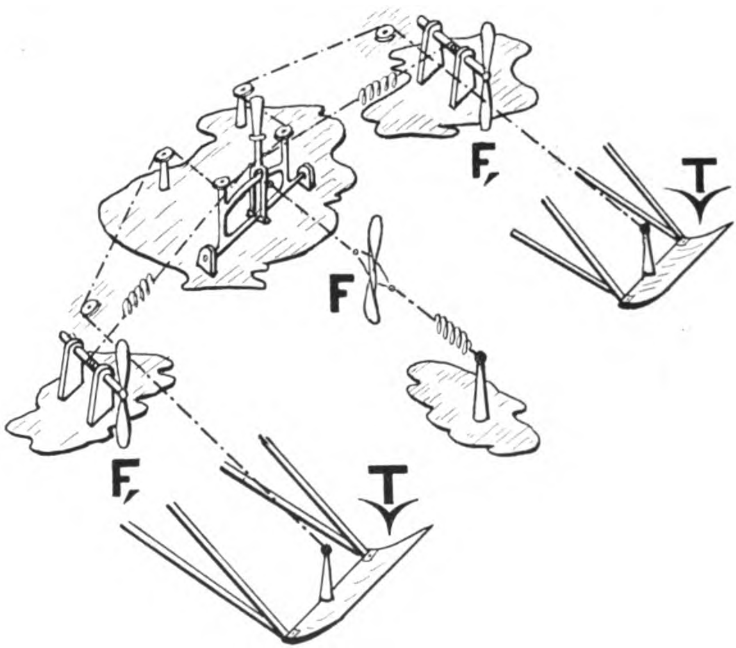

FIG. 56.

touch is made more sensitive to changes of lateral pose, by adding suitable masses, *w*, near the extremities of the machine, and preferably forwardly of the lateral centres of pressure. Such lateral masses also tend to steady the absolute velocity of each extremity, and have other advantages, but they are *not essential* to the equalising-lift action, either in theory or practice. In some cases, a machine is better without them.

"*Stability*" *Additional to* "*Flyability*"

Although the machine of fig. 55 is so exceedingly flyable that a pilot used to the old non-diving, "naturally stable" machines would consider it possesses all the stability he ever expected to have, yet it may not

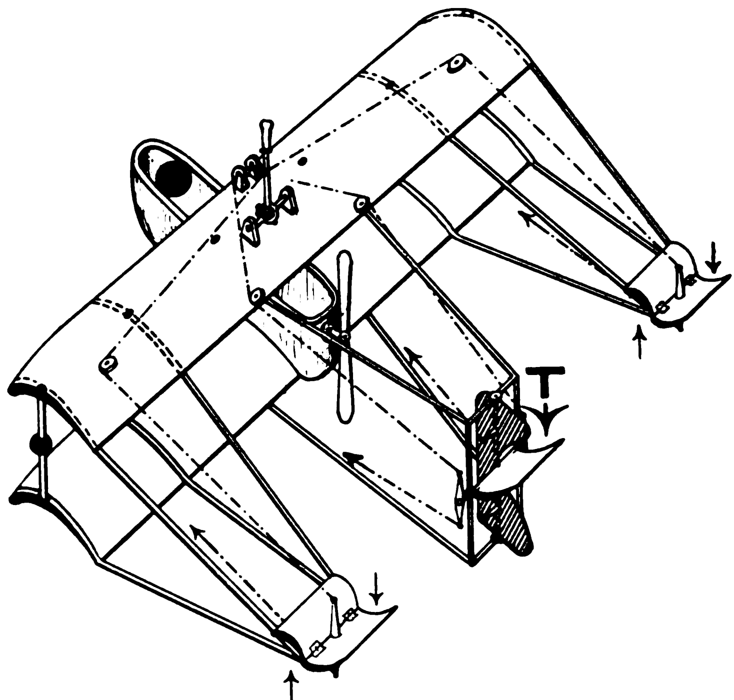

FIG. 57.

be self-flying, and in certain circumstances is liable, as a consequence, to disaster.

In the control diagram of fig. 56, the necessary self-flying power, or stability, is provided for by the addition of a slow-fan F, arranged to supervise the average longitudinal pose in the manner already described in this book. Lateral fans, F_1, F_1, are also shown supervising the *lateral* control by letting *down* the lateral elevator T of the higher and *faster* wing when the machine tilts and circles, but these lateral fans, F_1. F_1, are more optional than the longitudinal fan F.

In view of all that has been written in this book about the dynamical equivalent of gravity, in the relationship

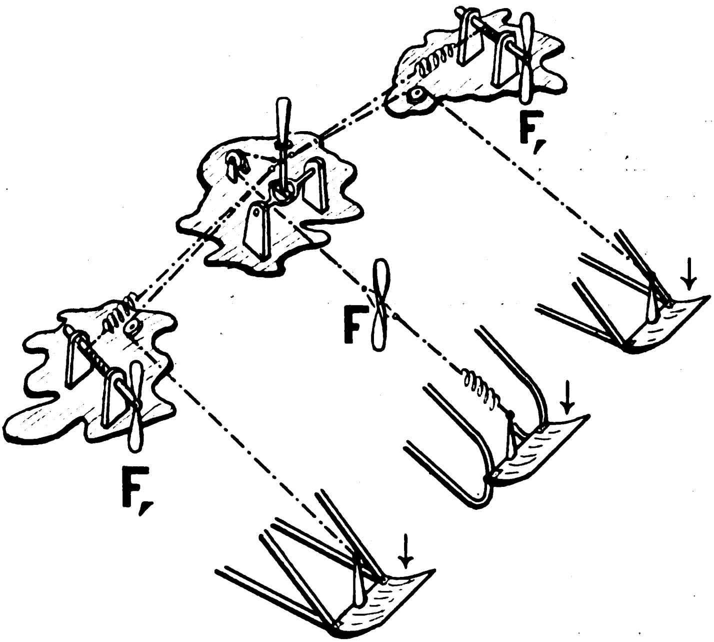

FIG. 58.

of the machine to the air, being liable to sudden disturbances of direction in gusts, it is scarcely necessary to point out that no misguided efforts should be made to strengthen, or make too prompt, such lateral righting effects as that due to the lateral fans F_1, F_1.

Other Practical Types

In fig. 57 another practical type is obtained by the addition of an elevating plane, on a central tail, employed to compensate for the more forward weight [1] and relieve the lateral elevators in looking after the longitudinal pose. As shown in fig. 57, the machine is only an exceedingly flyable machine, and not necessarily a stable self-flying one. That is to say, although it is incapable of being disturbed suddenly by gusts, it is defective as regards means of preventing slow and permanent changes of pose.

More complete stability and self-flying properties are obtainable by the addition of the longitudinal slow-fan control, F, shown in fig. 58, and the lateral slow-fan control, F_1, F_1, also shown in that figure.

General Remarks on the Type Evolved

Although downwardly warped wing tips,[2] positive and negative[3] dihedral angles, side resistances,[4] elevated keel planes,[5] side masses,[6] flywheel fans,[7] gyroscopes,[8] and similar arrangements have their uses as improvements or modifications, and as such will be discussed, it must always be realised that the machine of the general type of fig. 55, with controls of the general type of fig. 56, is *the* machine that possesses, in a unique and wonderful degree, the essential property of "flyability," longitudinally and *laterally*, or, to use an alternative expression, the property of *tactile stability* as distinct from the conventional and less essential stability of complete self-flying.

[1] See page 260, third paragraph.
[2] See page 269, middle paragraph; and claim 5, on page 273, etc.
[3] See page 252, last paragraph; also claim 8, on page 266.
[4] See end of page 262 and top of page 263.
[5] See pages 257 and 258; also claim 7, on page 266.
[6] See page 259, last paragraph; also claims 9 and 10, etc., on page 266.
[7] See page 254, and page 268 onwards.
[8] See pages 260 and 261; also claim 14, on page 267.

The pilot *feels* that type of machine in the same way a bird may be presumed to feel its body, and he controls it with little manual effort in disturbed air, because he is required to do little more than *yield* his levers to the machine's *control of itself* when sudden gusts attack it.

The Most Distinctive Feature of the New Type

There is a great difference between the lateral balancing elevators, T, T, of fig. 55, and the lateral balancing flaps formerly employed. About the year 1909, as alternatives to directly warping the main planes, they were made rigid, and auxiliary lateral planes, flaps, or ailerons were introduced, but pulled *down* on the extremity that had to be raised, so that the flap at that extremity might *directly* increase the support at that extremity.

The practice was a bad one, because the down-pulled flap retarded the headway of the lower wing, and, in some cases, this diminished the wing's lift to as great an extent as the down-pulled flap was intended to add to the lift—unless the rudder was manually operated to steer the machine away from the side of the lower wing.

In Germany, some time later, a more rational method was adopted, resembling the construction of fig. 1 (page 261) of the author's patent 8531 of 1909, in which lateral extensions or flaps at the rear extremities of the rigid wings were operated so that the flap of the higher extremity might be pulled *up* to reduce the lifting moment of that higher wing, and create a head resistance to retard the wing and so further reduce its lifting moment. After the publication of the first edition of this book, and the study directed to the author's patents, up-pulled flaps became almost universal.

Now such lateral balancing flaps have always acted to produce the righting force *themselves* in lieu of wing warping. The main plane has, in each case, been made as *rigid as possible*, for any yielding in it occasioned by the up-tilted flap in its rear would have warped the wing to produce *more* lift at that extremity, and thereby have annulled, more or less, the object—*reduced* lift—for which the flap was tilted up. Fig. 55, therefore, is markedly different from the old constructions, in that the auxiliary plane and the warpable main plane constitute an *advantageous* combination, and the distinction is further emphasised by the fact that each rear auxiliary plane is tilted in exactly the *opposite* direction to that necessary in the old construction in order to raise or lower its own side of the machine. For example, to lower the right-hand extremity of the machine, the rear auxiliary elevating plane is tilted in a *down-steering* sense. The pressure that may be thus brought to bear on its *under* surface, operating through the *leverage* of the tail frame, *warps* the main plane so powerfully to lower that side, that the feeble *direct* action of the auxiliary plane to raise that side of the machine is comparatively of no account.

Rigid Lateral Righting Effects

While rigid constructions will not permit a machine to possess those constant-lift, yielding properties which are indispensable to steady flight in disturbed air, they will permit a machine to have certain slow, self-righting properties which may form *part* of its stability in disturbed air, and these self-righting properties may, with advantage in some forms, be embodied in the yielding constructions.

Down-Pressed Lateral Surfaces

In fig. 59, I., an aeroplane flying towards us, and consisting only of left and right elements of main plane, M_L and M_R, is supposed to be tilted up a little (too little to show) on the side of its M_R wing. For the usual reasons, the machine will then proceed to describe a curved path of some radius R, and the outer and faster wing, M_R, experiencing greater lift, the lateral tilt will tend to increase.

An obvious way of obtaining an equal and opposite tilting effect to the above is to turn the machine of fig. 59, I., upside down, as in fig. 59, II., so that the surfaces become *down-pressed*, negative-lift, non-supporting surfaces. A combination, therefore, of fig. 59, II., with fig. 59, I., will have no undesirable self-tilting effect, but, unfortunately, it will also have no lift, since the downward lift of fig. 59, II., exactly equals the upward lift of fig. 59, I.

The problem of having the down-pressed surfaces small enough to neutralise only a *portion* of the upward lifting forces, and yet be able to neutralise or compensate the *whole* of the lateral self-tilting effect of the lifting surfaces, finds its solution in placing the reduced down-pressed surfaces at a great distance or leverage from the longitudinal axis of the machine, as in fig. 59, III.

The Down-pressed Surfaces are a General Solution

That the above is a general solution of the problem of obtaining a lateral self-righting effect in a main plane

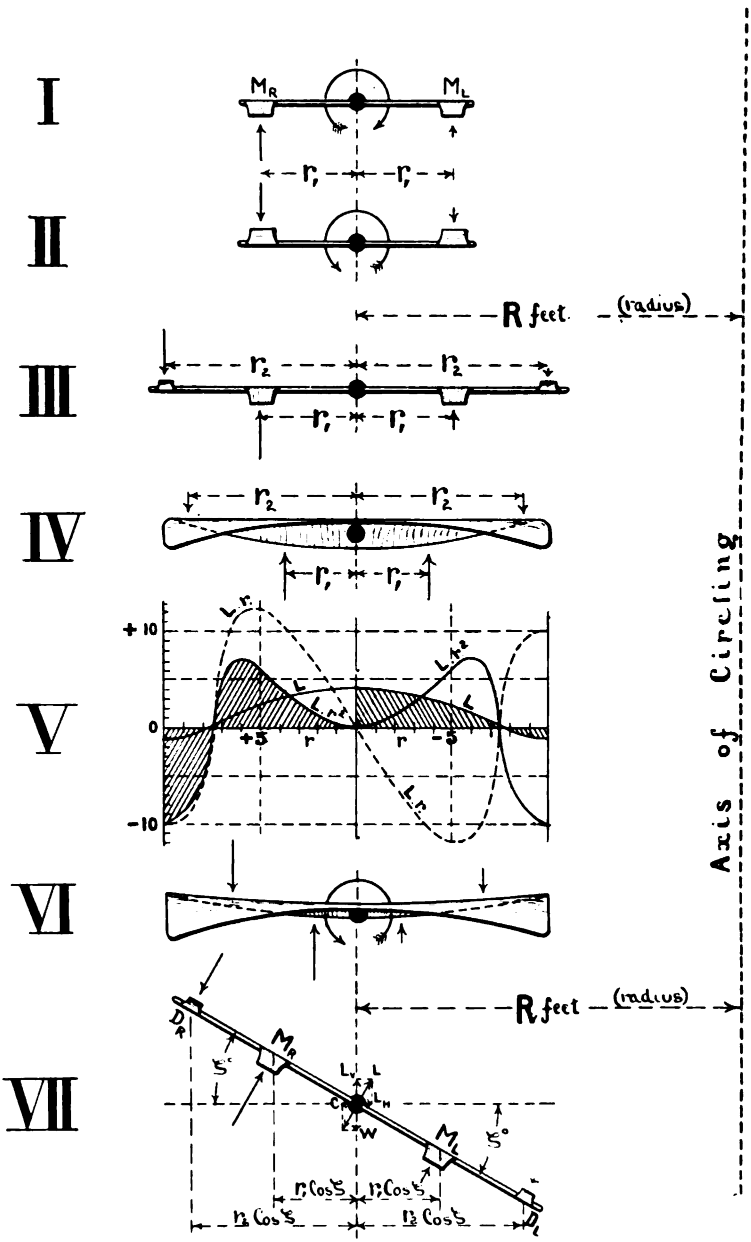

FIG. 59.

may be shown with the aid of fig. 59, VII. In this figure, the machine is drawn tilted laterally through the angle ζ, and, in order that it should, *if possible*, continue circling *without* righting itself, it is made to have such speed and lift L as make the vertical component of the lift, or L_v, exactly equal to the weight W.

The plane element M_R, flying, in this rigid machine, at constant angle of incidence, has a certain lift, say K_1 lbs., at unit headway, and therefore, as is well known, a lift K_1V^2 at any other headway V. But the headway of M_R is obviously greater than V_a—the actual headway of the centre of the machine—and equal to :—

$$V_a\left(\frac{R + r_1 \cos \zeta}{R}\right) \quad . \quad . \quad . \quad . \quad (36)$$

Hence, the lift of surface M_R is :—

$$K_1V_a^2\left(1 + \frac{r_1}{R} \cos \zeta\right)^2 \quad . \quad . \quad . \quad . \quad (37)$$

Multiplying by r_1, we find the lifting moment about the centre of mass is :—

$$K_1.V_a^2.r_1\left(1 + \frac{r_1}{R} \cos \zeta\right)^2 . \quad . \quad . \quad . \quad (38)$$

Similarly, we find the opposing lifting moment of the symmetrically placed plane element M_L is :—

$$K_1.V_a^2.r_1\left(1 - \frac{r_1}{R} \cos \zeta\right)^2 \quad . \quad . \quad . \quad (39)$$

which differs from (38) in the sign of $\frac{r_1}{R} \cos \zeta$ owing to the radius of circling being *less* than R, instead of greater than R.

The net righting moment due to the surfaces M_L and M_R is obviously formula (39) minus formula (38), that is :—

$$-4 \cdot \frac{V_a^2}{R} \cdot \cos \zeta \cdot K_1 r_1^2 \quad . \quad . \quad . \quad (40)$$

If, now, there are only two positive lifting surfaces, the minus sign in formula (40) confirms common sense in showing that there can only be a *negative* righting moment, that is, an *upsetting* moment; but if there is another pair of surfaces with constant K_2, at distances r_2 from the longitudinal axis (see fig. 59, VII.), their righting moment is similarly :—

$$-4 \cdot \frac{V_a^2}{R} \cdot \cos \zeta \cdot K_2 r_2^2 \quad . \quad . \quad . \quad (41)$$

and the resultant righting moment, being the algebraic sum of formulæ (40) and (41), is :—

$$-4 \cdot \frac{V_a^2}{R} \cdot \cos \zeta (K_1 r_1^2 + K_2 r_2^2) \,. \quad . \quad . \quad (42)$$

Now, even after K_1 and r_1 have been fixed, formula (42), unlike formula (40), *can* be made positive, but only by making $K_2 r_2^2$ negative and greater than $K_1 r_1^2$; and since r_2^2 is essentially positive, $K_2 r_2^2$ can only be made negative by making K_2 negative; that is, by making the *lift* K_2 negative, or the surfaces D_R and D_L, in the figure, *down-pressed* surfaces.

The condition that $K_2 r_2^2 \nless K_1 r_1^2$, in association with the still more fundamental condition (for a net lift) that $K_2 < K_1$, becomes $(<K_1) r_2^2 \nless K_1 r_1^2$, or $r_2^2 \nless \frac{K_1 r_1^2}{<K_1}$, or $r_2^2 > (1 \times r_1^2)$, or $r_2^2 > r_1^2$, or :—

$$r_2 > r_1 \quad . \quad . \quad . \quad . \quad . \quad (43)$$

Main Plane of Many Elements

If the machine has three sets of surfaces instead of only two, the net resultant righting moment is given by the algebraic addition of *three* formulæ of the class of (40) and (41), so that formula (42) is superseded by:—

$$-4 \cdot \frac{V_a^2}{R} \cdot \cos\zeta(K_1r_1^2 + K_2r_2^2 + K_3r_3^2) \quad . \quad . \quad (44)$$

where K_3 is the supporting effect per unit headway for each third surface, and r_3 its distance from the longitudinal axis of the machine.

But a real machine has a great number of strips of surface symmetrically disposed, in pairs, at a variety of distances from the longitudinal axis. For such a machine, formula (44) for the net righting moment obviously develops into:—

$$-4 \cdot \frac{V_a^2}{R} \cdot \cos\zeta(K_1r_1^2 + K_2r_2^2 + \cdot \cdot \cdot + K_nr_n^2) \quad . \quad (45)$$

That is:—

$$-4 \cdot \frac{V_a^2}{R} \cdot \cos\zeta \cdot \Sigma(K_1r_1^2) \quad . \quad . \quad . \quad (46)$$

where the sign Σ must be interpreted as meaning, as usual, "the sum of all such terms as."

Practical Application to Down-pressed Surfaces

The practical meaning of formula (46) is conveyed by figs. 59, IV., V., and VI. In fig. 59, IV., is shown a front view of a main plane that supports well at the middle, but is actually down-pressed at the extremities.[1] In fig. 59, V., is a chart corresponding, as regards

[1] Resembling the main plane of fig. 2 of patent 6051/10. See page 271 and the references in the specification.

width, to the span of the main plane, and, vertically, to the quantities we have to plot vertically.

Dividing the 20-foot span main plane into foot-wide strips from the longitudinal axis, the normal supporting effect of each strip is supposed to be as plotted in the curve L, for which normal headway has been taken as the unit of headway. Since the height of each foot-wide vertical strip of the curve L is the pounds support of the corresponding strip of the main plane, the whole area[1] of the curve L above the horizontal zero line is the whole supporting effect or positive lift of the main plane, and the area of the curve L below the horizontal line is the *negative* lift near the ends of the main plane. In the example, the negative lift is satisfactorily small in being only a small part of the difference between the two, or of the net positive lift.

Multiplying the heights of the lift curve L by the distances from the centre of the main plane, and plotting the results, we find the curve Lr_1, or curve of lifting moment at each point of the main plane. This curve of *first* moments of the lift is of little interest in the present connection, beyond showing, by its equal positive and negative areas, that the machine may be in lateral equilibrium in normal flight, as might have been guessed from the machine's symmetry.

Multiplying the heights of the L curve by the *squares* of the distances from the centre of the main plane, or multiplying the heights of the Lr_1 curve by the distances from the centre, we obtain, on plotting, the Lr_1^2 curve, or curve of *second* moments of the lift; and

[1] The unit of area being, of course, a rectangle one foot unit of length on the horizontal scale, by one pound unit of height on the vertical scale. Vertically, in the diagram, multiples of ten are ignored.

seeing that, with normal headway as the unit of headway, L becomes representative of K of formula (46), this curve is clearly the curve of $K_1r_1^2$ for the corresponding strips of main plane. The fact that the positive area of this Lr_1^2 curve above the horizontal zero line is just about equal to the negative area below the horizontal zero line shows, of course, that, for this main plane, the $\Sigma(K_1r_1^2)$ of formula (46) is zero, and, therefore, the net lateral righting moment being zero, the plane is "compensated." If we wish the main plane to be definitely self-righting, the negative area of the Lr_1^2 curve must be made to exceed the positive area, as by placing more down-pressed surface left and right of the machine.

We may, accordingly, consider the two following rules established for a symmetrical main plane flying head-first at constant angle of incidence; it being understood they refer to a chart like fig. 59, V., drawn for the main plane:—

> (1) If the L curve (*i.e.* the lift curve) of the main plain has greater positive than negative areas, the main plane has the essential property of giving a net lifting effect.
>
> (2) If the Lr_1^2 curve (*i.e.* the curve of second moments of the lift) has greater, equal, or less positive than negative areas, the main plane is laterally under-compensated, compensated, or over-compensated, respectively, and so will be laterally self-tilting, neutral, or self-righting, respectively.

How the Lateral Compensation Varies in Flight

Fig. 59, VI., relates to a matter that can only be properly explained by a prior reference to fig. 1

(Plate 1), where DB is a side gust, and the machine is flying straight *away* through the paper at the moment at which the gust attacks.

Since AD functions as gravity, and BD as a component, it is evident that the centre of mass of the machine *starts* to curve to the left in a parabolic path having an initial radius of curvature given by $R = V^2_f/a$. Now, as the main plane wheels to the left, it will not, if it is a compensated, constant-incidence main plane like fig. 59, IV., alter its truly level lateral pose, but as it dives "down" from the virtual level AF (fig. 1, Plate 1), it will gather headway and a lift exceeding AB, and therefore rise up a path such as AI. If the constant-lift means, which may be or include the pilot's personal control, are now added to the machine to prevent the longitudinal disturbance up AI, such means will, of course, operate by altering the angle of incidence of the main plane in a down-steering sense, so that, looked at from the front, the main plane may appear like fig. 59, VI., instead of fig. 59, IV. But in fig. 59, VI., the down-pressed surfaces are seen to have increased their negative angles of incidence, and to have greatly increased in area at the expense of the lifting surfaces that, so far as they are still existing, have decreased their positive angles of incidence. The main plane, therefore, has changed from a merely compensated one into a much *over-compensated* one, and will, accordingly, in fig. 1 (Plate 1), and as it flies away, tilt up and raise its *left* wing.

In order, therefore, for a main plane to be just laterally compensated, by down-pressed surfaces, with regard to the *average* side gust, it must normally be somewhat *under*-compensated. This is fortunate, because the amount of down-pressed surface necessary for universal full compensation, even when carried as far as possible to the left and right of the longitudinal axis, is usually a very serious detraction from the lifting effect of its main plane. There is also nothing to regret in this difficulty in obtaining strong over-compensation by lateral down-pressed surfaces, for the further reason that, in fig. 1 (Plate 1), this over-compensation would, as a prompt lateral righting effect, act to turn the lateral pose of the machine quickly through the angle CAF. This is in accordance with the rule that too prompt self-righting effects for still air become equally prompt self-upsetting effects in disturbed air. (See page 7.)

Machines of the type of figs. 48 to 57, it may be mentioned, act in a very superior manner in the side gust DB of fig. 1 (Plate 1). Since the extremities of the machine preserve constant and equal lifts, the machine does not tilt laterally as it wheels to the left; neither does it rise up longitudinally from the truly level plane AC. In figs. 55 and 57 the main planes are bent to have slightly negative angles of incidence, or be down-pressed, at their extremities. Such extremities may produce, or aid, the slow lateral self-righting effect of the machine.[1]

The Positive Lateral Dihedral Angle

To designers of the empirical school, nothing seems more suitable for a lateral self-righting effect than a

[1] And they have another great advantage in that, when warped, the extremity of the machine we are trying to lower by means of the warping has its head resistance increased owing to the negative angle of incidence of that extremity being increased. This increased head resistance retards that extremity, and thereby tends to reduce the lifting moment of the wing about the longitudinal axis, and so aid the restoration of a level pose. These actions were referred to in patent specification 6051 of 1910. (See pages 269 and 270.)

considerable lateral positive dihedral angle, or "veeing" of the main plane. It seems so obvious that such a machine must bed down in the air in the same way as a boat. When persistent trial shows it does not always act as expected, it is given up for the declared reason that "the air gusts are always getting under one or the other wing and overturning the machine." It is in connection with this that designers often make their first puzzled acquaintance with the fact that, whatever apparently common-sense means they adopt to keep the machine upright with respect to common gravity, gusts take advantage of those very means to upset the machine in accordance, of course, with the principles formulated on page 7.

In fig. 60, I., a main plane with a total dihedral angle of 20° is shown flying towards us and tilted. It is flying at such speed that the vertical component of the lift, or L_v, is exactly equal to the weight W. The machine, therefore, pursues a level path, which, however, is necessarily circular under the influence of the horizontal centripetal component of the lift, L_H, that finds its own equilibrant in the centrifugal force C.

Now the machine has been started so that, if it is at all possible for it to continue in tilted flight, without righting itself, or even without upsetting itself further, it may so continue, so far as the condition of equilibrium in both the vertical and horizontal forces is fulfilled. But the equally important condition that the resultant L and resultant of C and W shall pass through one point is not fulfilled. So long as the two wings present the same angles of incidence in the direction of the flight path, the outer, faster, and higher wing must be better supported than the inner, slower, and lower wing, and the centre of lift, L, moving *outwardly* from the centre of mass, must act to increase the lateral tilt in a progressive manner.

In order that the machine shall right itself, there must exist means of making the inner wing lift better than the outer wing, so as to bring the lift L *inside* the

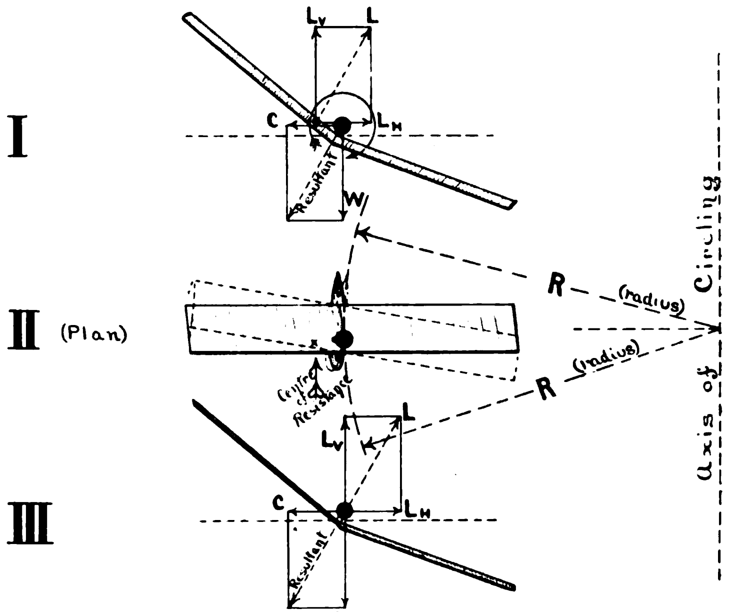

FIG. 60.

centre of mass, or nearer the axis of circling; and it so happens that all machines do inherently possess such means of causing the dihedral angle to tend to right the machine.

In an actual machine, each wing has *head resistance*, and the head resistance of the outer and faster wing being greater than that of the other, the centre of head resistance of the whole machine moves outwards in a similar way to the centre of lift. Then, as seen in the plan view of fig. 60, II., the outer wing is pressed back or retarded, relatively to the other wing, into the dotted position, so that the machine commences to fly cornerwise with respect to its circular trajectory. But, when the machine of fig. 60, I., having the dihedral angle there shown, is pressed back into the dotted pose of fig. 60, II., it presents, to an observer in the direction of its flight path, the appearance of fig. 60, III., so that the angle of incidence of the outer wing (as denoted by its thin appearance) is reduced relatively to the angle of incidence of the inner wing. The outer wing, therefore, may, despite its greater speed, lift *less* than the inner wing, so that the centre of lift where L acts may not only be brought to the centre of mass, as in fig. 60, III., but actually be brought to the *lower* side of the centre of mass—in which case the machine is self-righting.

With a given dihedral angle this self-righting may be strengthened by increasing the head resistance by dead resistances concentrated near the tips of the wings, but, as stated before, only a *weak* self-righting effect is permissible in any machine.

The Inverted Dihedral Angle

Although not producing a self-righting effect, some reference should here be made to the inverted dihedral shown in fig. 61, I., with the forces as they act in the absence of head resistance. When the head resistance presses back the outer wing, and so causes the machine, as viewed from the front, to appear as in fig. 61, II., the outer wing is obviously made to lift *still better* than the inner one, and the machine, consequently, to be strongly *self-upsetting*. Although in itself a self-upsetting effect, the inverted dihedral has its uses in combination with some more powerful self-righting effects, because, in the churning of the air consequent

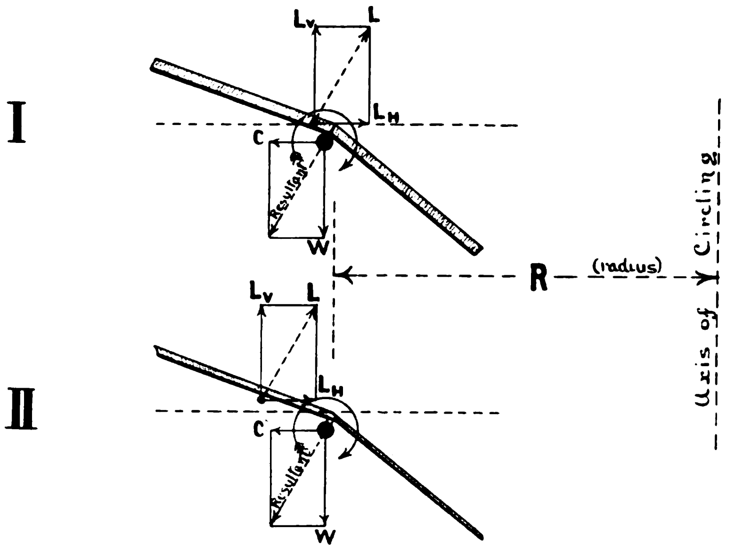

FIG. 61.

on the contention of the two opposed effects, the weak, resultant, self-righting effect may be made to find a certain amount of damping.

LATERAL RIGHTING EFFECTS BY VERTICAL SURFACES [1]

In fig. 62, I., a tilted straight main plane is shown flying towards us, circling, and of course tending to tilt more because of the centre of lift being outside the centre of mass. Now, as the machine is circling, the outer wing tends to be retarded and pressed back, by reason of its greater head resistance, until the torque

[1] Such as the elevated keel surface of patents 8531/09 and 6051/10. See pages 252 to 273: and claim 7, on page 266.

so pressing back that wing finds itself equilibrated by a counter-torque. If we now put on a central vertical plane level with the centre of mass, as in the inset view of fig. 62, I., and with its centre of pressure (for small angles of incidence) a distance *d* in the rear of the centre of mass, the resistance torque, pressing back the outer wing, will soon find itself equilibrated by the

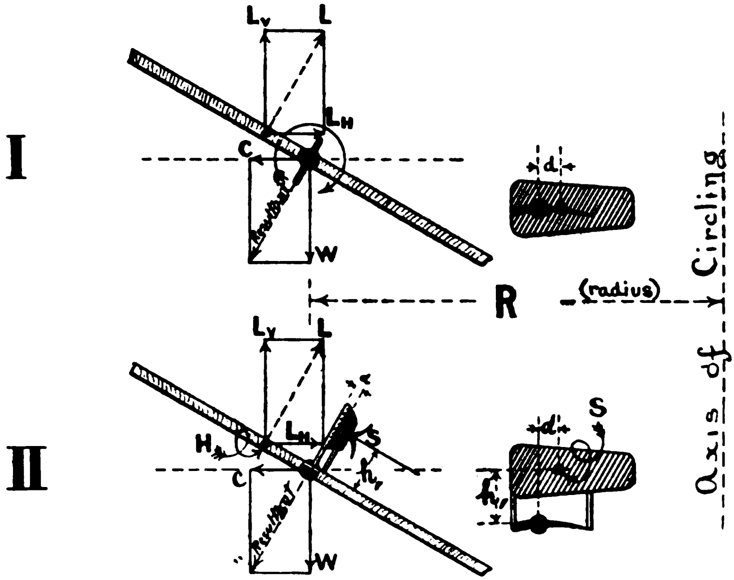

FIG. 62.

pressure which it brings to bear on the inner side of the vertical plane, behind the centre of mass, and this pressure on the vertical plane will obviously operate either to upset or right the machine according to whether the vertical plane is below or above the centre of mass in the side view of the machine.

The righting effect is illustrated in fig. 62, II., where the centre of pressure of the vertical keel plane is h_1 feet above the centre of mass, and *d* feet behind the centre of mass. The head-resistance force, H, multiplied by its distance from the centre of mass,[1] is, as a torque, equilibrated by the consequent pressure, S, multiplied by *d*, and the parts are so proportioned that S times h_1

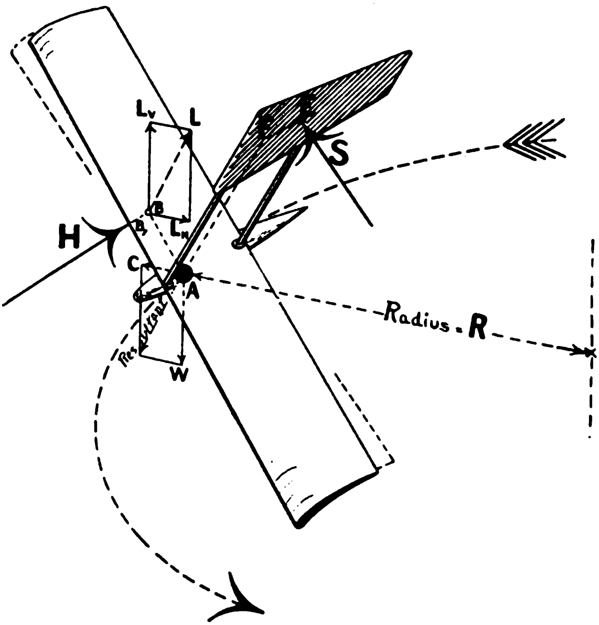

FIG. 63.

exceeds L times the distance of L from the centre of mass. The machine is then self-righting.

The perspective view of fig. 63 may perhaps show the righting effect more clearly. In this view :—

$$H \times AB_1 {}^{*} = S \times EF,$$

[1] In the figure, the distance of the force H from the centre of mass is shown the same as the distance of the force L from the centre of mass, as is likely to be the case with a plane similarly cambered from one extremity to the other, but, generally, in a well-formed plane, the point B_1 (see fig. 63) will be further out from A than the point B.

* By the distance AB_1 is meant the perpendicular distance or arm of the force H about the centre of mass A.

so that $$S = H \times (AB_1/EF) \quad . \quad . \quad . \quad . \quad (47)$$

Notice that considerable variations in the *area* of the keel plane do not effect S. If we double its area, the keel plane will merely content itself with half the former angle of incidence as it continues to comply with formula (47).

In order to increase S, H may be increased by adding everywhere to the head resistance; or AB_1 may be increased by concentrating the head resistances near the extremities; or EF may be *decreased*—so far as the risk of having the side-view centre of pressure at any time in front of the centre of mass, with consequent loss of head-first tendency, will permit.

The self-righting is now determined by the condition:—

$$S \times AF > L \times AB \quad . \quad . \quad . \quad . \quad (48)$$

so that, in addition to the means of increasing S, the self-righting is increased by increasing AF, or by decreasing AB.

The height AF may be increased up to about a quarter of the span of the machine, but, beyond that, other troublesome skew upsetting effects are brought into action, that, fortunately, do not require investigation because there is no need to strain after a strong righting effect that, in gusty air, would cause *disturbance* of pose. (Refer to page 7.)

The length AB may be reduced by concentrating the lift near the longitudinal axis, as by using tapered wings; but turning the extremities to negative angles of incidence effects this still better, and, at the same time, by adding head resistance at the extremities,[1] may increase the head resistance arm AB_1.

[1] See page 262, last lines; and page 269, last paragraph, continued on page 270.

Elevated Keel-plane Effects in Gusts

In some gusts, the elevated keel surface may, as an ordinary righting effect, have a disturbing effect, but there are other gusts in which it has a steadying effect.

In fig. 64, a head gust is supposed to attack the right wing of the machine, flying in the *straight* trajectory, and so tend to lift it relatively to the other

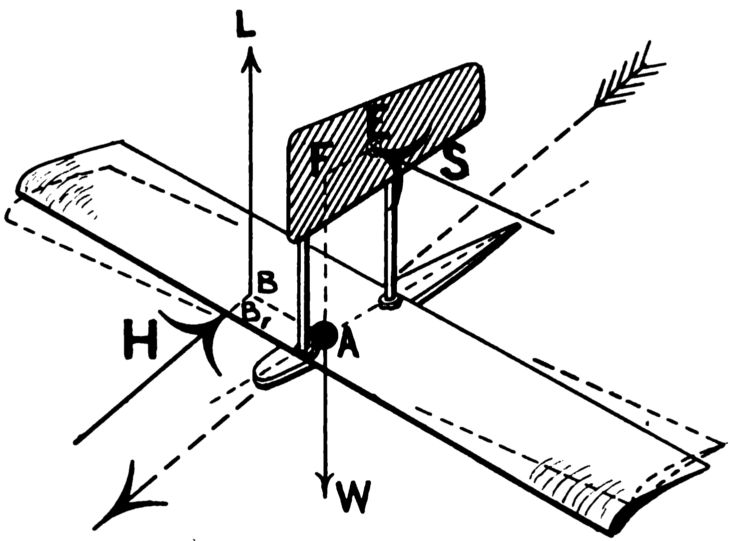

FIG. 64.

wing, and tilt the machine. But, owing to that right wing being at the same time pressed back relatively to the other wing, an air pressure S is brought to bear on the side of the elevated keel plane, and this air pressure, operating through the leverage of the height AF, of the keel plane, to keep down the right wing relatively to the left wing, may, by suitable proportioning of the parts, be made to counteract the lateral upsetting effect of the average gust. Nevertheless, the elevated keel plane, unlike the constant-lift extremities (figs. 48 to 57), is not recommended as a reliable general method of combating sudden gust disturbance, but only as a means of aiding the slow lateral self-righting effect of a machine.

THE RIGHTING EFFECT OF LATERAL MASSES[1]

In fig. 65, I., a tilted main plane is shown flying towards us and circling with radius R. In order that we may deal only with the kind of righting effect now to be considered, the main plane is supposed to be laterally compensated, so as to have its lift L remaining at the centre of mass and exactly equilibrating the resultant of the weight W and centrifugal force C, also acting at the same centre of mass. There is, therefore, no reason why the machine should not go on circling indefinitely, without tilting more and without righting itself.

Suppose, now, that the mass (or a part of it) at the centre is suddenly divided into two equal parts that are placed at the lateral extremities, as shown in fig. 65, II. The centre of mass (or centre of gravity) of the whole machine is, of course, still located at the centre of the machine, even in the extreme case of there being no actual mass there, but the action of the whole mass has been modified.

It will be noticed that the resultant of the downward weight forces is still the force W at the centre of the machine, and is therefore still equilibrated by L_v, the vertical component of the lift L. Now for the horizontal forces.

[1] See page 259, second paragraph and onwards; page 260, second paragraph. See also claims 9, 10, and 11, page 266.

In fig. 65, I., the centifrugal force was $MR\omega^2$ (where M was the whole central mass), and this was equilibrated by L_H, the horizontal component of the lift L. In

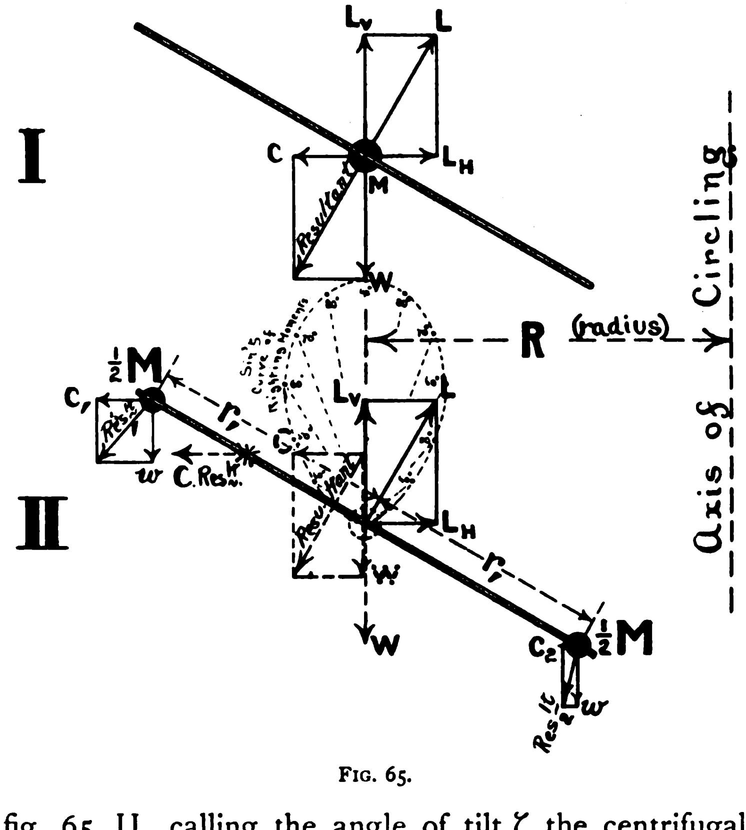

FIG. 65.

fig. 65, II., calling the angle of tilt ζ, the centrifugal force of the outer mass is, similarly :—

$$\tfrac{1}{2}M(R + r_1 \cos \zeta)\omega^2$$

and of the inner mass :—

$$\tfrac{1}{2}M(R - r_1 \cos \zeta)\omega^2.$$

Added together these become :—

$$M.R.\omega^2,$$

or just as in fig. 65, I. Hence, as regards *magnitude*, the force L_H *still equilibrates* the total horizontal centrifugal force C, but, owing to the centrifugal force of the outer and higher mass being *greater* than that of the inner and lower mass, the resultant centrifugal force acts *nearer the higher mass* and *above* the force L_H, and thereby produces *a torque or couple operating to right the machine.*

In this way, masses carried left and right of the longitudinal axis of the machine have the property of helping to right the machine. They also have, in some circumstances, the less desirable property of promoting lateral oscillations, but that is a far deeper question, and, in any case, the property is not an inevitable one.

Going a little more into details, the centrifugal righting moment of the outer mass, about the general centre of mass, is :—

$$\tfrac{1}{2}M(R + r_1 \cos\zeta)\omega^2 . r_1 \sin\zeta$$

and the corresponding lesser upsetting moment of the inner mass is :—

$$\tfrac{1}{2}M(R - r_1 \cos\zeta)\omega^2 . r_1 \sin\zeta.$$

Therefore, the net righting moment is the difference, or :—

$$M r_1^2 \omega^2 . \sin\zeta . \cos\zeta \quad . \quad . \quad . \quad . \quad (49)$$

Now when the machine is in circling equilibrium without reference to torques round the longitudinal axis (that is with reference only to vertical and horizontal forces), we know, from formula (35), but with the sign of equality, that :—

$$T^2 = \left(\frac{2\pi V_f}{g}\right)^2 \Big/ (\sin\zeta . \tan\zeta)$$

from which :—

$$\left(\frac{2\pi}{T}\right)^2 = \left(\frac{g}{V_f}\right)^2 \cdot \sin\zeta \cdot \tan\zeta \quad . \quad . \quad . \quad (50)$$

But $\left(\frac{2\pi}{T}\right)^2$ is ω^2.

Therefore, substituting this expression (50) for ω^2 in formula (49), the net righting moment becomes :[1]—

$$Mr_1^2\left(\frac{g}{V_f}\right)^2 \cdot \sin^3\zeta \quad . \quad . \quad . \quad . \quad (51)$$

In fig. 65, II., an aeroplane of 30-feet span ($r_1 = 15$) has been assumed, and of normal flight headway V of 44 ft. p.s. (30 m.p.h.). A mass of 15 lbs. is supposed attached to each wing extremity, so that M = 30 lbs.

The net righting moment is then, by formula (51) :—

$$30 \times 15^2 \times \left(\frac{32{\cdot}2}{44}\right)^2 \times \sin^3\zeta$$

or

$$3615 \sin^3\zeta \quad . \quad . \quad \text{poundals-feet torque,}$$

or, dividing by g, or 32·2 :—

$$112{\cdot}3 \sin^3\zeta \quad . \quad . \quad \text{pounds-feet torque.}$$

The polar curve in fig. 65, II., shows the way this

[1] The reader must not forget that this formula (51) gives the righting moment only under the specified condition that the tilted machine has its vertical and horizontal forces in equilibrium, the headway being such as suits this condition. If that condition is not complied with, the machine is in an evanescent unsteady state that does not itself concern an inquiry as to whether, in the long-run, it may or may not tend to right itself to a steady straight flight. Those who are aware that, as in formula (49), a centrifugal righting couple ordinarily vanishes for a tilt of 90°, must also notice that, in the above example, the velocity becomes infinite for 90°. The resulting righting couple at 90° is then of the form zero multiplied by infinity, but has the precise finite limiting value of formula (51). For the machine as a whole, the corresponding formula for the lateral dynamical righting moment is $I_1(g/V_f)^2 \sin^3\zeta$, where I_1 is the whole moment of inertia round the longitudinal axis.

righting moment tends to alter for every angle of tilt from 0° to 90°. It is not very powerful at moderate angles of tilt, but that is rather in its favour.

It might be mentioned that if the lateral masses are suitably arranged, as by being carried forwardly of the lateral extremities of the main plane, the centrifugal couple may be made to produce an additional righting effect by warping the planes,[1] but such augmented righting effect is usually not necessary, and often not desirable. Such lateral placing of forward masses may also aid the longitudinal stability, but for longitudinal stability alone they may as well be placed centrally, and be one mass.[2]

Lateral Gyroscopes[3]

So far, lateral stability has been considered (1) from the point of view of the elimination of sudden disturbing forces in order to prevent sudden changes of pose, and (2) from the point of view of the machine's possessing a weak self-righting tendency to supervise the mean pose and prevent slow and permanent changes of pose. In some machines, however, further means of resisting changes of lateral pose, and somewhat in the nature of damping, are desirable improvements. Such means are ready to hand in gyroscopic arrangements, applications of which are shown in fig. 66, and the frontispiece.

In fig. 66, at the nearer corner of the main plane, we see a gyroscopic fly-wheel that is kept spinning left-handedly as viewed from above. Should the aeroplane

[1] See pages 259 and 260. [2] See page 253.

[3] See page 260, last paragraph; also page 267, claim 14. Lateral gyroscopes are those used for lateral control, and are not necessarily placed at the wing extremities.

have that wing urged upwards, so that, as viewed from the front, the whole machine rotates left-handedly round its longitudinal axis, the fly-wheel is likewise tilted left-handedly as viewed from the front. Now when the fly-wheel, spinning as described, is tilted as described, it tries, in accordance with its well-known gyroscopic properties, to tilt down in front, and so

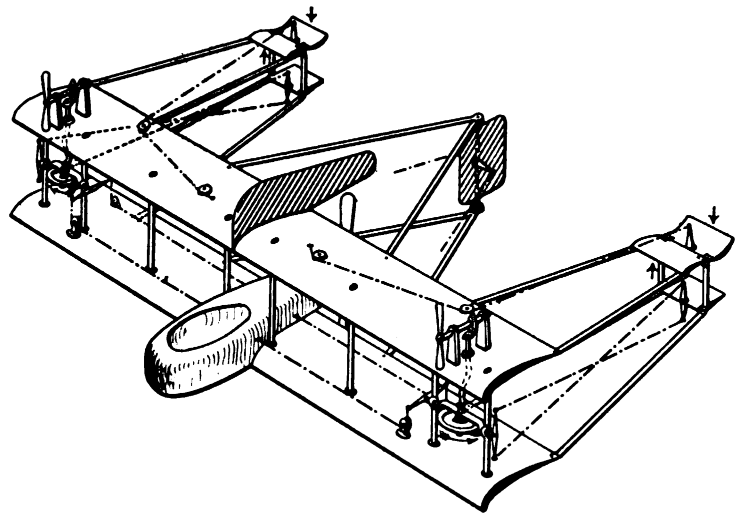

FIG. 66.

warp the main planes in the right sense to resist the wing being urged upwards. A small fly-wheel, however, no larger than an aviator would care to carry at each wing tip, while capable of giving a surprisingly large gyroscopic torque for its size, is usually not powerful enough to warp the main planes by direct action. It is better, therefore, to have the gyroscope mounted in gimbals, as shown, and connected to tilt a rear tail elevator of the class previously described. In that way the gyroscope may be made to warp the main plane as powerfully as desired. The action is then as follows :—

On the wing being tilted upwards, the gyroscope nods forwardly, and thereby, through the crossed cord connections,[1] tilts the lateral tail plane in a down-steering sense to the degree necessary to resist the upward *angular velocity* of the wing.

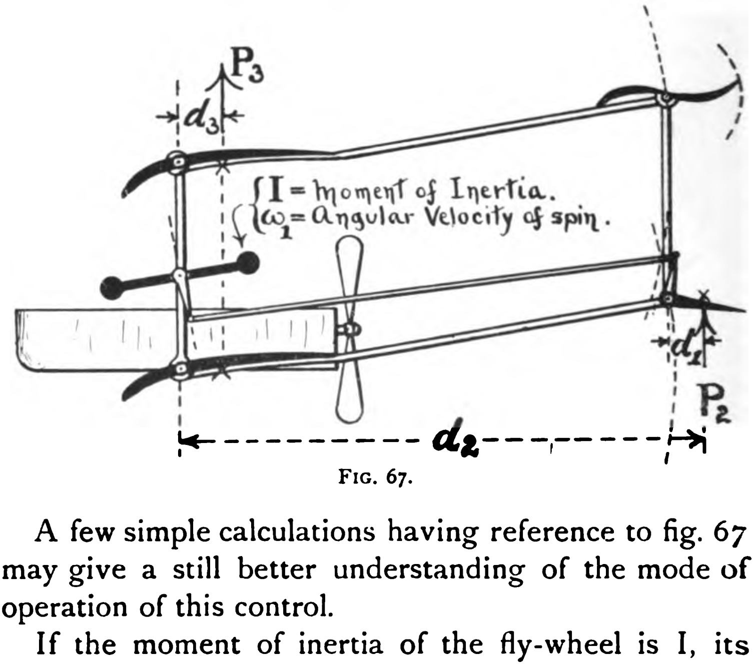

FIG. 67.

A few simple calculations having reference to fig. 67 may give a still better understanding of the mode of operation of this control.

If the moment of inertia of the fly-wheel is I, its angular velocity of spin is ω_1, and the angular velocity of tilt of the machine round its longitudinal axis is ω_2, then, by the well-known rule, the nodding torque of the gyroscope is :—

$$I\omega_1\omega_2.$$

[1] As shown, the crossed cords would lock each other. In practice, to avoid this, pulleys may be used, or segments of pulleys may be placed on the arms. In any case, the illustrations are only diagrammatic.

If the distance of the centre of pressure behind the hinge of the flap elevator is d_1 feet, the cord or link connection is not geared, and the pressure on the elevator is P_2, we evidently have :—

$$I\omega_1\omega_2 = P_2 d_1,$$

from which,

(52)

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wheel radius of $\frac{3}{4}$ of a foot, and runs at 10,000 feet p.m. (167 f.p.s.) at that radius. Then, the moment of inertia I is, in absolute units, $15 \times 0{\cdot}75^2 = 8{\cdot}44$. The angular velocity of spin, ω_1, is the velocity of spin, in feet per second, divided by 2π, or $167/6{\cdot}28 = 26{\cdot}5$ radians per second. The distance of the centre of pressure of the flap elevator tail behind its hinge, or d_1, may be taken to be $\frac{3}{4}$ of a foot; the distance of the elevator behind the warping axis of the main planes, or d_2, 15 feet; and the distance of the centre of

pressure of the extremity of the main planes behind the warping axis, or d_3, 1 foot. Then, by formula (53):—

$$P_3 = \left(\frac{8 \cdot 44 \times 26 \cdot 5 \times 15}{0 \cdot 75 \times 1}\right)\omega_2 = 4473\ \omega_2 \text{ poundals,}$$

or, dividing by g, or 32·2:—

$$P_3 = \frac{4473}{32 \cdot 2}\omega_2 = 139\ \omega_2 \text{ pounds.}$$

That is to say, an angular velocity of lateral tilt of one radian (about 60°) per second is resisted by a force, at *each* wing extremity, of about 140 lbs. Or we may say, a force of about 2½ lbs. is produced at each extremity *per degree-per-second* rate of lateral tilt.

It will be seen from formula (53) that this gyroscopic control sets up a resistance to tilting proportional to the *angular velocity* of tilting, that is, proportional to the *rate of tilting in degrees per second.* This is a contrast to mere dead masses, such as were shown in fig. 48 and some subsequent figures, for *they* only resist angular *accelerations* of tilt. It may also be noted, as part of the same contrast, that, whereas the dead masses tend to conserve or keep constant an existing *velocity* of tilt, the gyroscopic control tends to conserve or keep constant an existing angular *displacement* of lateral pose.

It is chiefly owing to this fact that the gyroscopic control shown is such a good *damper* of the lateral oscillations, for the machine is acted upon, *even in disturbed air*, exactly as if it were in a still fluid interpenetrating the air (like an ether) and related to fins upon the machine by a broadside friction proportional to velocity. To complete this peculiar analogy, the fins must be regarded as non-operative and non-existent as regards direct relationship with the common air.

The last sentence leads to further explanatory remarks. There is no reason for surprise that when the machine of fig. 66 is at rest, and the gyroscopes not spinning, the elevator of the gyroscopic control may easily be oscillated by laying hold of its rear edge; for the gyroscope, as a mere dead wheel, has comparatively little inertia round the horizontal axis upon which its frame is journalled. But it is usually a cause of surprise that even when the fly-wheel is rotating rapidly, *no more resistance to flapping the elevator is felt than before*, and though the *correct* inference is easily drawn that disturbed air, in its *direct* action upon the elevator, simply flaps the elevator so that the elevator is as good as not there, as regards its having any disturbing effect on the other yielding tail actions, the *incorrect* plausible inference has sometimes been drawn that the gyroscope cannot, *on occasion*, *keep* the elevator deflected with a strong air pressure on its surface.

The reason the fly-wheel can be so easily tilted fore-and-aft is that it has no cross-bearings, or complete gimbals, to permit of the free left-and-right nodding that is necessary to gyroscopic reaction. But when the lateral tilting of the whole machine occurs, the fly-wheel *does* find itself with the necessary cross-bearings to permit of *fore-and-aft* nodding or precession, and the gyroscopic torques manifest themselves. In the example that was taken, an upward tilting of the wing at one radian per second produced about 140 lbs. alteration in the pressure on the wing extremity at 1 foot leverage from the warping axis, and therefore about 10 lbs. pressure was being produced on the under surface of the flap elevator at its fifteen times greater leverage from the wing. It is curious to note that, so long as the machine continues to tilt laterally at the stated angular velocity, this pressure of 10 lbs. is *maintained* on the flap elevator, and local air currents, attacking the elevator, flap it up and down all the while that the pressure of 10 lbs. is *being maintained.*

The means of driving the gyroscope is, to a great extent, a mere detail, but not entirely so. Reliability is naturally of great importance, and, in this respect, the wind-operated driving fan shown in fig. 66 excels. The fan is shown driving the fly-wheel through bevel gear wheels and a flexible shaft. It is an improvement on the drawing to have the fly-wheel dished, and the top bearing placed in the hollow, so that the end of the flexible shaft has no occasion to alter its place as the gyroscope tilts.

The advantage of this wind-driving does not consist solely in reliability, for the fans act to some extent as fly-wheel-fan dampers of longitudinal pose, like the fan D of fig. 32, I. (Plate IV.). Moreover, since each fan acts to resist fluctuations in the headway of its own wing tip, it resists those fluctuations of headway that are associated with oscillations of lateral pose.[1] As a consequence, the fans can be shown to assist in damping the lateral oscillations of pose.

In some cases, a wind-driven fan may drive a dynamo that generates electrical power for transmission to motors forming parts of the gyroscopic fly-wheels.[2]

The gyroscopes in fig. 66 are shown connected by

[1] See page 261, second paragraph.
[2] See page 255, near its end, for a similar suggestion.

cords across the machine, so that each one helps the tilting of the other. These connections are advisable in order that the gyroscopes may not disturb the turning of the machine. The cords are shown passing through the body of the machine, where they may, if desired, be operated in addition by manual or other controls,[1] and even by a third horizontal or vertical[2] gyroscope, or pair of gyroscopes, pivoted to tilt *sideways* and operate the elevators in such manner as to set up a damping resistance to oscillations of *longitudinal* pose. Such longitudinal gyroscopes are liable, however, to be so carelessly arranged that they are a disadvantage, and, when well arranged, they are a luxury beyond the present requirements of an advance in stability.

Gyroscope Combined with the Other Effects

In the frontispiece, a bolder and better design than fig. 66 is shown diagrammatically. The tail booms are parallel—the vertical hinged link in the rear being quite as long as the distance between the main planes. The steering pillar is moved backwards and forwards to operate both rear flaps together as elevators for longitudinal control, and rotated with the attached pulley for the simultaneous differential lateral control of the flaps whenever the pilot wishes to use the flaps to steer with or to interfere with the automatic lateral

[1] In a large machine required to turn sharply, it is sometimes advisable to have the gyroscopes, and their connected tail planes, so operable from the pilot's seat, because the gyroscopic control, if left to itself, resists the necessary banking. The gyroscopes do *not* resist such tilting of themselves and their tail planes by *the pilot* (see pp. xiv, xv of Preface).

[2] Not necessarily horizontal; this gyroscope may have its plane of rotation at right angles to the longitudinal axis of the machine, and the pivots, of the frame in which it rotates, vertical, so that when the machine tilts down or up, the gyroscope nods round this vertical axis.

self-control of this type of machine. The weight is disposed approximately at the centre of pressure or lift of the central section of the main planes, because it functions in the required manner in a head gust by reason of its being carried forwardly of the fixed planes M_1—that are placed behind the mass in order that the mass shall be forwardly of them—and forwardly of the centre of pressure or transverse axis of

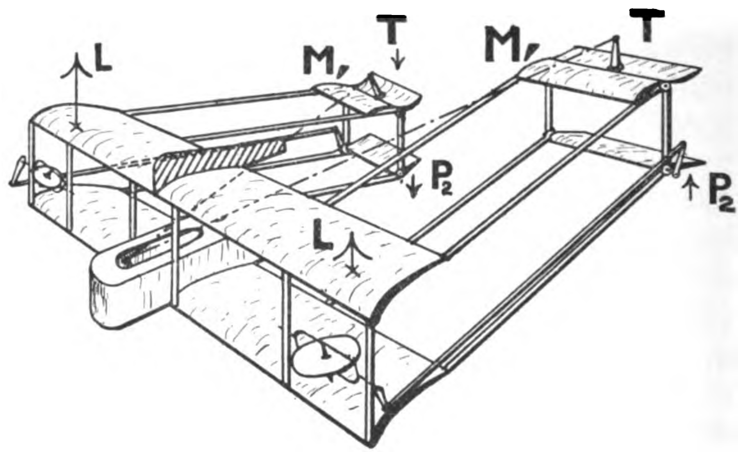

FIG. 68.

movement of the main planes in conjunction with the fixed planes M_1.

Fig. 68 shows, diagrammatically, how such a machine may appear while resisting an effort to tilt it left-handedly (as viewed from in front), and also while resisting an actual *velocity* of such tilting that it is supposed to have acquired despite the appliances. The machine may be regarded as being in a head gust on its left side, and in a rear gust on its right side.

The constant-lift action of the two sides of the machine, whereby, through the operation of the planes

M_1 and T in relation to the mass of the machine, the *acceleration* of left-handed tilting is eliminated by the warping movement depicted in the drawing, need not be described again.

But, in the drawing, the lifts L are *not* shown equal; the left one is shown much less than the right one. The reason is that the machine was supposed to have *acquired* a left-handed *velocity* of tilt (as viewed from the front). This, in the way already described, excites the gyroscopes to deflect their respective tail planes to reduce the lift on the left, and increase it on the right, and thereby resist the acquired *velocity* of tilt.

It may be remarked that every competent pilot is now, though without viewing the fact that way, using his warp so as to eliminate accelerations of tilt, and resist velocities of tilt, and thereby copy, more or *less* skilfully, the less fallible actions of the automatic lateral control described.

Whirling-table Tests

When a given aeroplane is required to possess lateral stability, the designer stands in need of some method of deciding when the machine has the desired properties.

In Chapter XII. we saw that the properties of a machine with respect to longitudinal stability could easily be investigated by wind-tunnel experiments. Similarly, many of the properties of a machine with respect to *lateral* stability may be investigated by whirling-table experiments.

Take, for example, a model of the type of fig. 48 (page 190). On attaching its centre (centre of mass) to the outer end of the arm of the whirling table by means of a *universal or ball joint*, and setting the whirling-table arm in motion at about normal speed, we shall be able to discover, by the *outer* wing gently *descending*, whether the model possesses the necessary slow lateral self-righting effect. If the outer wing does not descend, we may ensure its doing so by such means as adding suitable lateral down-steering surfaces, like M_1, M_1 of fig. 51, at the rear of each right and left main plane.

The models of figs. 49, 50, 51, 52, 55, 57, 66, 68, and the frontispiece may all be tested and adjusted in a similar way. In figs. 55 and 57 the down-steering planes, M_1, M_1, have to be turned more and more in a fixed down-steering sense till the necessary gentle sinking effect of the outer wing is obtained, the yielding tails being, each one, at the same time springingly held to counteract only the *mean* down-steering effect on its own side of the machine.

Fig. 59, I., tilts violently in the direction of the circular arrow when whirled round the axis of circling of the whirling table, or axis, shown on the right of the illustration. Fig. 59, II., on the other hand, tilts just as strongly in the opposite direction; consequently, when the two are united, we get no tilting effect, but, unfortunately, no net lift.

If the small down-pressed surfaces of fig. 59, III., have been properly arranged to compensate the whole machine, it, too, will not tilt on the whirling table, but, owing to the larger lifting surfaces, the model will have a considerable net lifting effect.

On tilting the compensated model of fig. 59, III., through any angle ζ, as in fig. 59, VII., the model will remain content with that tilt. This is because, by formula (42) or (46), the righting moment is zero for *all* values of ζ when once the sum of the terms in the brackets has been made zero by suitable disposition of the down-pressed surfaces. In this test, the model must have no lateral moment of inertia, for if it has, it will confuse our observations by tending to right itself through the operation of a centrifugal couple,[1] in the manner discussed in connection with fig. 65.

It will be obvious that the whirling table is very useful for the practical adjustment of compensated main planes of the types of fig. 59, IV. and VI., the curves of fig. 59, V., being left to look after themselves —*which they will do.*

So long as the machine is drawn forward by a *universal joint* at its centre of mass, the dihedral righting effect of fig. 60 is easily tested and adjusted on a whirling table. The outer wing gently descends when the adjustment is sufficiently correct, and, with a given dihedral angle, this result is promoted by anything that increases the head resistance of the ends of the wings. (Down-pressed lateral extremities do this, and give their own righting effect too.)

The whirling table will, of course, show the additional upsetting effect of the slight inverted dihedral of fig. 61, and it is an interesting test to overpower this by the elevated keel effect of fig. 62, II., and of figs. 63 and 64, for, in practice, such combination has some advantages.[2]

The righting effect of the lateral masses of fig. 65, I. and II., is easily tested by the whirling table, when

[1] Or, in the experiment, that particular centrifugal couple may be exactly annulled by putting masses on the *vertical* axis to give it exactly the same moment of inertia round the longitudinal axis that the transverse axis has round the longitudinal axis.

[2] See page 257 ; and claim 8, on page 266.

the masses are added, for preference, to a previously compensated main plane.

Finally, fig. 66 and the most complicated of models may, as a general rule, be initially adjusted, for lateral stability, by means of whirling-table tests. On the other hand, the fundamental properties of the gyroscopic control, and the difference between its action and that of the simple weights in resisting changes of lateral pose, are better shown in a wind tunnel in which the machine is pivoted around its own longitudinal axis.

Wind-tunnel Tests of Gyroscopic Controls

Let us take an experimental model of the type of fig. 66, but with perfectly flat main planes and auxiliary tail planes all arranged for *zero* angle of incidence. The planes are supposed to be as freely warpable as if they were hinged like those of fig. 48, and a heavy mass (which may take the form of one of the gyroscopic fly-wheels, *not* spinning in the initial experiments) is placed at each lateral extremity, as shown in fig. 66.

Let this model be now pivoted round its longitudinal axis, in a wind tunnel, and let a strong wind be directed upon it. If the model is at first horizontal in its lateral pose, it will remain so, for the fixed tail plane at each extremity keeps itself at zero angle of incidence, as it trails out in the wind, and thereby keeps the main plane also at zero angle of incidence. The *flap* tail planes, of course, have no disturbing effect.

Suppose, now, that we apply a mechanical torque to turn the model round the longitudinal axis. This torque will be resisted, but, so far as the model has no head resistance, only by the masses' *inertia* resistance to *accelerations* round the longitudinal axis. The planes, in consequence of their automatic warp, will still travel, in all their parts, edgewise through the air, and proceed in a spiral path *relatively* to the column of air directed upon the model. If each wing of the model has a head resistance, a component of that, and *that only*, will direct itself against the rotating torque, and equilibrate that torque when a certain speed of rotation has been reached—sooner or later, according to the magnitude of the masses. *Only* the head resistance, however, operates to limit the *speed* of rotation, the masses themselves operate *solely* to limit the *rate of change* of the speed of rotation, or the angular *acceleration* of rotation, for a given applied torque. They are content with *any existing* steady speed of rotation, and tend to prevent its change only.

Now let the gyroscopes be set spinning by their wind-driven fans, and again apply the same mechanical torque to turn the model round its longitudinal axis in the wind tunnel. As the model gathers *speed* of tilting, the gyroscopes additionally warp the main planes, through the auxiliary tail planes acting with the leverage of the tail frame, so that the planes no longer travel edgewise, but present themselves at an angle of incidence that tends to counteract or resist the tendency of the machine to rotate round the longitudinal axis. Since the resistance thus set up to lateral *velocity* of tilt is substantially proportional to that *velocity* of tilt, the model behaves almost exactly as if the ends of its main planes were scraping the sides of the wind tunnel with a friction force proportional to the rotary *velocity* of such lateral scraping.

Since the gyroscopes resist *velocity* of tilt, the final velocity of tilt that a given applied torque can produce is much reduced when the gyroscopes are spinning, and it should not be forgotten that when the gyroscopes are not spinning, there is *no limit* to the final velocity of tilt, so far as the planes are perfectly warpable and *have no head resistance.*

Further instructive experiments may be made by attaching a spring to the perfectly warpable model, so that the model may oscillate round its longitudinal axis, in the wind tunnel, like the balance-wheel of a chronometer.

On making a vacuum in the wind tunnel, the oscillation period of such model may be, let us say, one second with the gyroscopes not spinning. (With the gyroscopes spinning, the oscillation period in the vacuum would be somewhat increased by their *direct* action, but that action is so comparatively feeble as to be of little interest.) When the air is let into the wind tunnel and directed, as a wind, upon the model, the oscillation period still remains about one second, but the oscillations will be found to die down more quickly, because a component of the head resistance of each warped extremity keeps resisting the angular velocity of tilt. If the model had no head resistance, the oscillations would not differ in any way from those in the vacuum.

On now permitting the gyroscopes to spin, a great contrast will be noticed; the oscillations will be found to have been made much slower, perhaps several seconds in period, and practically *dead-beat.* The model, in fact, will act laterally very much as if it had been surrounded with a thick viscous syrup, or as if the extremities of its wings were scraping the sides of the wind tunnel with a friction proportional to the rotary velocity of scraping.

Now that, as was found before, is just how the model acts in free flight. The lateral oscillations of *absolute* pose are resisted exactly as if the extremities of the wings were continually making contact with and scraping the walls of an invisible wind tunnel with a friction exactly proportional to the angular velocity of lateral scraping.[1]

Diminishing Lift by Inverted Camber and Gearing of Elevators

In most of the illustrations, the rear yielding elevator is shown concave on the *upper* surface that sustains the downward air pressure, and, in many cases, this is done for a deeper reason than mere efficiency. When such a strongly cambered flap elevator is pressed back by gusts to a smaller angle of incidence, its centre of pressure tends to retreat further from the hinge, and the total air pressure, as a consequence, to *diminish* as it continues to equilibrate the torque of a spring or other substantially constant force. But the reduced air pressure on the top of this elevator determines the reduced loading on the main plane (or its extremity, as the case may be) that is loaded solely by reason of the downward pressure on the elevator. Thus, a strongly reversed camber to such elevator may itself, if we wish, cause or aid a machine, or each of its extremities, to be a diminishing-lift machine, even if

[1] No friction of *this* kind should be regarded as appertaining to the *forward* movement of the extremity, as distinct from the lateral movement round the longitudinal axis.

the main plane has not a retreating centre of pressure with diminishing angle of incidence.

This effect is illustrated in fig. 69. The arrows show the forces of the weight *w*, the lift L, and the tail pressure T, in equilibrium for the given machine, or its extremity, for a headway of 30 m.p.h. On the slow-fan F being clamped, and the headway being increased to 40 m.p.h., the elevator is blown back to a lesser angle of incidence, and, being strongly cambered, its centre of pressure travels further from the hinge. But

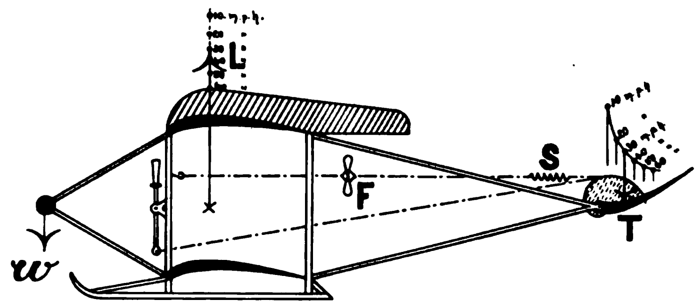

FIG. 69.

at that further distance or leverage the pressure T, equilibrating a spring S, is necessarily reduced, as indicated by the lesser height of the arrow at the figure "40 m.p.h.," and since the lift L is determined by the pressure T, the lift L is necessarily *reduced* by this *increase* in headway from 30 m.p.h. to 40 m.p.h. The position and magnitude of the force T, for other headways, are similarly suggested by the numbered curve drawn above the elevator, which curve resembles, in its interpretation and effect, the curve that was drawn above the main plane of fig. 39, page 123.

Alternatively or additionally, the diminishing-lift effect is obtainable by gearing the spring S, or the muscle of the pilot's arm, or other pulling device, in a variable manner to the elevator, so that the pulling device has a reduced mechanical advantage over the elevator as the headway increases. In the one way shown in fig. 69, a pulley on the axle of the elevator, round which the cord is lapped, is cam-shaped, so that the spring S has a less leverage over the elevator as the elevator flattens out, and thereby induces a reduced counteracting pressure on the elevator. This reduced pressure on the elevator in turn determines a diminished lift in the main planes, as an accompaniment to the increase in headway. Instead of cam-shaped pulleys, cranked levers and other mechanical equivalents may be used to obtain effects of this kind.

It will be seen, therefore, that a diminishing-lift effect may be secured in three ways that have been disclosed :—(1) By having main planes, or main planes in combination with rigidly attached planes, with retreating centres of pressure with decreasing angles of incidence. (2) By having yieldingly-held elevators with retreating centres of pressure with diminishing angles of incidence. (3) By having the device pulling the yielding elevator, so linked, connected, or geared to the elevator that the pull upon the elevator *weakens* with increasing headway.

In general, it is not advisable to dispense with the first method for obtaining a diminishing-lift effect, but a thorough discussion as to when, and in what proportions, to employ the various methods, especially when the gyroscopes of fig. 66 and the frontispiece are used, must be regarded as beyond the scope of this supplement.

In this connection, it might be observed that, while simple "flyability," or tactile stability, is easy to produce by designing machines bearing "rule-of-thumb" resemblances to those suggested by the principles described in this book, the production of a good self-flying machine, having what is conventionally understood by the word "stability," requires a somewhat higher order of skill and knowledge in the designer. Mere copying and obtaining resemblances will not do; the designer must have a proper sense of the importance of small changes in the design, and *understand* the why and wherefore of all he is doing.

Classified Requirements for Complete Self-flying Stability

Complete self-flying in an aeroplane, in disturbed air, consists in :—

(1) The elimination of sudden changes of pose—an indispensable fundamental property in any machine.[1]
 (A) Longitudinal.
 (B) Lateral.

(2) The prevention of slow and permanent changes of pose by the provision of a self-righting, supervising effect with respect to a mean pose.[2]
 (A) Longitudinal.
 (B) Lateral.

(3) Means of damping or resisting oscillations of pose about the mean pose.[3]
 (A) Longitudinal.
 (B) Lateral.[4]

[1] See page 253, first paragraph.
[2] See page 253, first paragraph.
[3] See top of page 254 and of page 255.
[4] See page 261, first paragraph.

MEANS OF FULFILLING THE REQUIREMENTS

The best ways of providing for the above requirements are as follow :—

(1A) **The elimination of sudden change of longitudinal pose** is most easily brought about by placing the mass (or a mass) forwardly of a main plane (or other plane or planes) and maintaining the substantially invariable load or lift upon these planes by means of the yieldingly-held rear flap elevator that compensates for the forward mass (see figs. 39, 41, 55, 57, 66, the frontispiece, etc.).

(2A) **Slow and permanent changes of longitudinal pose** are easily prevented by manual control of the yieldingly-held flap elevator, at least in small machines; but in large heavy machines on important flights, and in all cases where the personal element in control requires minimising, wind-operated slow-fans (F in the various illustrations) and springs should be used to keep the yielding elevator in adjustment (see figs. 32, 39, 41, 56, 58, etc.).

(3A) **Damping of the longitudinal oscillations of pose** may also be easily performed by personal control in small machines, but the simplest automatic means consists of a fly-wheel fan, such as the fan D of fig. 32, I. (Plate IV.). More powerful but more complicated gyroscopic means may be employed in the future.

(1B) **The elimination of sudden change of lateral pose** is most simply brought about by making each lateral extremity of the machine automatically self-warping, in a *reliable* manner, so as to preserve substantially constant lift at each extremity. The best way of doing this is to place a tail frame behind each warpable extremity, carrying an up-pressed fixed tail plane and a down-pressed yieldingly-held elevator. Masses near the lateral extremities may be used to aid this effect by their inertia (see figs. 55, 57, 66, the frontispiece, etc.).

(2B) **Slow and permanent changes of lateral pose** are preventable by manual control of the warping, but the best automatic means consist in giving the extremities of the machine a diminishing-lift effect relatively to each other (see figs. 48, 55, 69, the frontispiece, etc.). Other aids are:—(1) Down-pressed surfaces near the lateral extremities (see fig. 59). (2) A slight positive lateral dihedral angle (see fig. 60). (3) Head resistances concentrated near the lateral extremities. (4) An elevated keel plane (see figs. 62, 63, 64, 66, etc.). (5) Masses placed near the lateral extremities in order to give centrifugal righting couples (see figs. 55, 57, 65, 66, etc.).

(3B) **Damping of the lateral oscillations of pose** may also be effected by manual control, but it is a great relief, especially on large machines, to have it done automatically by means of lateral gyroscopes (see fig. 66 and the frontispiece). Fly-wheel fans at the lateral extremities are also an aid to this lateral damping, besides assisting the longitudinal damping.

It may be observed that directional stability round the vertical axis is seldom referred to independently. It is generally taken for granted that the machine is provided with the usual head-first tendency, by having the side-view centre of pressure, for small angles of incidence on the plane of symmetry, to the rear of the centre of mass.

BRITISH PATENT SPECIFICATIONS

Prefatory Remarks.—In this edition of this book several references have been made to the author's patent specifications printed below, for in view of the type of machines now being flown, and the present trend of design, it is expected these specifications will be of interest, and even prove indispensable knowledge.

The patents will be seen to be master-patents as regards the mode of stability dealt with in the book; and in respect to the elimination of sudden disturbance of pose by the adoption of a permanent diving or down-steering tendency due to the forward placing of the mass or a mass in relationship to a plane or planes, there is hardly a machine built or flown, *and flyable in gusts*, that is not liable under these patents. The parts of the specification considered of special interest in the present juncture are printed in italics, and in order to appreciate the invention the reader should endeavour to peruse the specification from the point of view of one in the state of knowledge prevalent in the year 1909.

Since the complete stabilising of an aeroplane necessarily consists in the complex co-operation of several devices or elements of design (as suggested in the first and second paragraphs of the parent specification 8531/09) one or the other of which could be left out without grave inconvenience or risk, the author took proper precautions against such use of his invention, by the insertion of the third paragraph of the parent specification. That paragraph was written especially with a view to circumventing attempts that it was correctly foreseen would be made to employ the means of preventing sudden changes of pose, particularly longitudinal pose, without the more highly specialised and more conspicuous means of preventing slow and permanent changes of pose and damping oscillations of pose.

Although, as stated on page 2 of this book, the author did not, till 1911, intentionally draw public notice to acceleration or rate of change of headway being the measure of a gust, it will be seen that these specifications suggested it, and took the fact for granted, in a very matter-of-course way, in several places. The specification 8531/09, and an anticipation of 6051/10, were placed before the Government Advisory Committee on June 30, 1910, and a covering communication, written on the back of the specification, in dividing gusts into those less than the gravitational 32·2 ft. p.s. p.s., and those greater than 32·2 ft. p.s. p.s., further intimated that gusts were to be measured by impressed accelerations of headway comparable with those due to gravity.

N° 8531 A.D. 1909

Date of Application, No. 8531, 8th Apr., 1909
Complete Specification Left, 8th Oct., 1909
Complete Specification Accepted, 7th Apr., 1910

COMPLETE SPECIFICATION

Improvements in Aeroplanes and the like

I, SAM LEONARD WALKDEN, do hereby declare the nature of this invention and in what manner the same is to be performed, to be particularly described and ascertained in and by the following statement:—

The object of this invention is to obviate by automatically operating devices changes of pose in aeroplanes, gliders and the like, and thereby preserve automatically the stability of movement of the apparatus through the air. *Complete automatic stability can be obtained if automatically operating devices are provided which obviate both sudden and slow changes of longitudinal pose and sudden and slow changes of lateral pose of the aeroplane.*

While, however, completely automatic stability of movement is thus the object of the invention, it will be understood that either in lieu of or in addition to any of the various automatic devices hereinafter described there may be used manually actuated or other known devices adapted to achieve or promote the desired result.[1]

According to this invention *sudden change of longitudinal pose is prevented by means of one or more masses carried on a main or other plane or planes forward of the transverse axis of movement of such plane, e.g.* at the outer end of longitudinal rods or frames which are preferably flexible in the vertical direction and *extend forwardly from the main plane or planes or from an auxiliary elevating plane or planes. Owing to the inertia of the mass or masses,* a sudden downward or upward change in the longitudinal pose of the aeroplane is opposed *and this inertia may also be arranged to produce a counteracting deflection or deformation of the plane or planes to which the mass or masses may be attached.*[2]

[1] For example, the slow-fan and automatic devices for supervising the mean pose and damping oscillations are scarcely missed by a pilot, on short flights. A pilot may then content himself with the automatic arrangements for obviating sudden changes of pose, and so reduce the machine to one having a mass or masses too far forward (as judged by previous practice) and requiring the elevator to be yieldingly held by hand, in lieu of by the fan and spring, to compensate.

[2] For example: the pilot, or the engine, or a searchlight, or any weight whatever, may be carried too far forwardly (as judged by previous practice) relatively to a main plane or a fixed tail plane or both, and arranged, by being compensated by a yieldingly-held elevator (by hand or otherwise), so that its inertia, in the event of a sudden head gust attacking the

Change of longitudinal pose in calm air and of average longitudinal pose in gusty air is resisted by means of a wind-driven continuously rotating fan or propeller which may be of considerable power and which, according to one construction, is journalled at the top of a standard rigid with the frame of the ship. The fan acts as its own flywheel (being if necessary additionally weighted for this purpose) or is geared with a separate flywheel which may also act as a counterpoise to the fan and standard or may occupy any other desired position on the ship. Change of speed of rotation of such a fan is resisted by the flywheel effect and as a consequence change in its translational velocity relative to the air is also resisted. Since in calm air a change of longitudinal pose of the aeroplane is accompanied by a tendency for the aeroplane to gain or lose speed relative to the air according as the ship sweeps downward or upward from the plane of steady gliding movement, and since the fan in the manner described resists sharing in the fluctuation in speed, a backward or forward force is produced at the top of the standard opposing the change in longitudinal pose by a properly directed torque acting upon the ship through the leverage of the standard.

In gusty air only fluctuations in average longitudinal pose with respect to a number of quick gusts are opposed in the manner described, since there is no longer the required ordered relationship between the pose of the aeroplane *and the instantaneous rate of change of relative headway.*[1]

It will be seen that the fan acts primarily to counteract change in the relative headway of the ship and this property is of importance in conjunction with devices hereinafter described for maintaining lateral stability which depend for their efficiency on the preservation of relative headway.

The stabilising action of the fan does not depend wholly

machine, produces a counteracting nodding or downward deflection of the main plane relatively to the yielding tail plane, that prevents the machine rearing up as it otherwise would do. This action is substantially the same as that of the weights *e* in the example of fig. 1, page 261.

[1] By which, of course, is to be understood that gusts are characterised by accelerations or rates of change of relative headway impressed upon the machine by independent movements of the air.

on its preferred elevation for if placed *level* with or even slightly below the centre of mass of the ship the backward and forward forces which it produces will still tend to damp out fluctuations of relative headway, and owing to the interdependence of fluctuations of pose and relative headway the damping out of the latter is accompanied by the damping out of the former.

When the ship is fitted with movable elevating planes the fan may instead of, or as well as, acting on the ship as a whole, be made in a variety of ways to turn the elevating planes in an up-steering or down-steering direction as a consequence of any increase or decrease respectively in relative headway. The fan may for example be mounted on a standard projecting from an elevating plane generally in an upward direction, but downwardly in the case of some rear elevating planes. A counterpoise may be applied to balance the plane and fan structure about the axis of oscillation of the plane, such counterpoise being if preferred a separate flywheel driven by the fan. Or the standard carrying the fan and counterpoise may be pivoted in any desired position on the ship and suitably linked with the elevating plane or planes which it is desired to actuate.

In some cases the fan may be made to drive its flywheel through a differential gear so that when the fan gains or loses speed relative to the flywheel the intermediate pinions of the gear will be rotated one way or the other around the axis of the driving and driven gear wheels and through suitable linkage or gearing made to turn the elevating planes in an up-steering or down-steering direction respectively. Any mechanical equivalent of the differential gear may be employed. For instance, *the fan may drive a dynamo electric machine usually acting as a generator and supplying current to a second dynamo electric machine usually acting as a motor in driving the flywheel*, and the current in the circuit, positive or negative in direction according as the rotation of the fan is accelerating or slowing, may be made to actuate any suitable electro-magnetic device for turning the elevating planes in an up-steering or down-steering direction respectively.

The main propeller of the ship may in similar manner act as *that form of the wind-driven fan above described in which it is placed substantially level with the centre of mass and resistance of the aeroplane*, and is not arranged to turn or deflect any main or auxiliary plane. In this case the propeller is substantially the wind-driven fan with a superimposed torque, and consequent thrust, arranged so as not to disturb materially its stabilising action.

I am aware that most propeller drives, especially those in which the engine torque is steady and the propeller and the rotating parts are heavy, must inherently possess to some degree the property of a stabilising fan such as I have described in that the propeller tends to thrust more or less according as the ship tends to slow down or accelerate relative to the air. I therefore do not claim such power-driven fans as my invention *apart from an associated device or arrangement whereby the stabilising property can be more effectively utilised.* I may, for example, fit an unusually heavy flywheel to the propeller as distinct from the engine and couple the engine with the flywheel and propeller through a free-wheel clutch so that the stabilising action does not depend on the engine speed being maintained. The heavy flywheel in this case also serves on occasion to keep the propeller from a sudden increase in speed due to increase in engine torque.

In all cases in which an elevating plane or main or auxiliary plane is turned or deflected by the fan or other of the automatic devices hereinafter described and is not self-centralising by air pressure on the plane or by inherent springiness, one or more centralising springs may be used to determine a normal position about which the temporary movements of the plane take place.[1]

To prevent slow and permanent change of the longitudinal plane of movement of the ship one or more fans of small power driven by the movement of the air relative to the ship may be correlated with an elevating plane or planes in such manner that they tend to give a definite pose thereto for a given speed of the ship so that an increase or decrease of this

[1] For instance, when the mass or a mass of the machine is placed so far forward as to require a yieldingly-held elevator to compensate, that elevator may be held to its mean position by springs, and supervised by hand.

speed will cause the elevating plane to be inclined so as to tend to steer the ship up or down respectively.

For example, such a fan may be arranged so as to tend to wind a cord on a drum the other end of the cord being attached to a vertically flexible longitudinal rod or frame extending rearwardly from the ship and carrying at its rear end a small horizontal plane. Or a wind-driven fan or fans (which may be damped by air vanes) may be set to wind or twist a cord or cords connected with a fixed point at one end and at the other end through a tension spring with another cord lapped round a pulley on the axle of the elevating plane and connected through a tension spring with a fixed point, or with a hand-operated winding device by which the "constant" of the apparatus may be varied to change the persistent pose of the plane.

In order to preserve lateral stability the horizontal supporting plane or planes are constructed as substantially flat surfaces without any vertical planes rising or depending or extending forwardly or rearwardly therefrom so as materially to arrest the lateral sliding movement of the centre of gravity which arises when the ship tilts to one side or the other, and as the rate of recovery is made to depend on the rate of this lateral sliding movement of the horizontal plane or planes, the latter are preferably constructed so as to increase the rate of sliding by arching them slightly transversely (*i.e.* from wing to wing) with the concave surface downwards—a construction which also possesses other inherent advantages.[1] *This curved shape is particularly advantageous when, as in one construction according to this invention, the righting is effected solely by means of an elevated longitudinal vertical plane which is carried on a standard or frame at a sufficient height not to interfere substantially with lateral sliding.* This plane, when it is desired that the ship should by its means automatically maintain its directional stability, extends so far rearwardly that the centre of pressure is in rear of the centre of

[1] One advantage in view was the damping effect due to the churning of the air consequent on the arched main plane trying, on its own account, to slide in one path, but being forced by the elevated keel plane to take a different path.

gravity of the ship, but with manually controlled steering devices this relation need not be observed. It will be seen that the resultant wind pressure on the elevated plane due to the lateral sliding of the main plane will act to restore the lateral balance of the ship, but it may also act to turn the ship about a vertical axis and make it wheel or circle to the side it leans to.

If the ship circles towards the side to which it is inclined the action of centrifugal force as well as the greater support afforded by the air to the outer or elevated wing than to the inner or depressed wing will militate against the righting of the ship, and consequently the restoring force due to the resultant wind pressure on the elevated plane will obviously be more effective if the ship continues to move substantially in a straight line than if it moves in a curve towards the direction of inclination, but since the lateral sliding movement may, if the ship's headway be maintained give rise to a resultant circling or wheeling movement of the ship as a whole towards the side to which it is inclined, the restoring force will in such circumstances be somewhat less effective. The full righting effect possible of the elevated plane may, however, be obtained if means are provided for automatically turning or distorting the plane so as to increase as much as possible the lateral pressure of the wind. This result may be obtained by mounting a pair of wind-driven fans near the two lateral extremities of the aeroplane and using the difference in their driving torque consequent on the circling movement of the airship (should such arise) to distort or turn the vertical plane. For example, the two fans may be geared with winding drums from which suitably guided cords are led to the front end of an elevated plane which is rotatable about a vertical axis. Or the two fans may drive the gear wheels of a differential gear in opposite directions so that the intermediate pinions move one way or the other round the gear wheel axis according as one fan is moving faster or slower than the other, and cords may be led from the moving pinions or a drum geared to them to the vertical plane so as to distort or turn the latter according to the movement of the pinions.

This differential rotation of the wind-driven fans may be used to restore lateral balance in other ways apart from or in addition to the distortion or turning of the elevated plane, as for example by actuating a rudder by means of a pair of similarly actuated cords so as to turn the ship towards the direction away from which it is circling,[1] or by producing a warping of the main planes by means of cords passing around pulleys on the rear edge of the plane so as to raise one side and lower the other, *or by actuating auxiliary elevating planes so as to raise or lower one side of the ship relative to the other.* Any one or more of these equivalent devices may be brought into action so as to restore lateral balance by means of wind-driven fans which are caused to rotate at different speeds by reason primarily of the circling movement which itself may be due to the lateral sliding which is allowed or promoted by constructing the plane or planes of the ship in the manner proposed.

The lateral tips of the aeroplane may be weighted, such weights acting to prevent sudden changes of wing tip velocity and so retard circling *and also to give a centrifugal righting couple on such circling occurring.*[2] These weights may be carried at the ends of forwardly projecting rods or frames which are preferably vertically flexible.[3]

Sudden changes in lateral pose are prevented by means of masses which are so disposed on the ship that, when the latter suddenly tilts laterally, they operate to bring into action forces which oppose the tipping movement, as for example by causing warping of the main plane or planes or by operating auxiliary planes or other devices adapted to counteract sudden lateral tilting.

[1] Several aviation disasters have been characterised by the machine making a prolonged, sharply converging spiral dive at high speed, and it is on record that Lieutenant Parke made a remarkable recovery from such a dive by having the time and presence of mind to "rudder" *outwards*, contrary to advice for this emergency, and contrary to his first action in the emergency. The above side fans actuating his rudder would obviously have effected the required rudder movement for him, and would have prevented many of the other disasters.

[2] See pages 226 to 230 of this book.

[3] It should be noticed that flexibility is quite optional, and in many cases is not preferable.

One way[1] of affecting this consists in providing two heavy metal balls which are carried by two vertically springy rods projecting forwardly from the lateral extremities of the main plane which is constructed so as to yield readily to warping forces. If there is a sudden inclination of the ship, *e.g.* so as to raise the left side and depress the right, *the lagging of the masses due to their inertia produces a downward flexure of the left wing and an upward flexure of the right wing*, and so long as headway is preserved this results in a rotary force opposing the disturbing forces.

Further, since most aeroplanes tend to wheel towards that hand to which they tilt, the masses in such cases produce a *centrifugal couple* which not only helps directly to restore the level position but also acts to increase the warping of the plane.[2]

The tendency of the masses to depress the front of the ship may be compensated by a small tail plane which is preferably carried on a vertically springy rod *so that the main plane and the tail are mutually dissociated to a considerable degree from the quick movements of each other.*[3]

Although the masses may be disposed as above described and may operate to produce an equilibrating warping of the main plane, *the masses may obviously be otherwise supported and may be made to operate auxiliary planes.* Further, instead of using inert weights, *small horizontal flywheels may be substituted which are rotated by wind-driven fans generally and preferably left-handedly on the left side and right-handedly on the right as viewed from above so as to act gyroscopically by the precession of the axes of the flywheels consequent on change of lateral pose of the ship to produce or increase the torsion force on the wings of the main plane or other equilibrating forces.*[4]

[1] Emphasis is laid on the "*one way*"; the masses may be anything that has mass, provided the mass is employed substantially as and for the purpose described, and not in a manner previously known to practice.

[2] See page 230 of this book.

[3] That is to say, during normal flight the masses weigh down the front of the aeroplane, apart from the compensation due to a yieldingly-held tail plane that may be held by hand in lieu of the slow-fan and spring.

[4] As dealt with in pages 230 to 239 of this book, and illustrated in figs. 66, 67, 68, and the frontispiece.

Instead of two or more flywheels a *single small flywheel may be used in this manner*, but in any case the present invention is limited by such flywheels being rotated by wind-driven fans.

It is to be understood that *such fans, driving flywheels, also act to assist the longitudinal stability of the aeroplane* by resisting changes in relative headway. Moreover when placed towards the lateral extremities of the aeroplane they assist the lateral stability by resisting change of relative headway of the lateral extremities and by resisting, in consequence, the commencement of the circling or wheeling

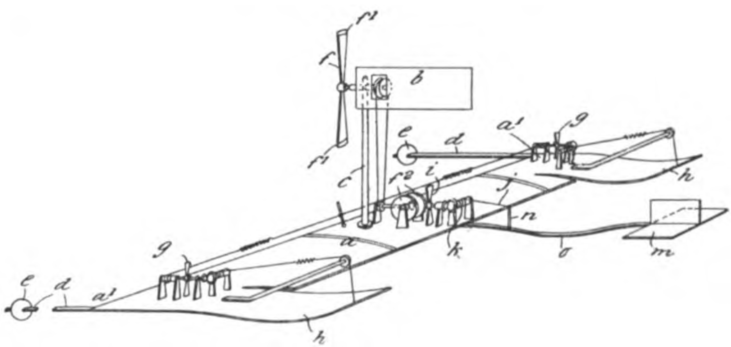

FIG. 1.—Patent 8531/09.

of the aeroplane which militates against the recovery of lateral pose.

In fig. 1 of the accompanying drawings there are shown as applied to a glider, automatically operative devices according to this invention, by which such an apparatus or an aeroplane or the like may be made automatically stable.

In this drawing there is shown a single main supporting plane *a* which may be flat but is preferably arched slightly transversely with the concave surface downwards so as to promote lateral sliding consequent on lateral tilting, particularly when the lateral righting is effected solely by means of the longitudinal vertical plane *b* which is carried on a vertical standard *c* at such a height as not to interfere materially with lateral sliding.

Projecting forwardly from the front corners a^1 of the main plane are rods *d* which are vertically springy and carry at their extremities heavy masses *e* which operate not only to counteract sudden change of longitudinal pose by increasing the longitudinal inertia of the ship and by causing flexure of the main plane but also sudden change of lateral pose by causing warping of the main plane, one wing being downwardly and the other upwardly flexed.

Carried on the standard *c* is a fan or propeller *f* which is mounted to rotate in a transverse plane and is of such size as to be capable of generating considerable power. The standard *c* is mounted direct on the main plane at a point preferably near the centre of gravity of the ship. Change of the speed of rotation of the fan *f* is resisted by the flywheel effect, and as a consequence change in its translational velocity relative to the air is resisted. Consequently change of longitudinal pose which tends to produce change of velocity of rotation of the fan is resisted.

It is to be understood that *the fan* f *need not be elevated above the main plane as described*, but may in some types of ships be mounted substantially co-planar therewith, or may even be slightly below the main plane; also, that the fan is either itself weighted to act as a flywheel or is coupled with a flywheel; and further that *the main propeller itself may be the fan*, and although in this case the fan is primarily a power-driven one, it may operate as an automatic stabiliser by reason of its resistance to change of relative translational velocity of air and fan just as may be done in the case of the wholly air-driven fan. As shown in fig 1, additional flywheel effect may be obtained by weighting the tips f^1 of the fan blades, or the fan may be geared with a flywheel, or preferably two oppositely rotating flywheels f^2.

In order to ensure the full righting effect of the elevated plane *b* when, consequent on the lateral sliding movement and the maintenance of relative headway, the ship begins to circle or sweep round as a whole towards the side to which it is inclined, a pair of similar wind-driven fans *g* are mounted near the lateral extremities of the aeroplane to rotate about fore and aft axes. *These fans themselves act to diminish circling by reason of the difference in pressure on their surfaces* *to which circling gives rise*,[1] and they may also be geared with the plane *b* in such manner that the difference of rotation of the fans consequent on the circling movement of the ship will by means of cords attached to the plane and wound on drums driven by the fans turn or distort the vertical plane *b* so as to ensure the maximum lateral wind pressure thereon.

The fans *g* or another pair of wind-driven fans may also be used to raise or lower one side of the ship relative to the other and so restore lateral equilibrium by actuating *auxiliary planes or flexible extensions such as* h, h *of the main plane* a. These wing tips h *also operate to reduce circling of the ship* as a whole and consequently to increase the righting efficiency of the vertical plane *b*.

The preferred device for counteracting slow and permanent

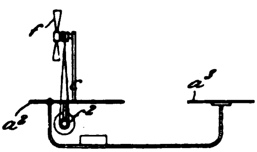

FIG. 2.

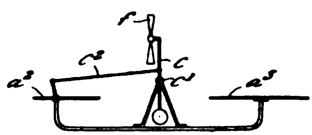

FIG. 3.

Patent 8531/09.

change of longitudinal pose consists in the wind-driven fan *i* which tends to wind a cord *j* on a drum *k* and consequently to tilt the horizontal tail plane *m* through the connection of the cord with an arm *n* rigidly fixed to the rearwardly extending and *vertically springy* rod *o* carrying the tail plane.

In the modified arrangement of wind-driven fan stabiliser shown diagrammatically in fig. 2, the fan *f* is journalled on a standard *c* mounted directly on a forward tilting plane a^2 and is geared with a flywheel f^2 carried by a depending bracket and serving to counterpoise the fan so as to bring the centre of gravity of the fan and its accessories co-planar with the normal horizontal position of the plane a^2. The resistance

[1] An example of the lateral stabilising effect of dead resistances placed towards the lateral extremities of the machine. See pages 219, 220, and onwards to page 226.

to change of translational velocity of the fan *f* causes the plane a^2 to be tilted when the longitudinal pose is disturbed.

In fig. 3, the standard *c* is pivotally supported at c^1 on a bracket rigid with the main frame and balanced by a counter-weight and is connected by a link c^2 with the front plane a^2. The rear plane a^3 may be fixed or it may be linked with the front plane a^2 so as to be automatically tilted simultaneously therewith although not necessarily in the same sense or to the same extent. As before, the plane or planes are tilted when the longitudinal pose is changed on account of the resistance to change of translational velocity offered by the fan.

In fig. 4, the fan *f* mounted on a standard *c* rigid with

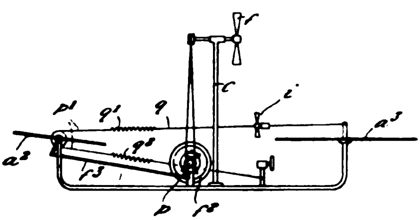

FIG. 4.—Patent 8531/09.

the main frame, drives the flywheel f^2 which is substantially coincident with the centre of inertia of the ship, through a belt and differential gear *p*. The intermediate pinions of the differential are connected with the front tilting plane a^2 by a link f^3 in such manner that the resistance to acceleration of the fan speed (as when the ship sweeps downwards) elevates the plane and thereby counteracts the movement of the ship producing this tendency to acceleration. This figure also illustrates the device for opposing slow and permanent change of the longitudinal plane of movement of the ship. *A wind-driven fan* i *operates to wind a multiple cord* q which is fixed at one end and at the other end is connected through a tension spring q^1 with another cord p^1 which is lapped around the axle of an elevating plane, such as a^2, and connected at its other end through a tension spring q^2 with a fixed point *or*

with a hand-operated device by which the tension of the springs may be varied so as to change the persistent pose of the plane.

I am aware that it has been proposed to maintain the normal longitudinal pose of aeroplanes in various ways, as by varying the area of a head plane or planes automatically by sliding one plane over another by means of a winch on which vanes are mounted, or by tilting a balancing plane or planes by means of a wind-driven fan the spindle of which is kept normally vertical by means of a pendulum but is by suitable gearing deflected through a greater angle with respect to the pendulum than the ship itself assumes on its longitudinal pose being upset. I am aware also that it has been proposed to use power-driven propelling fans as automatic longitudinal stabilisers by mounting them so that they automatically assume an invariable position independent of the momentary alterations in inclination of the ship as a whole, and to such arrangements I make no claim, but

Having now particularly described and ascertained the nature of my said invention, and in what manner the same is to be performed, I declare that what I claim is:—

1. In aeroplanes or the like, wind-driven fans or propellers mounted to impart a normally horizontal thrust to the ship and operating as automatic stabilisers, substantially as described.

2. In aeroplanes or the like, a wind-driven fan or propeller having flywheel effect mounted to impart a normally horizontal thrust to the ship and operating automatically to oppose change of longitudinal pose or of relative headway, substantially as described.

3. In aeroplanes or the like, an elevated wind-driven fan or propeller having flywheel effect mounted directly on the main frame or on a main supporting plane or an auxiliary elevating plane, substantially as described.

4. In aeroplanes or the like, an elevated wind-driven fan or propeller which necessarily has flywheel effect and is mounted either rigidly on an elevating plane or is connected with such elevating plane or planes so as to tilt such plane or planes automatically in a direction to oppose change of longitudinal pose or of relative headway, substantially as described.

5. In aeroplanes or the like, *one or more wind-driven fans or propellers operating by change of driving torque to prevent slow and permanent change of pose or of relative headway by warping or tilting an elevating or main plane or planes*, substantially as described.

6. In aeroplanes or the like, a pair of similar wind-driven fans or propellers mounted at opposite lateral extremities of the aeroplane or the like and actuating differentially one or more elevating wings or other planes, substantially as described.

7. In aeroplanes or the like, a vertical longitudinal plane supported at a height above and clear of the main supporting plane or planes which main plane or planes are practically clear of obstructions to lateral movement, substantially as and for the purpose specified.

8. *In aeroplanes or the like fitted with elevated planes as specified in the preceding claim, arching the main plane or planes transversely* (i.e. *from wing to wing*) *with the concave surface downwards*, substantially as described.

9. In aeroplanes or the like, *heavy masses concentrated at or near the lateral extremities of the aeroplane and operating to oppose change of wing tip speeds and also to give a direct centrifugal righting couple*, substantially as described.

10. In aeroplanes or the like, *heavy masses concentrated at or near the lateral extremities of the aeroplane and operating to oppose change of pose by causing warping or turning of a main or auxiliary plane or planes*, substantially as described.

11. In aeroplanes or the like, *heavy masses concentrated at the forward ends of longitudinal rods or frames extending forwardly from the main supporting or other plane or planes*, substantially as described.

12. In the apparatus of the preceding claim, *supporting the masses at the forward ends of vertically springy rods or frames*, substantially as described.

13. In combination with the apparatus of the preceding claim and of Claims 2, 3 and 4, *a tail plane carried at the rear end of a vertically springy rearwardly extending rod or frame*, substantially as described.

14. In the apparatus of Claims 9 to 13, *substituting for the concentrated masses horizontally revolving wind-driven fly-wheels*, substantially as described.

Dated this 8th day of October, 1909.

ABEL & IMRAY,
Birkbeck Bank Chambers, London, W.C.,
Agents for the Applicant.

N° 6051 A.D. 1910

Date of Application, 10th Mar., 1910
(Patent of Addition to No. 8531, 8th Apr., 1909)
Complete Specification Accepted, 10th Mar., 1911

COMPLETE SPECIFICATION

Improvements in Aeroplanes and the like

I, SAM LEONARD WALKDEN, do hereby declare the nature of this invention and in what manner the same is to be performed, to be particularly described and ascertained in and by the following statement:—

In the Specification to Letters Patent No. 8531 of 1909 I have described the application of wind-driven fans to aeroplanes and the like as automatic stabilising devices and two types of such fans are specified—one type having considerable flywheel effect designed to resist changes of longitudinal pose or relative headway in calm air, and average changes in gusty air, and the other type to prevent slow and permanent changes. In describing the operation of these fans it was pointed out that *in gusty air* the action of the fans was to oppose fluctuations in average pose with respect to a number of quick gusts, there no longer being in such case the required ordered relationship between the pose of the aeroplane and *the instantaneous rate of change of relative* *headway.*[1] Consequently *the rapid changes of relative headway accompanying individual sudden gusts* of a series of such gusts must act on the fans to cause disturbances of the pose of the aeroplane, even although the devices[2] for counteracting sudden changes of pose resist such disturbances.

The primary object of the present invention is to improve or modify the automatic stabilising devices described in the above-mentioned Patent Specification No. 8531 of 1909 by establishing a momentary opposition which may annul or even overpower the disturbing action of the fans on the pose of the aeroplane *when these disturbances are consequent on changes in relative headway so sudden as to be chiefly due to gusts.*[3]

A secondary object of the invention is to help the aeroplane to utilise some of the energy of the gusts for maintaining its flight, by consistently delaying the tendency of the fans *to preserve the relative headway constant* by their up- and down-steering in the gusts.[4]

In carrying out this invention either or both types of fans described in Patent Specification No. 8531 of 1909 may have associated with them similarly wind-driven fans or equivalent devices which are arranged in a like variety of ways to tilt or otherwise operate the planes, but in the opposite sense, that is to say so as to steer the aeroplane downwards for a head gust and upwards for a rear gust. The continuously rotating fan which is associated with the fan having flywheel effect is preferably of greater tilting power than the latter for an instantaneous change of relative headway, but having less

[1] By this is meant, of course, that gusts, as arbitrarily varying impressed accelerations of headway, conform to no such rules as the simple impressed accelerations due to gravity alone—a further intimation that gusts are measured by impressed accelerations of headway comparable with the impressed accelerations, of headway, due to gravity.

[2] Such as the "too-far-forward" centre of mass.

[3] Which was yet another intimation that gusts are impressed accelerations of headway other than those due to gravity.

[4] That is, to give the machine a tendency to obtain a certain amount of the "delay soaring" described on pages 35 to 42, that were written two years after the above specification—itself necessarily based on prior knowledge of an assured nature.

flywheel effect only retards or overpowers the action of the other momentarily on the occurrence of a sudden gust.

Similarly, the other class of fan is arranged to be down-steering to a head gust (and up-steering to a rear gust) but, having less damping action than its associated up-steering fan, it has temporarily and relatively enhanced power in a sudden strong head gust.

As an alternative scheme, or in addition to the provision of the momentarily overpowering fan or fans, *the main supporting plane or other plane or planes preferably*[1] *near the ship's lateral extremities may be designed to produce a tendency to down-steer in head gusts* which increases faster than any tendency to up-steer, apart from that due to the stabilising fan or fans. For example, when an elevating plane carried at the end of a rearwardly extending flexible rod is provided as described in the Patent Specification above referred to, such elevating plane usually producing an up-steering tendency, a more persistent down-steering tendency may be introduced *by so forming the front edges of the lateral extremities of the supporting plane that the wind normally presses on their upper surfaces.* On a sudden head gust, the down-steering tendency increases faster than the up-steering tendency, since the latter is furnished by a surface which *yields* in such a way that its up-steering tendency increases *to a less extent than if it were rigid*, until the up-steering fan[2] has had time to tilt or set up the rear yielding elevating plane.

Using the front edges of the lateral extremities of the aeroplane in the manner above described has the additional advantage of aiding the lateral stability by *producing a righting torque*[3] *when the ship leans and circles to the side it leans to, and if such planes are additionally warped by hand or otherwise, especially if more warped on the side requiring lowering*,[4]

[1] "Preferably," but decidedly not necessarily, so far as longitudinal stability alone may be in view.

[2] Or, under the clause on p. 253, the hand of the aviator, in lieu of the fan, operating the yielding plane.

[3] As explained on pages 209 to 217.

[4] As a general rule, it is good practice to restore the lateral pose of a machine more by lowering the higher side or aeroplane than by raising

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as by means of cranked levers, ***there may be no necessity to steer the ship by a rudder to the side which is being lowered***, as ***has been found necessary in known systems of warping the planes.*** Alternatively, instead of using the front edges of the aeroplane, ***auxiliary down-steering planes may be used at the lateral extremities with the same advantages.***[1]

In the accompanying drawings fig. 1 shows diagrammatically an arrangement in which both types of stabilising fans with their associated auxiliary fans are linked with a tilting front plane, and fig. 2 shows diagrammatically a modified arrangement in which the down-steering or auxiliary fans are optional.

Referring to fig. 1, *a* is a front elevating plane pivoted

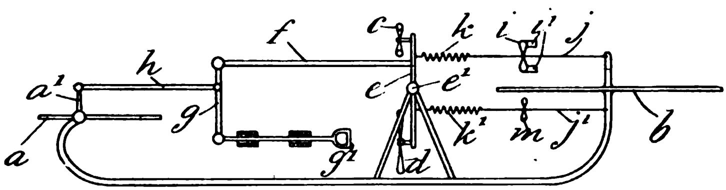


FIG. 1.—Patent 6051/10.

forward of its centre of pressure, and *b* a rigidly mounted supporting plane; *c* is a wind-driven fan which may be of small power, but is either itself loaded so as to have considerable flywheel effect, or is geared with a flywheel, and *d* is a larger fan which has less flywheel effect than the fan *c*. These fans are mounted and linked with the elevating plane *a*, so that fan *c* tilts the plane *a* to steer the ship upwards on the occurrence of a head gust, while fan *d* produces a down-steering effect. This down-steering effect momentarily reduces or overpowers the up-steering effect of fan *c*, so that the upward sweep of the ship on the occurrence of a head gust is

the lower side or aeroplane, because the raising of an aeroplane, or one of the side aeroplanes, always involves a tendency for that aeroplane to lose the headway upon which its lift depends, and bring about a change of course of the whole aeroplane, as well as a general loss of headway.

[1] Of which the planes M_1, in fig. 55, are specific forms not disclosed in this specification.

retarded and, for a very sudden head gust, it may even be preceded by a momentary downward sweep.

As shown in the drawing the fans *c*, *d* are journalled on a normally vertical rod or frame *e*, the former above and the other below a fixed fulcrum e^1 about which the frame *e* can rock in a fore-and-aft vertical plane. A link *f* attached to the frame *e* above the fulcrum may be connected directly with an arm a^1 projecting upwards from the plane *a* or its pivot, or as shown in fig. 1 it may be connected with this arm a^1 through a floating lever *g* and a second link *h*, this floating lever being provided with means such as the guided handle g^1 by which the plane *a* may be tilted by hand independently of and without interfering with the action of the fans *c*, *d*.

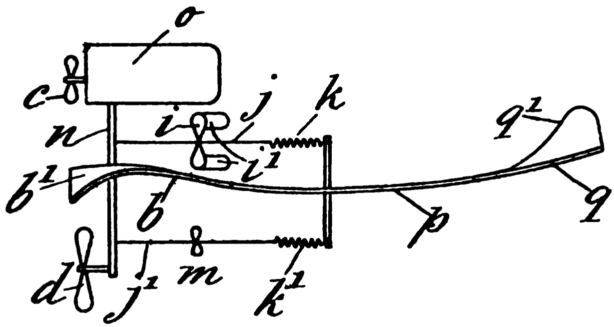


FIG. 2.—Patent 6051/10.

The wind-driven fan *i* which is of the type designed to prevent slow and permanent change of longitudinal pose, is arranged to wind or twist and so shorten the effective length of a cord *j* connected at one end to a fixed point and at the other end through a spring *k* to a point on the frame *e* above the fulcrum e^1. This fan *i* is of greater tilting power than the associated down-steering fan *m* and is suitably damped, as by means of the air vanes i^1. The down-steering fan *m*, which need only be of small tilting power and is comparatively undamped, is mounted in a similar manner to the fan *i* to wind or twist a multiple cord j^1 connected through spring k^1 to a point of the frame *e* below the fulcrum e^1.

In the modified arrangement of fig. 2 the up-steering fan *c*, which may have small power but has great flywheel effect, is journalled at the top of a fixed standard *n* which may also carry an elevated vertical plane *o* as described in the Patent Specification above referred to, and the damped fan *i* is mounted to wind or twist a cord which is attached forward to a fixed point and rearward through a spring *k* to an arm extending upwardly from a sufficiently flexible and elastic rearwardly extending rod *p* carrying a rear elevating plane *q* and also, if desired, a rudder or rear vertical plane q^1. On the occurrence of a head gust the fan *c* and the fan *i* will both act to steer the ship upwards, the latter by tilting the rear elevating plane *q* upwardly.

The temporary retardation or overpowering of these up-steering tendencies may be effected by means of fans *d*, *m* mounted as shown and corresponding in function and character with the fans *d*, *m* of fig. 1, but in lieu of or in addition to these down-steering fans ***the same temporary down-steering effect may be obtained by providing the fixed plane*** b ***with downwardly turned tips*** b^1 ***at its lateral extremities***, the effect of which on the occurrence of a sudden head gust will be to make the ship sweep down or tend to sweep down temporarily until the damped fan[1] has wound up the rear plane sufficiently to overpower the down-steering effect of the plane tips b^1. Though only one central fan *d* is shown, two or more may be used attached to the plane and nearer the lateral extremities.

Having now particularly described and ascertained the nature of my said invention and in what manner the same is to be performed, I declare that what I claim is:—

1. The combination of a stabilising fan having flywheel effect such as described in Patent Specification No. 8531 of 1909, with means adapted to oppose momentarily the tilting or deflecting action of the flywheel fan on the occurrence of sudden changes in relative headway, substantially as described.

2. In the combination claimed in Claim 1, a wind-driven fan of comparatively large power and small flywheel effect, operating substantially as herein described.

[1] Or—under the governing clause of page 253 in the parent specification 8531/09—the pilot himself, in lieu of the fan.

3. In combination with a wind-driven fan adapted to oppose slow and permanent changes in relative headway such as described in Patent Specification No. 8531 of 1909, means adapted to oppose momentarily the tilting or deflecting action of such fans on the occurrence of sudden changes in relative headway, substantially as described.

4. In the combination claimed in Claim 3, a comparatively undamped wind-driven fan of small tilting power operating substantially as herein described.

5. In the combination claimed in Claim 3, *down-steering surfaces preferably at the lateral extremities of the ship*, substantially as described.[1]

6. The arrangement of apparatus according to Claims 2 and 4 in which the associated fans tend to tilt or deflect an elevating plane or main plane in opposite senses on the occurrence of sudden changes in relative headway.

7. In conjunction with stabilising devices such as herein described operating to tilt a plane or planes, means for tilting the said plane or planes independently of and without interfering with the action of the wind-driven fans.

8. The arrangement of stabilising devices substantially as herein described with reference to fig. 1.

9. *The arrangement of stabilising devices substantially as herein described with reference to fig.* 2, *with or without any or all of the wind-driven fans*, c, i, m.[2]

Dated this 9th day of March, 1910.

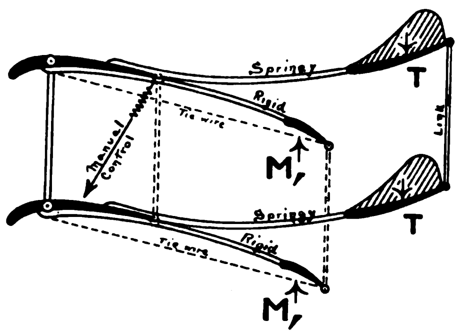
ABEL & IMRAY,
Birkbeck Bank Chambers, London, W.C.,
Agents for the Applicant.

[1] The governing clause, page 253 (parent specification 8531/09), under which the pilot or other known control may be functioning in lieu of the fan, should not be overlooked.

[2] And, under the governing clause (page 253) in the parent specification 8531/09, the fan *d* may be dispensed with, and especially may it be dispensed with when the machine has a main propeller that may render such fan less necessary, as explained in the parent specification 8531/09, page 255, last line and next page; and page 262, about line 23.

INFORMATION SUPPLIED TO THE BRITISH GOVERNMENT

EARLY this year, in addition to other information, a hand-drawn and hand-written copy of fig. 70, but with the dotted



A machine already having warpable tips mav be made more reliably self-warping by the addition of a simple springy rod or frame, carrying the automatically yielding plane T, *at the rear of each tip. In some cases, especially if the original tip was not so cambered as to be down-steering, the rigidly attached plane* M_1 *is advisable. The manual controi may remain, but it will be less used.*

FIG. 70.

lines omitted, was forwarded to the Secretary for War, the

Secretary of the Admiralty, and the Advisory Committee for Aeronautics. In the copy sent to the War Office the lower planes M_1 and T were not drawn, for if the main planes are linked at their rear edges, the upper planes M_1 and T will suffice to operate *both* the main planes of a biplane, provided the main planes are not rigidly braced.

This sketch was forwarded to the Government because they were then using the corresponding mode of longitudinal stability, and possessed machines with warpable extremities to which it would be no trouble to add such simple improving constructions as those suggested by fig. 70. Such additions would, of course, change their machines more or less into three-tailed machines, and as substantially constant-lift machines, independent of headway, they would be enabled to fly satisfactorily at unusually low speeds.

At the same time, a hand-drawn illustration of similar character to fig. 55, but without the control lever there shown, and without any central tail frame or rudder, was sent to each Government Department; and in the covering communication, gyroscopes operating the planes T, T were recommended.

INDEX TO SUPPLEMENT

(*Exclusive of Patent Specifications.*)

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