Catastrophic Instability in Aeroplanes*

The Conditions and Controlling Factors on Which it Depends

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THE object of the present paper is to call attention to and give a brief account of a form of instability that has up till the present time been virtually ignored. In the author's "Aerial Flight," vol. i, page 277, the following note will be found:

"If, secondly, we suppose that the leading edge has too much 'dip' the want of conformity is in the opposite direction, and the surface of discontinuity springs from beneath the leading edge as depicted in Fig. 2 (in contrast to Fig. 1); the result of this is destructive to the whole peripteral system of flow, for the moment the pressure region commences to occupy the upper surface of the aerofoil a condition of instability arises, and a new system of flow is inaugurated which produces a downward instead of an upward reaction. This is a fact demonstrated experimentally; a model in which the adjustment has been carried to its limits will behave in a most capricious manner, sometimes gliding perfectly and at others dropping suddenly in the midst of a flight like a bird when shot."

So far as the author is aware, the above is the only previous mention of the type of instability discussed in the present paper.

According to the suggestion contained in the quotation given, there should be a point when the attitude of an aerofoil is progressively changed, at which a sudden change in the direction of pressure takes place, a reversal, in fact, of the "lift" represented by a sudden change of sign—from positive to negative; with probably a region of ambiguity where two possible systems of flow exist.¹

A large number of forms of aerofoil have been tested at positive and negative angles by many observers, including a comprehensive series of tests by the National Physical Laboratory, and (so far as the author is aware) no such sudden reversal or region of peripteral instability has shown itself; the curves in every case appear to pass without discontinuity from the positive to the negative region as the inclination of the aerofoil is changed. A few typical examples are given in Fig. 5. It will be noted that the point of zero reaction is not usually that of zero angle; this is a point of no importance, it arises from the purely arbitrary habit of measuring the angle of attack from the chord of the section as datum.²

It is evident from the above that although the fact of catastrophic instability, based as it is on actual observation, cannot be disputed, the exploration given in the author's book as above quoted requires reconsideration.

It is yet possible that forms of aerofoil will be found that will show discontinuity in the character of their pressure curve; but in absence of positive evidence, nothing of the kind can with fairness be assumed.

In the first instance we will revert to the study of the simplest of all gliding models—the ballasted aeroplane.

This consists merely of a rectangular plate of mica,³ of aspect ratio = 4, ballasted by means of fishing-shot⁴ at its forward edge, the center of gravity being about one-quarter of its width from the leading edge. The author has frequently demonstrated these gliders in flight before an audience, and though it is usually quite easy, at times they have a most provoking way of starting their flight on an inverted path. In connection with the present subject it is the relation of this inverted flight path to the normal flight path that we shall investigate.

At the outset there is one feature of the ballasted plane to which attention may be drawn—namely, its symmetry; briefly it has no "right side up." Now we know that if any aerodone or gliding model be launched upside down at or about its ordinary flight velocity, its flight path is entirely modified in character; referring to Fig. 6 (Fig. 42 of the author's "Aerial Flight," vol. ii), a number of plottings of the theoretical flight path are given, and by a comparison of curves 2 and 11, or 3 and 10, for instance, we can appreciate the effect of the inversion of the glider at the instant of launching (at the vertical datum line these pairs of curves have the same velocity). Similarly, we might suppose an aeroplane in stable flight on a path, such as 2 in the diagram, suddenly turned over at the vertical datum line, so that its flight path becomes that numbered 11, which is past that which by convention we are accustomed to regard as the limit of stability; the machine is in the act of looping the loop. It is well that in actuality a flying-machine is not liable to be thus suddenly overthrown.

In the case of the simple ballasted aeroplane, however, we do not require to suppose the model turned over. It has no "upside down," and is in effect inverted by any cause that gives rise to a reversal of the pressure system; this may easily take place owing to a gust or eddy, or, as the author has frequently experienced to his discomfort, by a slight want of dexterity in launching.

In Fig. 7 we take O to be the point of launching, the two alternative flight paths, the straight glide and the tumbler curve, are shown by the two lines OA and OB . In OC we have the ordinary parabolic trajectory of a heavy body having the same velocity; it represents, in the equivalent case of an actual machine, the path that would be taken by the aeronaut or other heavy body not strapped in or secured to the machine. The pressure reaction in the case of the path OA being upward, the weight of the aeroplane is sustained. In the case of path OB , the pressure reaction being downward, the curvature of the natural trajectory is exaggerated in the resulting flight path. In Fig. 8 the alternative flight paths are represented more nearly as they would in practice appear; the horizontal straight line of Fig. 5 becomes inclined at approximately one seventh, as representing the coefficient of resistance or gliding angle, and the tumbler curve rapidly degenerates into an oscillatory flight path, owing to damping, which, in the case of the ballasted plane, is considerable. The diagram roughly represents

the flight path in its true proportion to the figure of a man depicted for mica planes such as used for indoor demonstration.⁵

It is evident from the foregoing that the ballasted plane, stable as it is in most respects, is an implement of flight totally unsuitable for aeronautical purposes; it is, using the title of the present paper, "catastrophically unstable." Any serious eddy comprising a sudden down draught, or even the reaction following an up draught, might at any time, without the least warning, reverse the peripteral-pressure region and invert the flight path, with almost certain disaster to the machine and its occupants. But it is not the ballasted plane alone that shows this form of instability; the author has frequently seen a model, whose behavior in the ordinary way is irreproachable, suddenly, when launched in the open air, take it into its head to fly upside down. In one particular case this frequently took place when the model reached the highest point in a tumbler curve flight otherwise at the highest point when looping the loop. At this instant the flight path curvature is greatest, and the tail length tends to modify the attitude of the aerofoil in such sense that catastrophic instability will be shown. In this case subsequent flight followed an undulating path at considerably above the normal speed with the model in an inverted position.⁶ There is, in fact, no reason why we should expect the phenomenon of catastrophic instability to be confined to any one form or type of flight model, though there are certain types that both theoretically and experimentally appear to be immune. Up to a certain point, the capacity of a model or machine to fly upside down may be taken as *prima facie* evidence of its being catastrophically unstable, but it is necessary to draw a distinction between models and actual machines, inasmuch as the constants of an actual machine may be altered at the will of the pilot, and so when flown upside down it may not, in the sense of the present paragraph be the same machine as when in normal flight.⁷ The change contemplated as actually made by the pilot is the variation of the inclination of the tail-plane or elevator of his machine. The essential point here is whether with a single fixed setting of the tail-plane the machine is capable of being flown both the right way up and upside down. It is the setting of the tail-plane corresponding to high speed that will tend to catastrophic instability—i. e., the down-trend position. Thus it is that when an aeronaut acts to initiate a *vol plane*, or to set his machine for a very rapid descent, especially where high velocity is intended, that the greatest danger from catastrophic instability is to be feared. It seems that there should be some check or limit prescribed to the turning downward of the tail members.

In the case of the simple ballasted plane the natural velocity in its two alternative positions is essentially the same, but in the case of the aerofoil of pterygoid form the flight velocity of a model in the inverted position is commonly higher than when the right way up; in the latter, consequently, if reversal should take place, the downfall is greater. A rough estimate indicates that in the case of a flying-machine of ordinary proportions and flight speed, the extent of the drop in the event of reversal, if not corrected by the pilot, might amount to some 600 feet or 700 feet.

Having discussed in a general way the character of the type of instability under consideration, we will proceed to examine more closely the conditions and controlling factors on which it depends. We may assume that the result brought out as the general result of experiment to date, that the absence of any discontinuity in the

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¹Such unstable regions in the attitude of an aeroplane actually exist in certain cases. Recent experiments with a square plane in which, on the one hand, the angle is gradually increased from zero and, on the other hand, gradually decreased from 90 degrees, show that two separate curves in reality exist, and that for over certain range of angle (between α_1 and α_2 in Fig. 3) a condition of instability exists, and the pressure reaction is liable to sudden change as the conditions pass from one curve to the other. It is evident that such a condition of things implies that there are two distinct systems of flow; it is probable that in this particular case the two systems are respectively characterized by vortices transverse to the line of flight for small angles, and vortices parallel to the ends of the plane for the larger angles; the said vortices occupy the dead-water region. Between the limits of angle, α_1 and α_2 , either system may persist. The idea tacitly implied in the passage cited from the author's "Aerial Flight" is that a similar condition of instability exists about the region when the reaction changes from positive to negative, as shown diagrammatically in Fig. 4. This view is negated by the experimental evidence that up to the present has been accumulated.

²It is easy to see that the measurement of angles from the chord of section is an arbitrary measurement, inasmuch as an extension of the aerofoil surface, forward or backward, to follow accurately the streamline flow will give an entirely new angle as measured to the chord without involving an essential alteration to the aerofoil from an aerodynamic standpoint.

³Mica is by far the best material available for the purpose, being as stiff as tempered steel, and but one-third the weight.

⁴Lead shot split half-way through.

⁵A mica plate about 2 inches by 8 inches; weight with ballast about 6 grammes.

⁶Compare "Aerial Flight," vol. ii, section 175.

⁷In the recent experiments of M. Pegoud, for example, there is no reason to suppose that the tail-setting was the same in the inverted position as in the normal flight.

pressure reaction holds good in all cases, and that the phenomenon under discussion therefore is not due intrinsically to any properties or individuality of the aerofoil. The following may consequently be laid down:

1. There must be a change of attitude of the aerofoil simultaneously and corresponding to the inversion of its flight path.

2. The change of attitude must take place in a sense that will cause the after or tail portion to move towards the pressure side—that is to say, when the pressure side of the aerofoil changes, the tail must swing in the corresponding direction. Conditions 1 and 2 are illustrated by the behavior of the ballasted plane in Fig. 8.

3. The model being by hypothesis rigid, the change in the attitude of the tail or directive member will be of like sense and equal in degree (equal angle) to that of the aerofoil itself.

4. A flight model or machine whose mass center coincides approximately with the center of pressure of its aerofoil, fitted with a tail-plane of ample area, will be catastrophically stable (example, author's 1894 model, Fig. 9), for the directive member (the tail-plane), carrying neither positive nor negative load, cannot change its attitude as necessitated by the reversal of the pressure reaction.

5. A flight model or machine designed with the mass center forward of the center of pressure of its aerofoil, so that the tail-plane carries a negative-pressure reaction, will be catastrophically stable, for its change of attitude consequent on the reversal of the pressure reaction is the reverse to that laid down in (2). If it is capable of flight one way up, it cannot possibly be capable of flight when reversed.

6. A flight model or machine designed with the mass center aft of the center of pressure of the aerofoil, so that the tail-plane carries positive-pressure reaction, behaves in accordance with condition (2) and may be catastrophically unstable.

7. The conditions that define the limit of catastrophic stability are closely akin to those that define directional stability in the vertical plane. If both aerofoil and tail-plane follow the law that reaction varies as angle, and if the influence of center-of-pressure changes be ignored, and if the tail-plane be arranged clear of the wake stream, the limiting conditions may be regarded as identical, and it would be virtually impossible to design a model to be directionally stable and show catastrophic instability.

8. A model or machine whose tail plane or member is loaded up to a point approaching the limit of directional stability (in a vertical plane) may be catastrophically unstable as the result of one or all of the following causes:

(a) The aspect ratio of the tail-plane being relatively low when compared to the main aerofoil.*

(b) The movements of the centers of pressures of both the main aerofoil and the tail-plane with changes of angle (owing to these movements contributing to the directional stability without contributing to the catastrophic stability, as in the ballasted plane).

(c) The influence of the "wash," or downward wake stream of the main aerofoil, by its influence on the flight attitude.

From the point of view of the present paper, one is inclined to direct a certain amount of criticism to some

*The importance of the relative aspect ratio of the aerofoil and tail member is due largely to the different character of the pressure law and the changing values of the constants where the aspect ratio differs in any considerable degree. It is established that for aeroplanes of high aspect ratio the reaction for small angles is approximately directly as the angle, whereas for aeroplanes of extremely low aspect ratio it more closely follows the $\sin^2$ law of Newton (see "Aerial Flight," vol. i, sections 150 and 151). It is consequently possible by designing a tail like that of a pheasant, of low aspect ratio, to reach a condition of catastrophic instability without destroying the directional stability in the vertical plane. A good illustration of the effect of aspect ratio in the present connection is given by the author's experiments of a falling "T," as shown in his lectures before the Royal Society of Arts and elsewhere.

of the features commonly met with in actual flying-machines, though it might be rash positively to assert that catastrophic instability has as yet been the cause of disaster.⁹ In the author's opinion it would be wise to avoid the deliberate loading of the tail member, its function should be purely directive. The author has always found that in practice a tail carrying no load or even slight negative load is preferable in model experiments. It would also appear to be desirable to pay attention to the tail member, giving it an aspect ratio comparably equal to the main aerofoil.

With due attention to these two points, and with the reasonable curtailment of the fore-and-aft dimension of the aerofoil, giving it a good pterygoid section and aspect ratio (abandoning all idea of obtaining stability from the movement of the centers of pressure on the aerofoil and tail members in the manner of the ballasted plane), and with a "stop" or limit to the elevator or tail control, there can be very little danger in the future of any disaster from the cause under discussion. Experiments also might be made with scale models in a wind channel to determine definitely the conditions as to upside-down flight, to prescribe limits of safe-load distribution and safe tail or elevator angles of adjustment, for any given model.

Flexibility of the aerofoil has an important bearing on the catastrophic stability, classifying such flexibility as weather-vane flexibility (as in a bird's wing) and drum-skin flexibility; it may be said in brief that weather-vane stability in the aerofoil tends to stability, and drum-skin flexibility to instability.

Catastrophic stability is not definitely related to the other well-known kinds of stability involved in the problem of flight; in order to realize more completely the true position it is of interest to digress and review the different forms of instability known and comprised in the ordinary treatment (mathematical or otherwise) of the problem.

There is, firstly, the whole question of longitudinal stability, involving (a) the stability of the machine relatively to its transient flight path—namely, as in the stability of an arrow, and (b) the stability of the flight path itself in relation to the direction of gravity, as dealt with by the author in his "Phugoid Theory." Both the above (a) and (b) involve complex questions of oscillations about the position of stable equilibrium and the damping of such oscillations as may be set up by disturbing causes. Secondly, there is lateral stability (superficially analogous to the stability of a ship), in which, also, the problem is complicated by considerations of oscillatory motion; thirdly, there is directional stability, concerned mainly with rotary motion about a vertical axis; and, fourthly, there is a kind of stability known as spiral or rotative stability concerned with the interaction of motions separately considered under the last two headings. All these kinds of stability have been made the subject of previous study, both by the author's method and by the mathematical method of Dr. Bryan; but the kind of instability dealt with in the present paper is entirely external to the conditions on which the two lines of treatment mentioned are based; it is presumably owing to this fact that the possibility of what in the present paper is termed "catastrophic instability" has been so widely ignored.

In the case of a machine or model that will fly either way up there are two entirely different sets of constants, each set giving equations satisfying the conditions of stability, but there is no necessity for relationship between the two; we may, in fact, look upon the model in its two positions as two different models; in the case of the ballasted plane and other symmetrical forms the two equivalent models may be regarded as duplicate.

Although the existing theories of flight enable us to deal individually with either of the two systems of flight,

⁹The recent accident to Major Merrick, which unfortunately cost him his life, and which took place some few weeks after the reading of the paper, appears to have been clearly due to catastrophic instability.

of which a given model is capable, they take no account of the possibility of a translation from the one condition to the other; anything of the kind is tacitly ignored.

As a concluding illustration of the importance of the present study we may revert to the case of the ballasted plane and compare the magnitude of single gust required to destroy the longitudinal stability with that required to exceed the limit of catastrophic stability. Referring to the chart (Fig. 6) we know that the limit of stability for longitudinal oscillation is reached in the case of the semi-circular path—that is to say, $\sqrt{3}$ times the natural velocity is the limit with the flight path horizontal. In other words, a head gust $\sqrt{3}-1$, or say, = 0.7 of the velocity of flight is required to bring about risk of disaster. Against this, in order to induce catastrophic instability, we only require a vertical gust well in excess of the vertical component of the angle of incidence, or, say, one sixth of the velocity of flight, so that, in the case of the ballasted plane, in order to change entirely the system of flight and induce catastrophic instability, it only requires a gust of about a quarter the magnitude that it requires to reach the limit of longitudinal stability. It is evident that where there are two systems of flight—that is to say, where a model will fly either way up—in no case can we afford to ignore the considerations raised by the present paper, and, in short any such model must be regarded with the gravest suspicion by the aeronautical designer.

Speeds for Turning Unusual Materials

THE *Practical Engineer* gives the following information on turning unusual materials: Slate, on account of its peculiarly stratified formation, is rather difficult to turn, but if handled carefully, can be machined in an ordinary lathe. The cutting speed should be about the same as for cast iron. A sheet of fiber or pressed paper should be interposed between the chuck or steadyrest jaws and the slate, to protect the latter. Slate rolls must not be centered and run on the tail-stock. A satisfactory method of supporting a slate roll having journals at the ends is to bore a piece of lignum vitae to receive the turned end of the roll, and center it for the tail-stock spindle. Rubber can be turned at a peripheral speed of 200 feet per minute, although it is much easier to grind it with an abrasive wheel that is porous and soft. For cutting a rubber roll in two, the ordinary parting tool should not be used, but a tool shaped like a knife; such a tool severs the rubber without removing any material. Gutta percha can be turned as easily as wood, but the tools must be sharp and a good soap-and-water lubricant used. Copper can be turned easily at 200 feet per minute. When machining commutators that is the speed commonly used. Light cuts are taken with a pointed tool and the surface is finished with a wooden buff lined with glass paper. This buff is in the form of a 90-degree segment and is approximately 1 1/4 inches thick. It is held against the commutator with the point of an ordinary tool and is fed back and forth across the surface. In this way the segments are gradually ground down until there is not the slightest gap or break between the copper segments and the mica insulation. Bath stone such as is used in the construction of pillars for balconies, etc., can be turned at 150 feet per minute, and the formation of ornamental contours is quite easy. Marble is a treacherous material to turn. It should be cut with a tool such as would be used for brass, but at a speed suitable for cast iron. It must be handled very carefully to prevent flaws in the surface.—*Machinery*.

Polar Bears in Arctic Exploration.—*Petermanns Mitteilungen* and other entirely serious-minded European journals state that Capt. Sedov's Russian arctic expedition, now in the field, proposes to utilize tame polar bears for drawing the sledges of the party on its journey from Franz Josef Land to the pole.