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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 485

RESEARCH ON THE CONTROL OF AIRPLANES

By B. Melvill Jones

From Nature, May 12, 1928

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RESEARCH ON THE CONTROL OF AIRPLANES.*

By B. Melvill Jones.

An essential factor in the control of anything, whether it be a motor car, a ship, or an airplane, is some means of applying the necessary force in the desired direction. The car requires its steering wheel, the ship its rudder. But this is not the only factor which decides the character of the control, whether quick or slow, difficult or easy. Other factors inherent in the craft to be controlled have to be considered. One such factor is inertia. A motor car has very little inertia compared with the forces which can be exerted through the road wheels; consequently, it responds at once to a movement of the steering wheel, and the turning stops immediately the wheel is centralized. A ship has great inertia compared with the force exerted by the rudder; consequently the rudder must be applied some time before an appreciable turn is started, and reversed against the movement long before the ship has swung to its new course. The character of the control of a ship is thus entirely different from that of a car, on account of this factor of inertia, which has nothing to do with the controls themselves.

Another factor is the stability or instability of the motion when the controls are not moved. A stable motion is one which,

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if slightly disturbed, will settle back into its original form; an unstable motion is one which, after a slight disturbance, will depart further and further from the original form. In a modern car, the pivots about which the wheels turn in steering are arranged like the casters of a chair, so that the wheels have a slight tendency to turn to the side towards which the car is trying to slip. If the car moves round a curve, the centrifugal force makes it try to slip outwards, and the wheels, left to themselves, turn outwards and straighten the path. Such a car is stable and easy to drive straight; if the wheels had the opposite tendency, it would be unstable, and the driver would have continually to be correcting tendencies to swerve to one side or the other. An unstable car is not impossible to control, and may even, by practice, come to be controlled by unconscious reflex action, with no more fatigue than is felt in walking, but experience has shown that it is better to make it stable. It should not, however, be too stable, for then it will be heavy to steer round corners at high speeds, when the centrifugal force is large, and it will try to run down hill, so that, when travelling on the side of the camber of the road, it will have continually to be held out of the ditch.

The motor car thus illustrates some important points which are common to the control of any kind of craft: although the control of an unstable craft may not be impossible, stability is on the whole desirable, but too great stability may introduce other undesirable qualities and may be as bad or worse than instability. A condition which might be described as benevolent neutrality is generally sought.

Again, a craft may be stable, in the sense that it tends to return when disturbed from a straight path, but it may overshoot on the other side farther than the original deviation, so that an oscillation of increasing magnitude may arise. Such an increasing oscillation is said to contain a negative damping term. Conversely, an oscillation which tends to decrease is said to contain a positive damping term. An example of a negatively damped oscillation occurs when a yacht's dinghy, loaded by the bows, is towed by a short rope. As the tow rope is shortened the dinghy starts to yaw from side to side with increasing violence and may ultimately be swamped.

A negatively damped oscillation is difficult to control; an inexpert hand on the controls generally makes it worse. It is even possible to convert a truly stable motion into an increasing oscillation by inexpert use of the controls; this is generally due to lag, or the time interval between the impulse to control and the muscular response.

Long before successful man-carrying airplanes were developed, a division of opinion on matters of control was apparent. One side, which contained on the whole the practical men who tried to fly themselves, was mainly concerned with providing control organs and acquiring the skill to use them. The other side, which contained mainly the theorists and the constructors of uncontrolled models, were mainly concerned with the stability of the uncontrolled craft. This division of opinion continued well into the war, and traces of it are still present. A short historical sketch of this controversy may serve to make the present situation more clear, and the sketch can be used to illustrate certain important points in the control problem.

The great problem before the protagonists of the control school was to remain alive long enough to achieve sufficient practice and to perfect their apparatus. Their difficulty was greater than they could guess. Nature laid a trap for them, the full cunning of which we are only just beginning to realize. To understand this trap we must look a little into the matter. The first essential of steady flight is that the air shall exert a lift on the wings equal to the weight of the airplane. This lift depends upon speed through the air and upon the incidence, or angle, at which the wings strike the air. A typical relationship is shown in Figure 1. If, in this example, the airplane weighs 2000 lb., it cannot be supported at speeds less than 50 M.P.H. At high speeds support can be obtained at a small angle of attack, but if the speed drops slowly towards 50 M.P.H., a point is reached at which the angle will have to increase rapidly, and just above 50 M.P.H., flight will be possible at two alternative angles, one considerably larger than the other. The minimum possible speed is called the stalling speed; the critical angle, at which the minimum speed is just possible, is called the stalling angle, and the airplane flying above this angle is said to be stalled. So long as the speed is considerably greater than the stalling speed, the achievement of stability and control is relatively easy, but as the speed falls and the stalling angle is approached, changes occur in the air flow about the wings which, unless special precautions are taken, render the airplane violently unstable and simultaneously destroy the power of control.

Now the nature of the trap is perceived. The early pioneers perhaps succeeded, with the help of the wind, in taking off at a speed greater than the stalling speed, which for their airplanes was very low. Possibly they carried out many flights without stalling and, delighted with the ease of control, were emboldened, on some favorable day, to glide to a considerable height above the ground. Sooner or later they were bound to stall and, if high up at the time, to kill themselves; for the motions following a stall are peculiarly violent, and liable to lead to heavy impact with the ground.

Herein lay the wisdom of the Wrights, the greatest exponents of the control school of thought. Warned by the experience of others, they suspected some such trap, and never in all their early work allowed themselves to get more than a few feet from the ground. They must have experienced the stall or the approach to the stall, for they discovered what is now known to be the simplest, though not the only counter to it - a powerful rudder. That was the turning point in aeronautics, when the Wrights managed to get trained in control without being trapped and killed by the stall. After this, increased engine power and experience enabled the stall to be avoided more easily, and deaths from this cause became relatively less frequent, though it has still remained the principal cause of fatal accidents up to the present time. Early progress, however, lay all in the improvement of normal flight, and the study of the stalled condition was not taken up seriously until after the war.

The Wrights achieved their success with an airplane which was definitely unstable in several ways, counteracting the effects of this instability by acquired skill. Early design naturally followed this lead, and stability came to be regarded by many of the pioneer flyers as of no practical interest and indeed, as a kind of bogy, invented by scientists for their own glorification. After a few important but not fundamental changes from the form in which the Wrights created them, control organs crystallized by about 1911 into a form typified by the BE 2 airplane, produced in the Government factory at Farnborough, under the guidance of Geoffrey de Havilland. Since that time the method of control, except for the introduction of balancing devices to lighten the pilot's effort on large airplanes, has scarcely altered, and the interest in the story shifts to the side of stability.

In 1896, Langley had worked out the general principles of stability sufficiently to make a model, driven by a small steam engine. This model was so stable and well balanced that it flew a distance of more than three-quarters of a mile.

About the same time, Lanchester, working with smaller gliding models, succeeded in unraveling the complicated factors which influence the stability of an airplane in normal flight (below the stalling angle), and his results, which he collected in a volume published in 1908, contained in essence most of the principles of practical importance which we employ today in the calculation of stability.

About 1911 two interesting things happened. Captain Dunne made and flew successfully his remarkable tailless airplane with swept-back wings, which was undoubtedly extremely stable, probably far too stable for comfortable flying; and Professor Bryan published a book in which he showed how calculations upon the stability of airplanes could be brought into line with conventional mathematics. Dunne's line of development was not followed up, but we shall see something of the sort cropping up again towards the end of this lecture. Bryan's book was the foundation of modern methods of calculating stability.

Bryan's idea was to measure the effects of simple disturbances, such as rolls or pitches, separately, and thus to obtain a number of characteristic quantities, or 'derivatives' as they are called, which could be used in the calculations of stability.

He did not have the means to make the necessary measurements, but the scientists of the National Physical Laboratory, who were already in possession of wind tunnels, set to work to determine these quantities for small models and to make the necessary calculations along the lines which he had indicated. The experimental campaign so started has been in progress ever since.

The application of this systematic study of stability to man-carrying airplanes was first made in the Government factory at Farnborough by Busk. He modified the unstable BE 2A into the stable BE 2C by relatively small changes in the position of the center of gravity and in the area and arrangement of the fixed surfaces on the end of the tail. This was a distinct step forward, and much notice was taken of it in the press, where the opinion was freely expressed, mainly by non-flyers, that the safety of flying was now assured. This view was wrong; the provision of stability alone is not sufficient for safety, as Busk and his fellow-workers well knew. Safety is mainly concerned with the taking off and landing of airplanes, when a rapid response to control is even more important than stability.

The opposing school of thought - lineal descendents of the pioneer flyers - were naturally aggravated by this widely advertised and erroneous view of the relation between safety and stability, and the breach between the two schools widened still further, culminating in two extreme examples, the very stable SE 5, produced in the Government factory at Farnborough, and the very unstable Camel designed by Sopwith. These two airplanes, diametrically opposed in every feature relating to stability, shared between them the brunt of the single-seater fighting during the later stages of the war; opinion ran high concerning their relative merits and the lines of thought which they represented. Readers of that remarkable diary "War Birds" will find the view of the supporters of the SE 5 forcibly expressed, but I have heard the other side equally strongly maintained. These two airplanes marked the culminating point in the controversy to which reference has been made. Later development has been all towards compromise, slightly on the stable side of neutrality: benevolent neutrality as I have called it.

Though the experimental technique and the mathematical calculations necessary for a thorough study of control and stability are difficult and elaborate, the main results are simply and easily stated.

The pitching motions of an airplane depend upon what is called its weathercock stability. An airplane hung up in a wind so that it can rotate about a horizontal axis through its center of gravity has weathercock stability if, like a weathercock, it desires to face the wind and returns to its original attitude on being disturbed. As with a weathercock, this kind of stability is increased either by moving the pivot - in this case the center of gravity - forward, or by increasing the area of the tail.

A free flying airplane which has this form of stability will, if disturbed from steady flight, first rotate rapidly so as to restore the angle of attack to the equilibrium value and then execute a series of long slow pitching movements, similar to a ship travelling over ocean waves. The length of these waves from crest to crest is between ½ and 1 mile, and the time taken some 30 seconds. These movements are so slow that they have little influence on control.

The weathercock unstable airplane, if pivoted like a weathercock, would very quickly turn round and face backwards. If this happened in free flight it would be unflyable, except by a pilot with the skill of a juggler, but it does not happen. Suppose the airplane is flying freely and the nose is accidentally deflected upwards; being unstable it will throw up its nose still farther, but at the same time the increased angle of attack will cause it to leap upwards with great suddenness. The direction of motion is thus rotated upwards faster than the airplane itself, so that the first quick adjustment is a fall of the angle of attack to nearly its original value. Afterwards the upward tilt and upward trend of the path increase relatively slowly, until the airplane slows up and stalls. There is, however, ample time for the pilot to correct this subsequent motion, provided that his attention has not wandered. This is the reason why the Wrights and others were able to fly airplanes which were unstable fore and aft.

So long as the instability is not too great, the airplane, like the motor car, can be controlled effectively whether it is stable or unstable. As in the motor car, too great stability is definitely objectionable, partly because heavy forces are then required to execute rapid maneuvers and partly because heavy forces, or adjustments of some sort, are required to 'trim' the airplane for different speeds. For alterations in speed must be accompanied by changes in angle of attack, which in a very stable airplane will require large control forces. A neutral airplane, on the other hand, if trimmed for one speed, will be in trim for other speeds within a wide range. The problem here before the designer is so to adjust the center of gravity and the tail areas as to produce a very slightly stable airplane.

The rolling and yawing motions of an airplane can also be simply described, though in detail they are very complicated.

When the airplane rolls the falling wing meets the air at a larger angle than the rising wing and experiences a greater lift; a very large couple opposing the roll is thus generated. This is the predominating factor in the lateral control, for it prevents rapid rolling and gives the pilot time to observe what is happening and correct it. This is the reason why the Wrights could control an airplane which was laterally unstable.

If the airplane has a 'dihedral angle' - tips of the wings higher than the middles - sideslip tends to raise the wing towards which the slip is occurring. If it has a large vertical fin on its tail, it will turn or yaw towards the slip. In normal flight the dihedral angle has a powerful stabilizing influence, because if one wing falls below the other, sideslip will occur towards that wing, and a couple will be generated raising the wing.

An airplane which has too large a vertical fin on its tail and too little dihedral angle will have what is called spiral instability; if slightly disturbed from straight flight, it will continue to roll and turn from its course, and ultimately descend in a spiral curve. This motion is, however, so slow in developing that it is of no importance so long as the pilot is in control, but like other forms of instability it is undesirable, particularly when long flights are contemplated.

Another motion possible to an uncontrolled airplane consists of a complicated rolling and yawing oscillation, generally of about six seconds period. This will become unstable and render the airplane practically unflyable if the vertical fin in the rear is too much reduced. Thus the exact proportions of these fin surfaces is a matter of great importance; if they are too small, the relatively quick oscillations will become unstable, with disastrous results; if they are too large, the slow spiral instability, which on the whole is undesirable, will occur. The problem is eased by giving a good dihedral angle, for this widens the limits permissible in fin size, without incurring either of these defects.

One other fact of interest has only lately come to light. If the dihedral angle is too small, the short-period oscillation to which reference has been made may become of the type which is caused to increase by a control which contains a lag. As there is always some lag between the pilot's intention and his performance, this latent defect may cause trouble; even though it may not be so bad as actually to cause the oscillations to increase, it may lead to great difficulty in damping them down. In bumpy weather, therefore, the oscillations may be continuous from one air bump to the next, with disastrous results both on the strength of the pilot and the stomachs of the passengers. The improvement in the bad weather qualities of some of the later cross-channel airplanes is attributed partially to increased dihedral.

No more need be said now about control in normal flight. In what precedes an attempt has been made to explain why the provision of good control qualities is more a question of proportioning the airplane and adjusting its load properly than of devising new control organs.

This brings us to about the end of the war. More data have accumulated and measurements have been refined, but most of the foregoing statements might have been made then. The trap which killed the early pioneers still, however, continued to take its toll of life, though in a much lower proportion to the hours flown. Ample power had become available to allow the normal flying speed to be so much greater than the stalling speed that accidental stalling became rare, except when a pilot was deliberately flying slowly with the object of making a landing. When it did occur, however, the same consequences followed as with the early pioneers; but the danger was increased, because of the higher loading and consequent heavier impact of the later airplanes. Throughout the history of flying to the present day this has been, and still remains, the most frequent cause of fatal accidents.

Shortly after the war, the British Research Committee for Aeronautics started a research campaign into the causes and cures of this trouble. The research was carried on in wind tunnels, by theoretical work, and in actual flight at heights sufficient to rob the stall of its danger, with the result that the principles underlying the matter are now understood and several ways of eliminating the danger are known.

One small part of this campaign of research is being carried on by the University Air Squadron at Cambridge. Our task is to endeavor to obtain precise experimental records of the motions of stalled airplanes, both when left to themselves and when the pilot is trying to control them. The apparatus which we use was developed and constructed at the Government Research Establishment at Farnborough and loaned to us for the purpose. It consists of a box containing three gyroscopes which are slightly deflected against a spring control when the airplane is turning. The deflection of each gyroscope is proportional to the rate at which the airplane is turning about some particular axis, and they are arranged so that, between them, they measure the three rates of turn about three axes mutually at right angles. These three records are recorded continuously upon a moving photographic film. Three other instruments record independently the movements of the three controls - elevator, rudder, and aileron - and all these records are synchronized from a central clock, which records half-second intervals on all the films.

Figures 2-9 show some graphs drawn from records selected from more than a hundred sets which we have obtained. These results, which will now be described, have all been predicted, at least in their general features, by calculations based on wind-tunnel observations of the forces acting upon models supported in various ways in the wind tunnels of the National Physical Laboratory and the Royal Aircraft Establishment. The wind tunnel experiments and calculations were made long before precise records in free flight had been obtained, but for lecture purposes I shall reverse the chronological order of the events and describe the results first before explaining why they occur.

Figure 2 shows a record of one such flight. The experiment began at the vertical line marked 4 seconds, when the elevator was pulled right back and the angle of the wings (not shown in the figure) was between 19° and 20°. From that time the controls were held fixed until 16 seconds, when the experiment ended. This experiment began exceptionally favorably, with no rotation of any importance occurring. Straight flight continued undisturbed until 10 seconds, when some slight disturbance started the unstable motion characteristic of this airplane at this angle of attack. Increasing rates of rolling and yawing, both to starboard, were then recorded, which in six seconds had grown to some 30° per second. The airplane by this time had rolled through some 60° from the horizontal, and the pilot then stopped the motion by pushing forward his elevator and reducing the angle of the wings below the stalling point. The rapid check to the roll which followed this last control movement should be noted. The reason why a rapid roll at a low angle of attack is impossible has already been explained.

Superimposed on this unstable motion is a slight rolling oscillation; this feature of the movement is by some accident more clearly shown in Figure 3, where the amplitude of the roll is seen to increase automatically.

This particular airplane at this angle of attack shows, therefore, two distinct forms of instability, one technically known as a divergence, which approximately doubles itself in every second, and the other an oscillation with a tendency to increase.

Figure 4 shows the effect of applying ailerons, in straight stalled flight, at about 20° angle of attack. For the first second after they are applied the airplane rolls in the direction to be expected, but almost immediately its direction of roll is reversed and it plunges wildly over on the opposite side.

Figure 5 shows that this failure of the ailerons is even more marked when they are used to check a roll which has already started.

Figure 6 shows that the rudder, applied in straight flight, has the desired effect of turning the airplane, but that it also causes it to roll in the sense that the wing which is being pushed forward, rises.

Figure 7 shows that the rudder can be used to check a roll which has already started, if it is applied so as to reverse the turn which accompanied the roll (i.e., to push forward the falling wing tip). The delay in the action and the violence of the reversed roll which follows should be noted.

Figure 8, however, shows that if applied too late the rudder may, in certain circumstances, fail to check this unstable motion, though for the first two seconds after it was applied it appeared to be going to succeed.

Figure 9 shows the ultimate history of an attempt to control these unstable motions by means of the rudder alone; note the liability of the oscillation to increase despite the pilot's efforts to check it.

These results have been chosen because each shows some particular aspect of the matter clearly. In many of the other results obtained these various aspects are so mixed together that a practiced eye is required to disentangle them.

The utter uselessness for any practical purpose of control with the above characteristics requires no emphasis.

As has been stated, these results can all be explained, in general terms, by mathematical analysis based on data obtained from wind tunnels, and though the analyses are intricate the broad explanation can be given simply.*

The primary cause of the trouble lies in the change, when the airplane stalls, of the effect of rolling upon the rolling couple. Instead of a large couple opposing the roll being generated, as in normal flight, a slight couple is generated in the sense to increase the roll. This is because (see Fig. 1 at 20° angle of attack and above) the increased angle of the falling wing tip no longer increases the lift upon it, but slightly decreases it. There is thus nothing but the inertia of the airplane to prevent rapid rolling. The complicated effects of inertia, such as those we observed in relation to ships at the beginning of the lecture, are thus introduced, and the valuable factor of time for the pilot to think is absent.

The instability of the motion is easily explained. When a stalled wing rolls there is not only a slight couple increasing the roll, but in addition a couple tending to retard the falling wing. This is because drag increases very rapidly with increase of angle of attack on a stalled wing. Now in stalled flight,

*The explanations which follow will be more easily understood with the help of a model airplane which can be held in the hand and moved in the ways described. Failing a model airplane, a piece of card in the form of a T to represent wings and body should suffice.

even a small rate of yaw generates a large rolling couple depressing the retarded wing. This is partly because the advancing wing is traveling faster than the retarded wing and partly because of the sideslip which follows the yaw. (It has been found that the rolling moment produced by sideslip is, for some as yet unknown reason, very much greater on a stalled than on an unstalled wing.) Any slight disturbance in yaw therefore generates a rolling couple, and the resulting roll both tends to increase itself and to cause the rate of yaw to increase still further. Such a process is obviously cumulative.

The increasing oscillation can also be explained, but the explanation is too involved to be given in the time at my disposal.

The outstanding feature of the whole problem is, however, the great influence of yawing motions on rolling couples, and this should be borne in mind when the action of the controls is considered.

The characteristic feature of aileron control in stalled flight is that, while the rolling couple which they can exert is weak, they also exert a powerful yawing couple retarding the wing tip which they are trying to raise. This starts the airplane yawing, and a large rolling moment is soon indirectly generated by the yaw, which entirely swamps the direct action of the ailerons. The apparent success, in Figures 4 and 5, of the ailerons, for the first second after their application, followed by complete failure, is thus explained.

The action of the rudder in causing the airplane to roll, so that the retarded wing falls, is now easily understood; the roll follows after yaw has been generated. The difficulty of using the rudder in a way which will not cause an increasing oscillation arises from the fact that its effect on roll is delayed until it has succeeded in generating a yaw. We saw in the beginning of the lecture that delay in the control of a motion which automatically tends to increase, is fatal.

To sum up. The motion is violently unstable in two ways. The ailerons are a positive source of danger, since they produce an effect which at first appears satisfactory but is ultimately the opposite of that expected. The rudder, though effective, provides a kind of control very difficult to use and, moreover, is often too weak even to prevent the first unstable plunge from continuing.

The continuous series of accidents resulting from accidental stalls near the ground are thus explained, for, though the motion can always be checked by thrusting the stick forward, and so diving to regain speed, this remedy is of no use when the ground is near. The pilot's reflex response when he finds himself suddenly rolling over and diving into the ground is to pull the stick back and to the side away from the roll. This, as we have seen, has disastrous results.

There are two lines along which a cure can be effected. One is to eliminate the instability and the other to improve the control. After what has been said above, there will be no difficulty in realizing that the final solution will be along both lines.

The simplest way of improving the control was that originally used by the Wrights: to supply a powerful rudder. This prevents the worst consequences of stalling, but it does not, as we have seen, provide a satisfactory control. Moreover, it can only cause the airplane to roll after it has started it yawing, and this may be very undesirable if there happens to be a house or tree on the side towards which the yaw has to be made. An effective rudder, however, though not a sufficient cure, is a necessary factor in any complete cure.

Another solution is to provide some form of control at the wing tips, which will lift the wing powerfully and simultaneously push it forward, rather than push it backwards, as does the standard aileron. The yawing action of the aileron will thus indirectly reinforce the direct rolling action, instead of opposing it as at present. There are several ways of doing this; one is to provide a surface beyond the wing tips which, even when the main wings are stalled, will be inclined downwards so as to meet the air edgeways. This surface will not itself be stalled, and if its angle is controlled by the pilot it can be made to exert either an upward and forward or a downward and backward force, which is just what is required. Such surfaces will also prevent rapid rolling and eliminate the instability. This device is used in Hill's Pterodactyl, a tailless airplane, which is said to be as stable and controllable when stalled as in normal flight.

A second method of achieving the same result is to place one of Handley Page's slots in front of the wing tips. If these slots are left permanently open they will delay the stall on the tips until long after it has occurred on the remainder of the wings; the characteristics of unstalled wings which prevent rapid rolling from occurring will thus be retained, and the tendency for rolling to cause yawing will be eliminated. Stalled flight then becomes very stable and easily controlled, though the rate of control is not rapid. If in addition the slots are interconnected with the ailerons, so as to close on the side to be depressed, but to remain open when the stick is central, the power of rapid control will be secured in addition to stability, for the closing of the slot will cause the wing tip to stall, with a consequent large loss of lift and increase of drag by comparison with the other tip on which the slot remains open. The large direct rolling moment generated in this way is thus reinforced by the indirect effect of the yawing moment resulting from the increased drag on the wing tip which it is desired to depress. This is the reverse of the action of normal ailerons, which exert an increased drag on the wing which it is desired to raise.

Unfortunately, the slots cannot be left open permanently, because the wings will then absorb too much power in normal flight; hence schemes have had to be devised to cause them to shut automatically, when the angle of attack falls below the stalling angle. Handley Page has devised one very successful method of doing this, of which accounts have been given in the daily press. Another somewhat different method of doing the same thing has been devised by McKinnon Wood at Farnborough.

Which of these methods will ultimately prevail is as yet uncertain, but that a complete cure in a practical form can be found is now beyond doubt, and we can confidently look forward to a time when, its principal danger having been eliminated, flying will be ready to take its place in the world's transport, on terms which, in respect of danger, will compare not unfavorably with the older and more established methods.

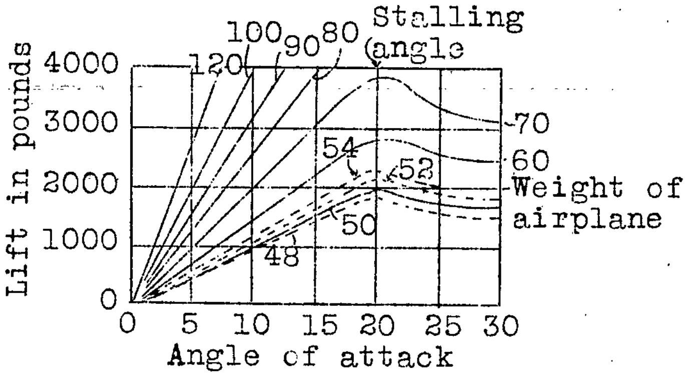

Fig.1 The aerodynamic lift, at different speeds and wing angles, of an airplane which stalls at 50 miles per hour. (Numbers on curves show speed in miles per hour).

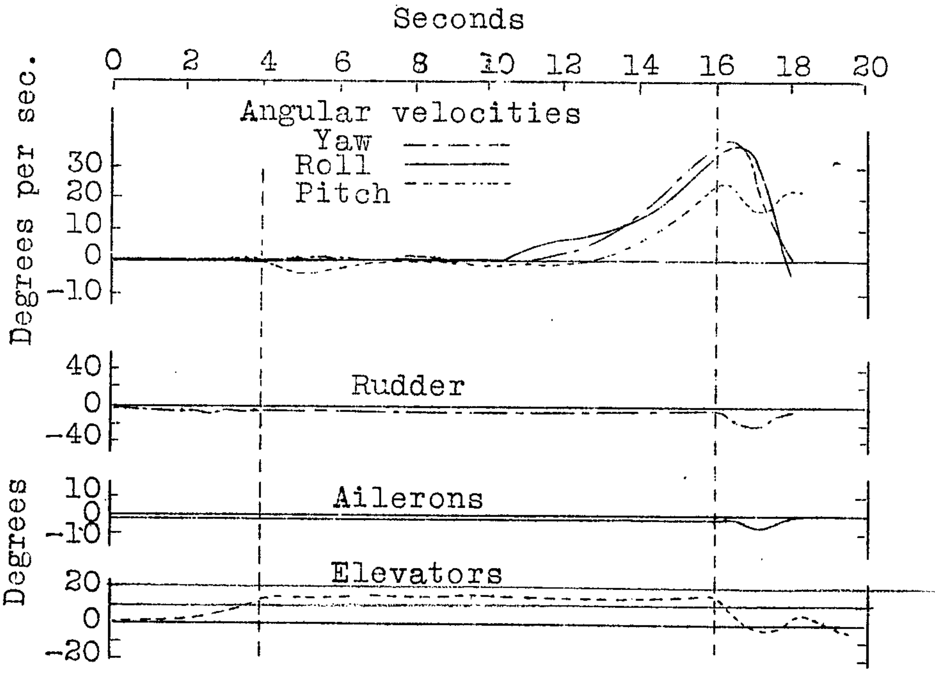

Fig.2 Controls fixed. The unstable rolling turn.

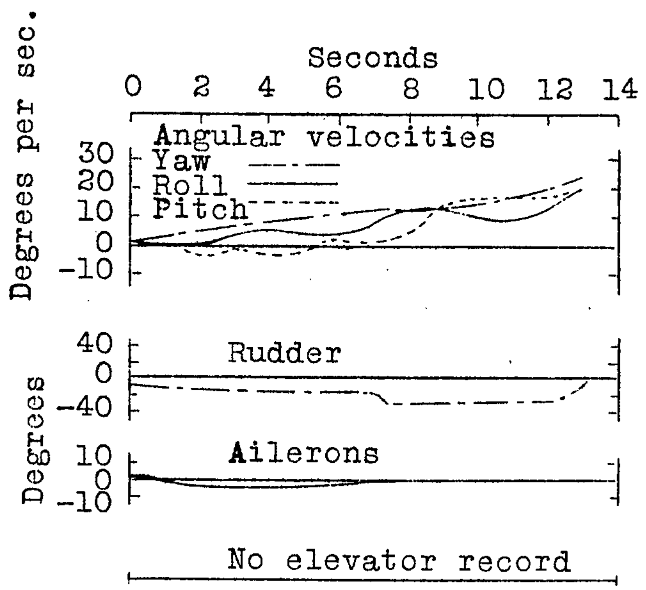

Fig.3 Controls fixed. The increasing oscillation.

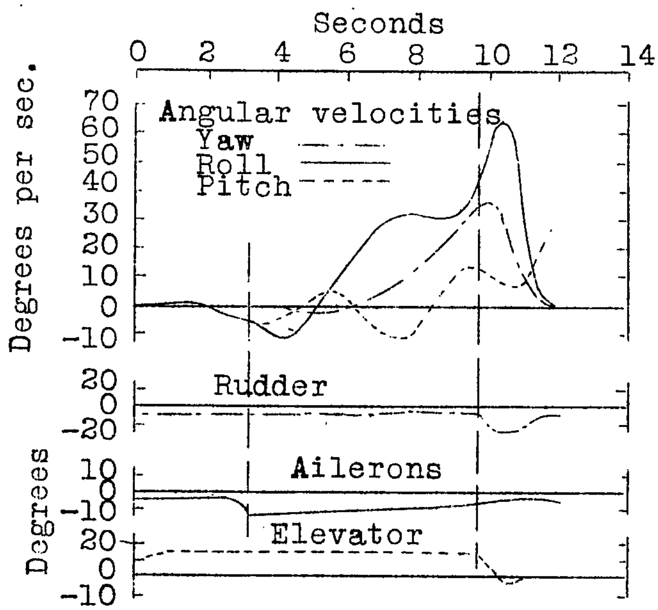

Fig.4 Failure of ailerons applied during steady flight.(Note apparent success at first).

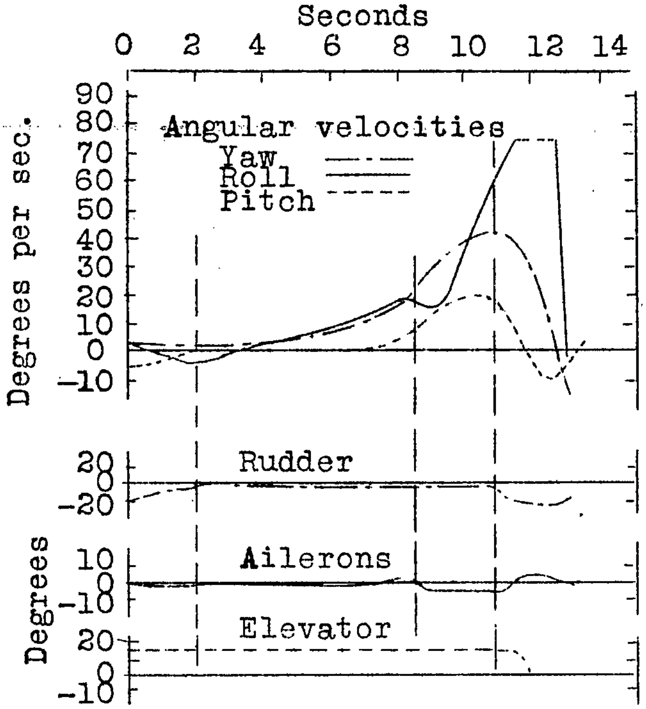

Fig.5 Failure of ailerons to check a rolling turn.

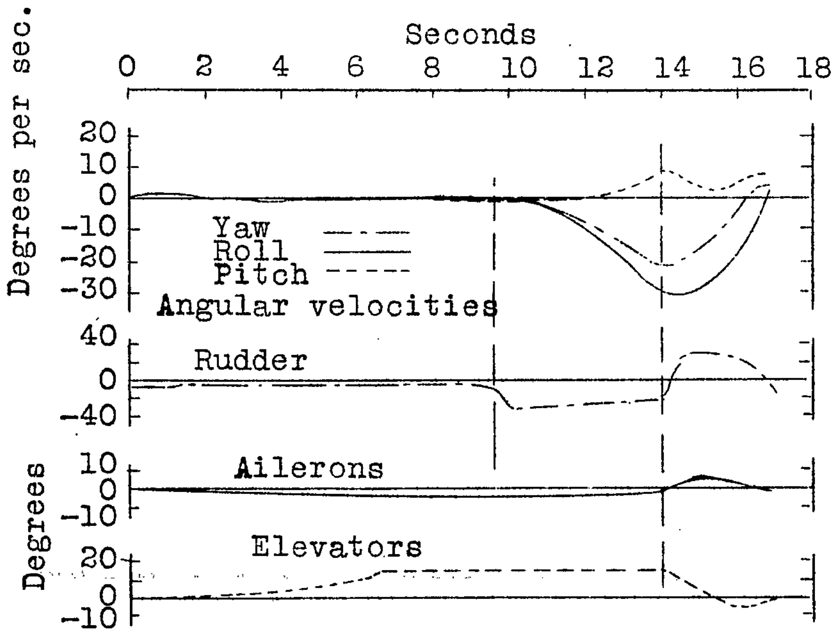

Fig.6 Effect of rudder applied during steady flight.(Note indirect influence on rolling).

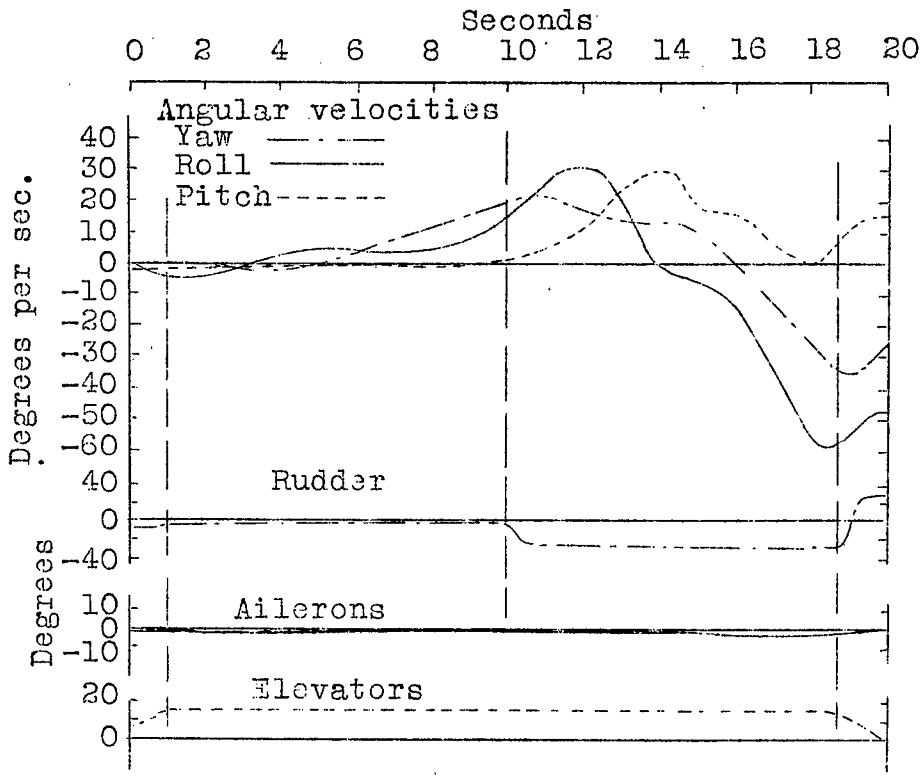

Fig.7 Rudder succeeds in checking a rolling turn.(Note delay in action).

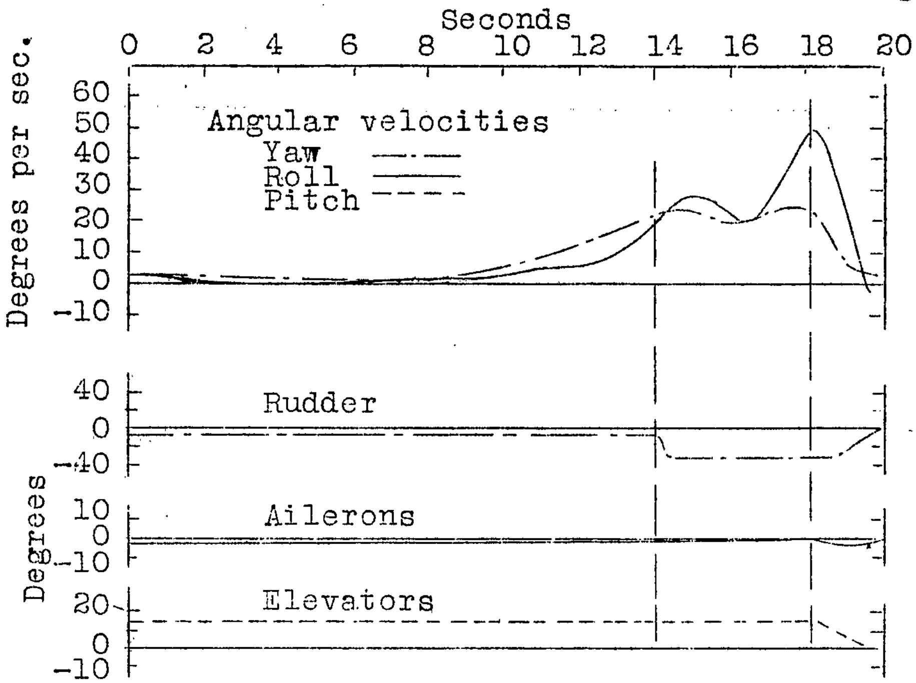

Fig.8 Rudder fails to check a rolling turn.

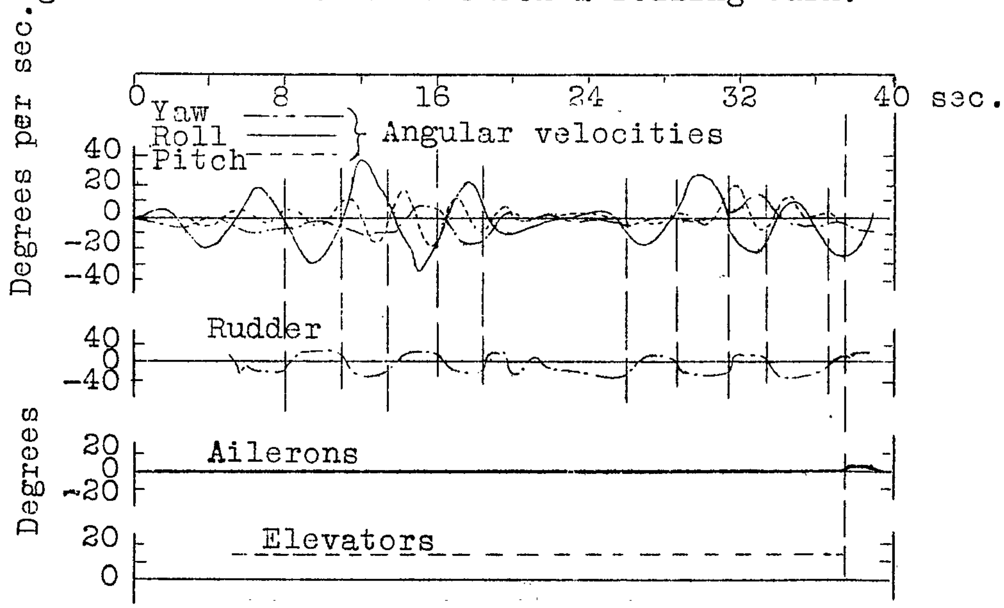

Fig.9 Attempt to control the roll by means of rudder alone.