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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 230

CONTROL OF AIRPLANES AT LOW SPEEDS

By R. McKinnon Wood

Paper read at International Air Congress, London, 1923.

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CONTROL OF AIRPLANES AT LOW SPEEDS.*

By R. McKinnon Wood.

Loss of control over the orientation of an airplane as the incidence approaches and enters the region of stalled flight is a prolific cause of serious accidents. The airplane very soon passes into the state of motion known as a spin. The instinctive action in a spin is to move ailerons and rudder against the rotation, and pull up the elevators to raise the nose of the airplane. The correct action is now well known. If the elevators are depressed the airplane passes out of the stalled state, the spin stops, and normal flight is resumed. With this knowledge the spin loses its terror and becomes a safe and sometimes useful fighting maneuver, provided that a sufficient height is available for recovery. It is, however, near the ground that an airplane is most likely to be stalled involuntarily, and the poverty of control at the stall is a source of danger still claiming a large toll of life and at the same time cramping the maneuvering power of pilots. At a safe height the properties of a stalled airplane are used deliberately to obtain quick maneuvers. In an emergency, a pilot may risk the dangers of stalling as the only means of effecting a landing in a confined place; but in general a landing ground is approached with a good margin of speed. A margin of speed is required for flattening out from the glide,

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* Paper read at International Air Congress, London, 1923.

and this method of landing is unexceptionable, given an airdrome of adequate proportions and good surface. The possibility of forced landings in small fields must, however, be faced. In some such cases complete control in stalled flight would enable a landing to be made without injury to the craft or its occupants; in other cases it would greatly reduce injury by ensuring that the airplane landed flat with wings level and with tail down, and by avoiding telescoping the fuselage or overturning.

The present method of landing consists essentially of using the excess of speed above the stalling speed and the reserve of lift coefficient on the glide to destroy the vertical velocity of approach to the ground, the undercarriage dealing with errors in execution. The airdrome is commonly surrounded by trees, buildings, etc., and the airplane must cross the boundary with a margin of height above them and strikes the ground well into the airdrome. The distance is often reduced by sideslipping and S turns, and can be lessened by any device for steepening the gliding angle. If the control in stalled flight could be sufficiently improved, a lower speed of entry might be used with a resulting steeper gliding angle and reduced run after landing. It does not seem impracticable to design undercarriages capable of absorbing the whole vertical velocity of a stalled glide without injuring craft or occupants. This is not suggested as a normal method of landing upon airdromes, but might well provide a valuable emergency method. Flight at very large angles might be useful for the initial part of the glide to the landing ground, but the vertical velocity would probably be beyond the capacity of a practicable undercarriage, and it would only be at angles not much above the stall that an airplane could be built to glide straight on to the ground.

The following table gives typical figures for a biplane loaded 8 lbs. per sq.ft., and shows the nearly constant speed of flight and inclination of the airplane to the horizon, and the rapid increase in the rate of descent with increasing incidence, while the last column(*) gives the travel of shock absorber required with a uniform retardation of five times gravity:-

Incidence of Airplanes deg.	Angle of Glide deg.	Speed of Glide M.P.H.	Rate of Descent f/s	* ft.	
10	8	62	13	0.5	7
15	10	54	14	0.6	.58
20	18	53	25	2	18.5
30	32	52	41	5	50"
40	42	50	50	8	74"

It is conceivable that the autorotative properties of a stalled wing might prove to be helpful in landing in very disturbed air, such as occurs in alighting on the decks of ships, if the problem of control could be satisfactorily solved. The resistance to rolling in unstalled flight causes the airplane to respond rapidly to a rolling disturbance. At the stall this resistance vanishes, and above the stall a much weaker tendency to reverse rotation is present. By flying stalled, the violent rolling resulting from a gradient of vertical velocity across the direction of flight would therefore be greatly reduced.

The longitudinal control of many airplanes is inadequate to maintain stalled flight, but this does not prevent them from entering this region unintentionally, and the accidents which arise from the existence of a dangerous state of flight provide the first incentive to research upon control in this state. The fear of losing control by stalling, moreover, cramps the action of the pilot in unstalled flight. The possibilities of a considerable increase in power of maneuver by the deliberate use of the stalled state, particularly in respect of forced landings, enhances the importance of the subject.

As in unstalled flight, the initial simplification may be made of considering the stability and control of more or less rectilinear motion under the divisions of longitudinal and lateral motions, although it must be borne in mind that the stalled flight achieved today does not strictly involve only the "small disturbances" of the theory of airplane stability. In the second division bank and sideslip, rolling and yawing are interdependent. In neither division is the control of the ordinary airplane at all adequate. In the lateral division the subject is the more complex and the difficulty of improving control the greater.

It has frequently been shown that it is possible to fly some airplanes in the stalled state, although this requires considerable skill and calm air. The pilots of the Royal Aircraft Establishment have succeeded in controlling the Bristol Fighter, when gliding at several degrees above the stalling incidence, sufficiently accurately and continuously for the lift and drag of the airplane to be determined. For this experiment the center of gravity was moved back by attaching weight at the tail, so reducing the stability as well as providing a down load on the tail. An Avro 504 K, the British training airplane, has been provided with water tanks whereby weight may be transferred to and from the tail in flight. This airplane has been flown at greater angles than the Bristol Fighter, and with the addition of a very large rudder of three times the power of the standard rudder a glide at 40 deg. incidence has been achieved with the center of gravity 1/4 of the wing chord further back than the standard Avro. The large movement of the center of gravity needed to reach this angle of incidence without altering the tail setting is significant.

Model tests show that as the wings stall the center of pressure travels back fairly rapidly, while beyond the stall its position becomes more or less stationary, but moves back slowly. The stability therefore increases at the stall, and the airplane also tends to put its nose down. For these reasons, an unstable airplane may be easier to land than a stable one. The angle of downwash at the tail follows the lift curve, and above the stalling incidence the mean downwash is more or less constant. For this reason, the stabilizing power of the tailplane is increased, but the power of the elevators is not affected. At very large angles the tailplane also will be stalled, its stabilizing power will be weakened and the effectiveness of the elevators may be expected to be seriously impaired. In stalled flight there is therefore a large longitudinal restoring moment for any change of incidence from equilibrium. As the longitudinal control is designed to cover the range of unstalled flight, it is inadequate to hold the airplane at an angle much above the stall. The tendency of an airplane to drop its nose and dive after stalling may be countered by the provision of a "trimming" tailplane with a sufficiently large range of negative movement. Control may also be obtained by moving weight back. Model tests on S.E.5A airplane at the N.P.L. show that there is still a large restoring moment for a change of incidence (and presumably a high degree of longitudinal stability) with the center of gravity as far back as 0.5 of the mean chord up to an incidence of 35°, but flight might become longitudinally unstable above that angle. This large restoring moment makes the airplane very insensitive to elevator movements and calls for powerful controls; but the pilot does not have to contend with instability.

The longitudinal control requires further investigation, but the lateral problem is the more pressing and the more difficult. The most prominent feature of the flight of a stalled airplane - by which its state of flight may be at once recognized by an observer on the ground - is the tendency to drop one or the other wing, against which the pilot continually contends. The airplane rolls erratically all the time. The well-known phenomenon of autorotation occurs over a range of incidence starting a little beyond the stall, and in this region flight is unstable and the airplane will, if left to itself, generally pass into a spin which is a stable motion. Model experiments show that the ailerons should be capable of preventing or stopping autorotation, and yet in practice they appear to be very ineffective. It is necessary to consider in some detail the effect of the use of the ailerons, and this is conveniently done by a vectorial representation of the moment which the use of the ailerons exerts upon the craft. Below the stalling angle the aileron moment vector is nearly parallel to the wing chord, but the angle between them increases rapidly as the incidence increases through the stall. The ailerons are usurping the functions of the rudder, and increasing use of rudder is required merely to neutralize this effect. This renders the control confusing and difficult, as it is desired to use the ailerons to produce rotation about an axis which may be but vaguely defined, but at any rate is roughly along the fuselage; but pilots would learn to surmount this if the consequences were not commonly more serious. For any angle of incidence a closed curve may be drawn from wind channel data, such that a suitable combined use of ailerons and rudder can be made to produce any moment whose vector lies within the curve. A vector may also be drawn to represent the moment resulting from any specified air disturbance or motion of the airplane, and by comparison the power of the controls to produce equilibrium under the given conditions may be seen. For adequate control a margin is of course needed. Wind channel tests have shown that the rudder must have great power judged by present standards of design if the resultant vector due to ailerons and rudder is to have the required direction under all circumstances. The power of the ailerons is therefore limited by the power of the rudder. At the same time the rudder may be used to roll the airplane to a far greater extent than in unstalled flight, as the application of rudder causes one wing tip to move faster than the other and therefore rise, while the wings have a tendency to roll when stalled in place of the resistance to rolling present in unstalled flight. The pilot therefore receives the impression that the rudder is the more important organ in stalled flight, and the provision of a very large rudder has been found of considerable assistance. The increase of rudder power alone, however, cannot produce satisfactory control, as independent control of over bank and direction must be simultaneously provided.

The two vector diagrams of Fig. 1 illustrate the various points discussed above. The aileron vector, i.e., the axis about which the ailerons tend to rotate the airplane, is inclined at an angle above the wing chord by an amount which increases rapidly as the incidence increases and has become quite large at 18°. The closed curves defining the limit of combined aileron and rudder control show how the rudder limits the production of a couple to roll the airplane about the line of flight and at 18° limits the couple obtainable about the wing chord axis (the rudder control defining the width of the area in the direction marked "rudder vectors"). The same conclusions would obtain if the aileron movement were limited to +10°. Two further lines are drawn, marked horizontal gust and vertical gust, and show the axes about which horizontal and vertical gusts acting upon one wing only would tend to rotate the airplane. The ability of the controls to counteract either type of gust acting alone is seen to be limited by the rudder at both

12° and 18°, but at 18° a combined gust could give a moment whose vector would lie along the length of the control area and require full use of the ailerons. Above the stall a vertical gust under one wing has an entirely different effect from below the stall, although the effect of a horizontal gust is much the same.

For the investigation of lateral control the Royal Aircraft Establishment has designed apparatus whereby model wings can be rotated in a wind channel about the wind axis and the rolling and yawing moments measured. By a modification pitching moment may be measured instead of yawing moment. The complete moments on the wings are so determined when an airplane is executing a pure roll, and the method may also be expected to give approximately the effects of a corresponding rotation of the air through which an airplane is flying.

Yawing motion cannot be reproduced in a wind channel, but the small whirling arm of the National Physical Laboratory is available for this purpose. The acquisition of data from the rolling motion has been regarded as of greater importance in the first place.

From the data obtained with this apparatus two sets of curves have been drawn, in both of which the abscissae represent incidence and the ordinates the rate of roll expressed in the non-dimensional form ps/v. Each curve in the first diagram corresponds to a particular setting of the ailerons, and in a second to a particular rudder angle, and together the diagrams give the aileron and rudder angles required to produce equilibrium at a specified rate of roll. It has been assumed in drawing these curves that the moment due to the rudder is independent of the rate of roll, as the method of experiment did not provide information on this point. These curves are shown at the top of Fig. 2, and the pairs of diagrams below give corresponding results for pure yawing and sideslip respectively.

The convention of signs employed is the following:- Positive roll means starboard wing falling, positive yaw a turn to starboard; positive aileron means starboard aileron down, and positive rudder means rudder moved as for a turn to port. The control movements have therefore the opposite sign to the rotations which they would naturally be used to produce.

The rate of rolling and of yawing have been expressed by the ratio of the excess speed of the wing tip to the mean speed of the whole airplane, and it must be remembered that a greater value of this ratio will be required at lower speeds in order that the airplane shall rotate through a given angle in a given time. They are therefore directly applicable to the execution of a maneuver in a given distance flown, while the time is inversely proportional to the speed if the distances be equal.

The set of curves for the ailerons for rolling (top left) show the autorotation range of the wing and the rapid rate of banking that could be obtained when stalled if the tendency to yaw could be countered. These curves also indicate that quite a small amount of opposite aileron should stop rolling, if yawing be prevented. They suggest that, although the aileron control appears in practice to be ineffective, the requirements may be, not for an increase in the rolling moment that they can produce, but for elimination or reversal of the yawing moment caused by their use.

It is also to be noted that in the autorotation range the positions of both ailerons and rudder for equilibrium in a pure roll at a rate less than the autorotation rate have opposite signs from the positions in unstalled flight.

The curves here reproduced refer to the Bristol Fighter. It is evident that the rudder control is inadequate for stalled flight, the dotted +40° curve being beyond the range of the actual rudder and drawn to indicate twice the moment given by 20° rudder. This airplane is recognized as one having insufficient rudder, and is peculiarly unsuitable for stalled flight. Similar curves for the Avro indicate that the standard rudder, which is considerably more powerful than that of the Bristol Fighter, is barely powerful enough for stalled flying, while the large experimental rudder should provide sufficient control. Flying experience is more or less in agreement with this conclusion. The standard Avro can be kept roughly on an even keel and travelling in a constant direction by a continual vigorous use of the rudder after a certain amount of practice; but the airplane cannot be described as in any sense maneuverable, and if allowed to get up a large oscillation becomes almost uncontrollable. The large rudder was found to be distinctly more effective in checking oscillations. It is evident that any airplane typical of present design will suffer from poverty of rudder control.

Professor B. M. Jones has calculated corresponding curves for pure yawing for the S.E.5 airplane, the two central diagrams of Fig. 2. It will be seen that the aileron angles required to prevent rolling when yawing are quite large, while the rudder has to be used in the opposite sense above the stall. Powerful aileron control seems therefore to be needed more to prevent rolling when yawing than for producing roll without yaw.

A further set of curves for the S.E.5 from a National Physical Laboratory test in the wind channel gives the aileron and rudder angles for a pure sideslip (Fig. 2, bottom). The rudder angle required changes sign at about the angle at which autorotation starts and large aileron movements are required at large angles of incidence.

Maneuvering power in stalled flight is restricted by the impossibility of increasing lift by change of incidence, and the control sought is the power to fly steadily on a mark, and to make changes of direction more or less slowly, and primarily to prevent the airplane from taking its own course after stalling. Stalled flight is inherently unstable on account of the change of sign of the derivative Lp, the coefficient of rolling moment due to rolling. Lateral instability in stalled flight is of far greater importance than in unstalled flight on account of the far greater rate at which the motion changes. Suppose that the starboard wing is falling slightly. Its incidence is increased by the falling and its lift reduced. The rolling therefore tends to increase, and at the same time the airplane starts sideslipping to starboard. The dihedral is ineffective or even tends to increase the roll, and the airplane is yawed into the relative wind by the fin and rudder, and the yawing further increases the rolling. The airplane banks, sideslipping downwards, the nose drops, and the roll and yaw increase and the spin develops. If the ailerons are used to pick up the falling wing, the yawing is increased and the motion accelerated. To avoid the spin the rudder must be used to turn the airplane to port or the elevators depressed to regain unstalled flight. The latter involves a dive and loss of height. More or less straight flight may be maintained by prompt and vigorous use of the rudder, and the greater its power the better, or by a suitable combined use of aileron and rudder. Ailerons giving a yawing moment in the opposite direction should be of great assistance. So long, however, as the instability remains, continual prompt and vigorous use of the controls will be required, and the need for eliminating the autorotative tendency is clearly indicated, and a small resistance to rolling would be advantageous.

Consider also the case when the airplane is turning slightly to starboard. The starboard wing tends to fall on account of its lower speed, and the autorotative rolling couple comes into force, sideslip to starboard starts, and the motion develops into a spin as before. In the same way the reversal of the dihedral effect above the stall will lead from a sideslip to a spin.

The statement that the motion changes rapidly in stalled flight is perhaps liable to some misconception. The oscillations which result from the conflict between the instability of flight and the vigorous counteracting operations of the pilot are certainly quick, but the pilot is more impressed by the ineffectiveness of his controls than by the rate at which a spin develops. The motion takes place at a low speed of flight and in a short distance, and is rapid in space more than in time.

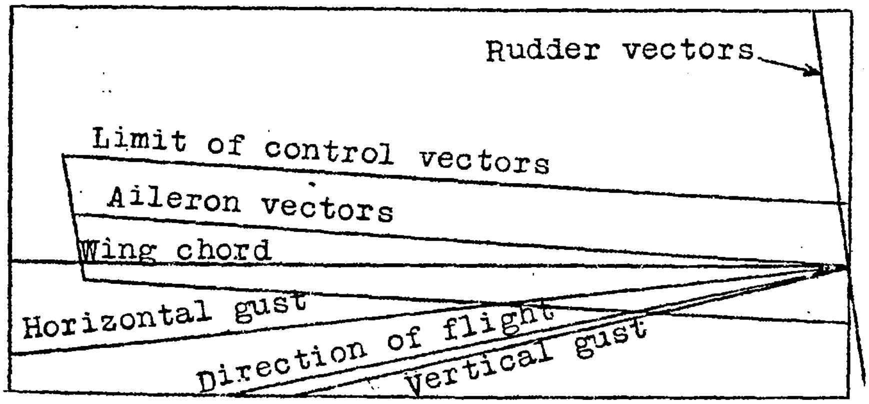
In the same way, the motion which eventuates from a movement of the controls is necessarily slower at low speeds than at high speeds for the same motion in space, while the initial response to control movements is poorer because the accelerating forces are proportional to the square of the speed, other things being equal. Slow response to the controls at low speeds is therefore in part a consequence of the low speed.

The line of reasoning outlined above suggests lateral control by means of non-lifting surfaces as a solution of the main problem of control in stalled flight. This solution is inherently deleterious to performance. The simplest method is by rigging up the conventional ailerons, but this sacrifices lift, and is not easily made sufficiently effective. Subsidiary control planes carried between the wings behind the rear interplane struts have been tried. An isolated surface is, however, very ineffective compared with the conventional ailerons, and the drag is rather seriously increased. The surfaces tried were allowed freedom to set themselves together along the relative wind, and were controlled differentially to produce rolling moment. It was found, however, by model tests that better results were obtained with the mean position of these surfaces parallel to the wing chord, and with this arrangement autorotation disappeared and the yawing moment was reduced, but not eliminated. The opinion of pilots who flew the modified airplane was, however, that the control was not improved; the yawing effect was reduced, but the rolling control was insufficient. It was still possible to spin the airplane with the aileron control held central. It is therefore evident that a powerful rolling control is needed, and the yawing effect of the aileron must be eliminated or reversed, while the autorotative tendency should be replaced by resistance to rolling.

There is some prospect that considerable progress may be made by the use of Handley-Page slots as a lateral control. The opening of such a slot on a stalled wing increases the lift and decreases the drag, and might be used in conjunction with ailerons to provide the control desired. But the slot has little effect until the wing is thoroughly stalled, and would provide a control which becomes more powerful with increasing incidence up to some large angle, but would probably be ineffective at the stall, which is in the first place the more important region. The slot might also be opened equally over a portion of the space at each wing tip in order to provide resistance to rolling after the lift of the whole wing has reached its maximum. Other devices are available which increase the drag on the side of the upgoing aileron, and in addition give rolling moment and are effective at the stalling incidence, and a system of gearing is being tried whereby the upgoing aileron moves faster than the downgoing.

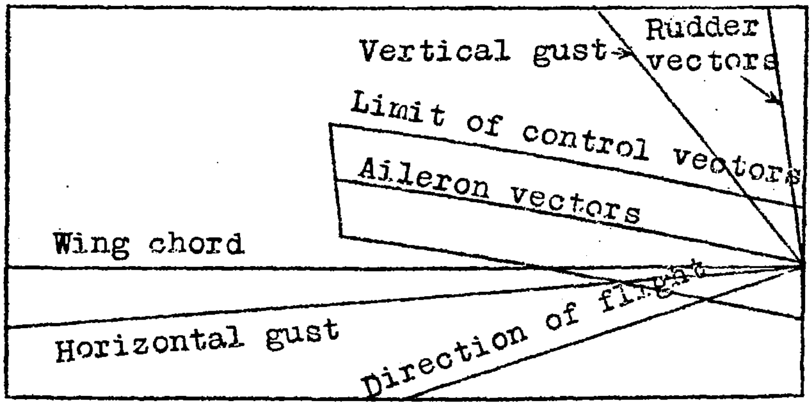
It is desirable that lateral control should be obtained by an increase of lift on one wing and a decrease on the other. A device which increases the lift of a wing may presumably be applied to the whole wing to reduce the stalling speed, as the conventional aileron becomes the "Fairey flap," and the Handley-Page slot has hitherto been regarded as a device for reducing the stalling speed. The old warping wing control shows lateral control obtained without use of any device to increase lift beyond the maximum of the wing section, and becomes almost ineffective at the stall. The aileron is an improvement, but suffers from the disadvantage that increase of lift is accompanied by a large increase of drag. It is clear that no device can be used to its full value to provide lift without loss of control, or the addition of a further device. Control at specified low speeds is increasingly obtained as stalling speeds are reduced, and flight is thereby made safer; but the dangerous stalled region is still present and may always be entered in attempting to make full use of the lowest speed available. It may be better not to use the full reduction of stalling speed that devices provide, but to retain something in hand for control after stalling. There will certainly be a tendency for load-carrying airplanes (commercial and bombing) to use the increased lift to increase the load carried, although fighting airplanes may retain light loading for the sake of climb at great heights.

Fig.1.



Bristol fighter 12° incidence

Ailerons limited to ± 15° Rudder to ± 20° movement



Bristol fighter 18° incidence

Ailerons limited to ± 15° Rudder to ±20° movement

Fig.1.