REPORT No. 120

PRACTICAL STABILITY AND CONTROLLABILITY OF AIRPLANES

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SUMMARY.

The effect of the characteristics of an airplane on balance, stability, and controllability, based on free flight tests, is discussed particularly in respect to the longitudinal motion. It is shown that the amount of longitudinal stability can be varied by changing the position of the center of gravity or by varying the aspect ratio of the tail plane, and that the stability for any particular air speed can be varied by changing the camber of the tail plane. It is found that complete longitudinal stability may be obtained even when the tail plane is at all times a lifting surface. Empirical values are given for the characteristics of a new airplane for producing any desired amount of stability and control, or to correct the faults of an airplane already constructed.

INTRODUCTION.

There has been a great deal of work done on stability, but the larger part of it has been either with models or with mathematical theory; so there is at present very little technical data to aid the designer in predicting the exact amount of stability an airplane will have when it is first taken into the air, or what changes are necessary to correct a particular fault. The feel of the controls on a new airplane determines probably more than any other one thing the test pilot's attitude toward it, and after all the pilot is the court of last appeal on the fitness of the airplane. There have been great numbers of airplanes built which in nearly every particular were excellent, but because of an undue force on the stick or too great an amount of stability or instability, were condemned to be "washouts." On the other hand, the few airplanes that do possess excellent longitudinal control in many cases are arrived at by copying some previously successful machine or are simply accidents. It is the object of this paper to bring together what practical data there are available from free flight tests on stability for the aid of the designer, and to indicate in what direction future research should be guided in order to solve some of the many existing problems.

There are always three ways to obtain the data for any design: First, from mathematical theory; second, from previous practice; and, third, from experimental research. In this subject of stability the first will not be of much aid to us, for there are so many unknown conditions that the theory must always follow the experimentation. In fact, the huge mass of mathematical theory on stability, a mass laboriously constructed on the insecure foundation of insufficient assumptions, has actually been a hindrance to a sound understanding of this problem. The second way will enable us to design a safe and satisfactory airplane, but if everyone followed this method there would be no general improvement in airplane design. The third way is the more effective, as it will not only tell us how to construct our airplanes so as to give the best results but it will also give us data on which we may base a satisfactory theory. Above everything else the pilot and the designer should get together, as only in this way can a satisfactory airplane be evolved.

In order to show how unnecessary are automatic stabilizing devices on properly designed airplanes, it is interesting to see what has actually been done in the way of inherent stability. A large number of machines show that without any radical departure from standard design it

is possible to make an airplane which will fly even in bumpy weather with absolutely no attention from the pilot. These airplanes will not only fly themselves, but they will acutally fly more steadily when left alone than when controlled by the pilot.

It should be noted that the results and conclusions in this report are based entirely on the data from tractor biplanes, and in some cases from only a single airplane, so that care should be taken not to assume a general applicability of the results. It is strongly recommended that all new airplanes be tested for stability and controllability and that the characteristics of the controls be recorded, in order to extend our empirical data on the subject. Such tests are fully as important as the usual performance tests.

BALANCE.

An airplane is said to be well balanced when there is no force on the stick or rudder with the airplane flying at its normal speed. It should be noted that the balance of the airplane is entirely

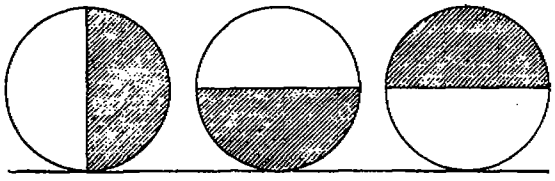

FIG. 1.—Illustration of balance.

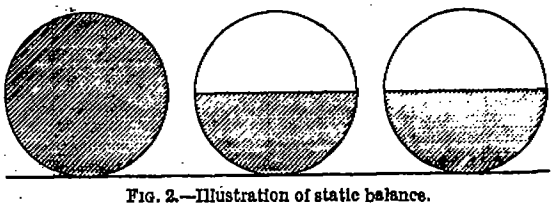

FIG. 2.—Illustration of static balance.

separate from its stability—that is, the airplane may be balanced and yet be unstable—but stability, of course, will have no significance until the airplane is balanced. In order to illustrate this more clearly reference may be made to figure 1, which represents the cross section of a cylinder which is divided along its diameter, one-half being of brass and the other half of aluminum. In the first position the cylinder is evidently unbalanced, for if it were left to itself it would roll over into a new position. In the second position the cylinder is evidently balanced, as no force is required to hold it in its position, but further than this it is also stable, because if it is moved from this position forces will be set up to bring it back. In the third position it is still balanced, but in this case unstable, because if moved even slightly from its equilibrium position it will turn completely over.

LONGITUDINAL BALANCE.

The following factors are the ones which mainly determine the longitudinal balance of an airplane:

1. The longitudinal position of the center of gravity.
2. The angular setting of the tail plane.
3. The weight of the elevators—that is, the moment produced about the elevator hinge by their own static weight.
4. The vertical position of the thrust line in respect to the center of gravity.

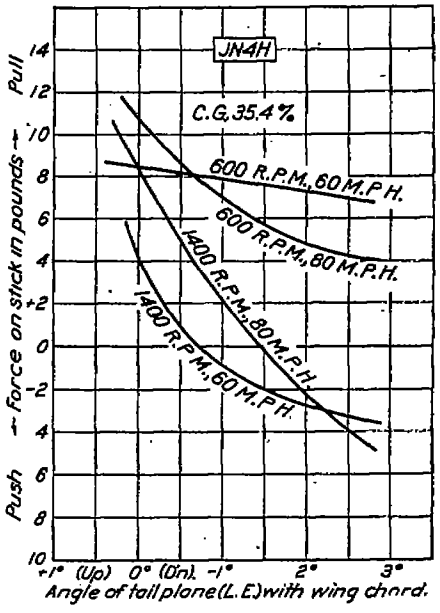

FIG. 3.—Effect of tail-plane angle on balance.

The only available data which shows the change in stick force with a given change in center of gravity position is that obtained on a JN4H; these results, however, should apply approximately to any tractor biplane. It was found on the JN4H that a movement of the center of gravity forward along 2 per cent of the chord required an additional pull on the stick of 1 pound to hold the machine at the same angle of flight.

The effect of the tail plane setting on the control force has been obtained both on the JN4H and on the DH4, the results being shown in figures 3 and 4. Although the change in stick force was not the same for all engine speeds, it may be safely assumed that when the tail plane is changed

1° the stick force changes by 4 pounds on the JN4H and by 6 pounds on the DH4 when the tail plane is turned through an angle of 1°. An adjustable tail plane is a most excellent method of balancing an airplane, and such a device should be applied to all but the smallest airplanes.

It should be noted that either moving the center of gravity forward or decreasing the angle of the tail plane increases the longitudinal stability of the airplane, so that by proper adjustment of these two factors it is possible to change the balance to any degree without appreciably affecting the stability characteristics.

The effect of the elevator weight on balance is quite obvious—that is, if the weight of the elevator is increased it will add a proportional pull on the stick. The effective weight of the elevator can be changed by a balance weight on some part of the control system—that is, if the stick gave a pull of 2 pounds at a speed where it is desired to have it balance, an effective weight of 2 pounds on the control system would give the required balance. Balance can also be obtained by springs, but it should be noted that this is not a true balance except for uniform flight, because in turns where the motion is accelerated the spring force would remain constant while the elevator weight would be proportional to the acceleration.

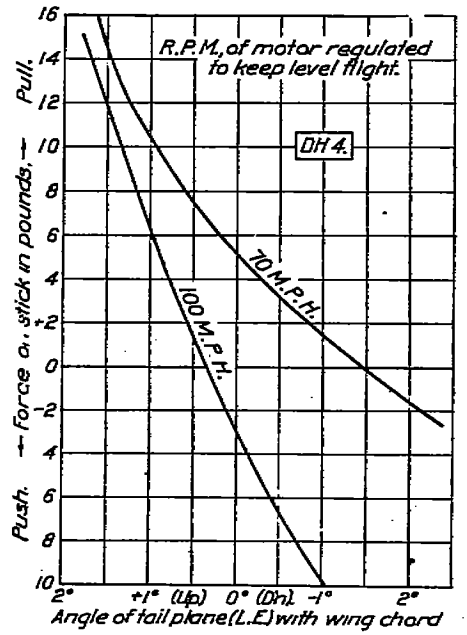

FIG. 4.—Effect of tail-plane angle on balance.

LATERAL BALANCE.

There have apparently been no tests made to determine the angle through which the tips of the wings must be changed in order to balance a given lateral force on the stick. Some tests have been made, however, in Germany[1] on a conventional biplane of about 400 square feet in area to determine at what angle the ailerons must be placed to balance a given angular warp in the wing itself. The results of these tests are shown in figure 5, and it is evident that a warping of the wing at the outer struts of 1° corresponds to 2° angle on the aileron.

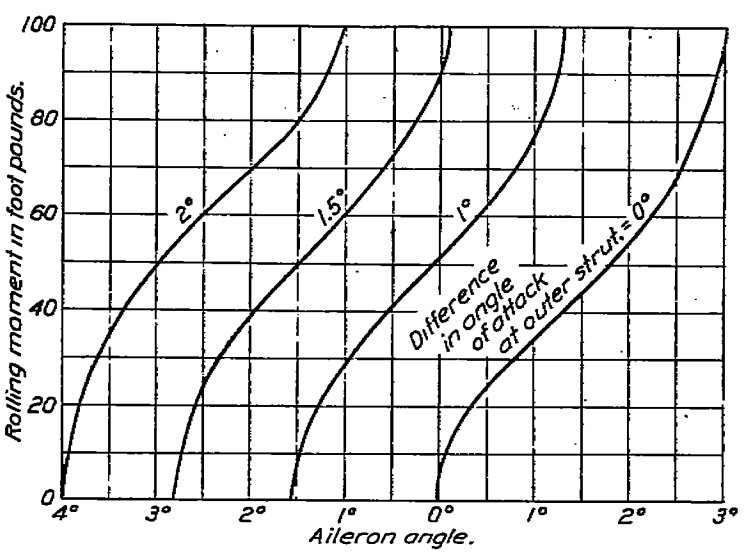

FIG. 5.—Effect of wing warp on lateral balance.

DIRECTIONAL BALANCE.

Directional balance, which depends upon the forces acting upon the rudder, is unfortunately quite different with the engine on and off. It is very simple to effect a balance of the rudder either by moving the leading edge of the fin or by applying an adjustable tension on one end of the rudder bar with an elastic cord. The airplane should always be balanced directionally after the wings have been properly aligned for balancing the airplane laterally, otherwise a small change in the angle of attack of the wing will considerably change the forces on the rudder. To design a rudder which is balanced at all engine speeds is a rather difficult problem and is perhaps best solved in some of the British machines, such as the SE5 where the rudder extends for a considerable distance below the fuselage so that it will be evenly acted upon by the rotation of the slip stream.

[1] N. A. C. A. Technical Note No. 38

STATIC STABILITY.

In order to define clearly the meaning of static stability, reference will be made to figure 2, which shows a cross section of the same cylinders as in figure 1. In the first position the cylinder is considered to be made of a homogeneous material, so that it will rest in any position in which it is placed; and in this case the stability is said to be neutral. In the second position the cylinder is evidently stable, for if it is displaced from its equilibrium position forces will be set up tending to return it to this position, but in the third position the cylinder is unstable, for if it is moved even slightly from its equilibrium position, forces will be set up tending to make it depart even further from its equilibrium position.

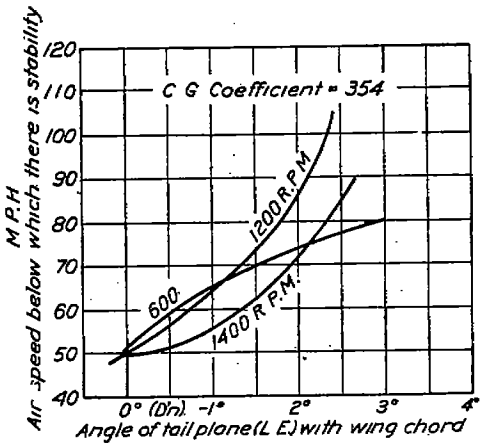

FIG. 6.—Stability of JN4H with free controls.

It is usually desirable to have only a small variation in control force for various throttle positions; but if there is a variation it is desirable to make the airplane more nose heavy with the throttle closed. The lower the thrust line is, compared with the center of gravity, the more will this tendency be, but in the usual case when the majority of the tail is in the slipstream the pitching effect will not be zero when the thrust line passes through the center of gravity, because of the large influence of the slipstream on the tail surface. By raising the thrust line high enough a position would of course be found where torque about the center of gravity would neutralize this downward force on the tail plane so that the tail plane would have the same balance for any throttle setting, but this is usually impossible to accomplish in the usual tractor airplane. As shown later, increasing the aspect ratio of the tail plane decreases the amount of area in the slipstream, thus giving more uniform balance at different engine speeds. By the use of a geared engine the thrust line is raised without changing the vertical position of the center of gravity, so that this type is of considerable advantage in giving a constant balance with changes in engine speeds.

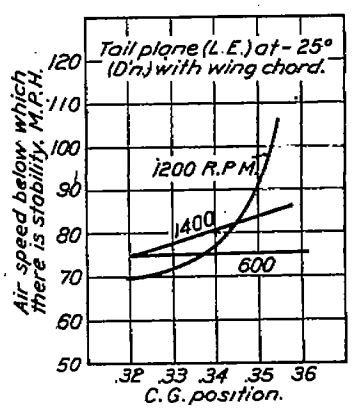

FIG. 7.—Stability of JN4H with free controls.

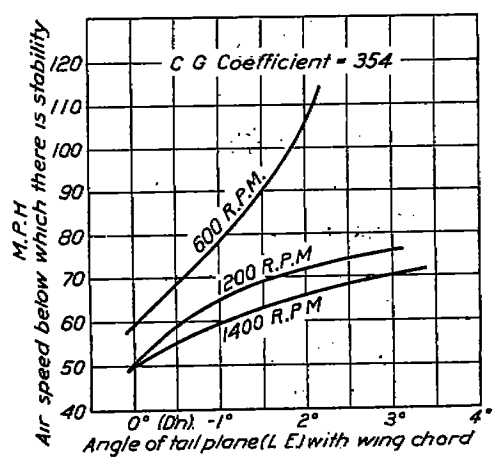

FIG. 8.—Stability of JN4H with locked controls.

In an airplane the question is slightly more complicated, as we may have stability in one case with the control surfaces locked in position and in the other with the control surfaces left free to rotate as they will. An airplane is said to be inherently stable with free controls when it is able to fly at some speed steadily without the attention of the pilot and is stable with locked controls when it will fly in the same way with the controls fastened in one position. When the control positions and forces are plotted, as in this report, stability is indicated by a negative slope of the curve. In the majority of cases, although not always, an airplane will be more stable with locked controls than with free controls, so that in making wind tunnel tests the control surfaces should be either entirely removed or else freely hinged. Due to the inevitable friction in the controls it is practically impossible to have free controls, so that what we call free controls is a combination of free and locked controls.

It is desirable in every airplane to have a small degree of static stability, sufficient to allow the machine to be flown even in very bumpy weather without using the controls, and yet not so stable that the airplane is not at all times subservient to the pilot's will.

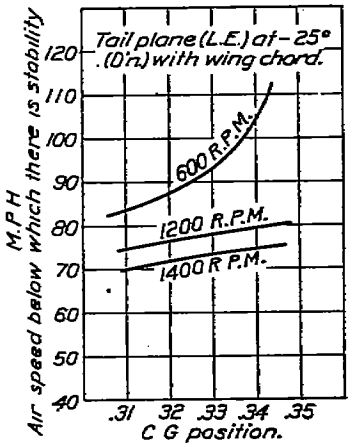

FIG. 9.—Stability of JN4H with locked controls.

LONGITUDINAL STABILITY.

The longitudinal stability is generally affected by the following factors:

1. Horizontal position of the center of gravity.
2. Angle of the tail plane.
3. The aspect ratio of the tail plane.
4. The section of the tail plane.
5. The area of the tail plane, and the length of the body.
6. The chord and center of pressure travel of the wing.

It is not within the scope of this report to give a detailed analysis of the effect on longitudinal stability of changing the horizontal position of the center of gravity, but in figure 6 are shown elevator force curves which have been obtained in free flight on a JN4H airplane. The stability is somewhat influenced of course by the slip stream, but in general it may be said that the further forward the center of gravity the more stable will be the machine, not only in this particular case but on any machine. The stability with locked controls with a given change in center of gravity is shown in figures 8 and 9, and the same conclusions hold true for this case.

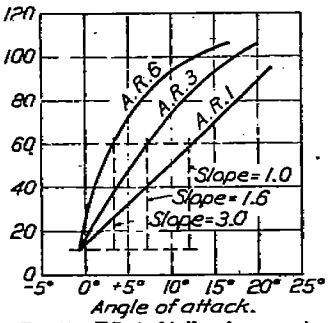

FIG. 10.—Effect of tail surface aspect ratio on lift.

The angle of the tail plane has some effect on stability, that is, a more positive angle decreases the stability. At the same time a more positive angle tends to reduce the difference in forces between various engine speeds. By using a tail of high aspect ratio it is possible to obtain stability even when the center of gravity is 42 per cent back on the mean chord, in which case the tail will be lifting at all times. It thus seems evident that for the sake of aerodynamic efficiency and equal balance at all engine speeds, it is desirable to place as much positive load on the tail as consistent with a moderate degree of stability. In figure 7 are shown curves obained in free flight, showing the effect on stability of a variation of the tail plane angle, but the data are not complete enough to give more than approximate results.

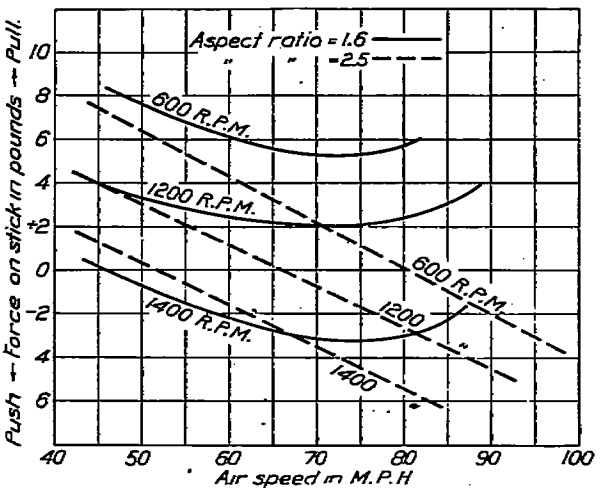

FIG. 11.—Effect of tail surface aspect ratio on stability with free controls.

The aspect ratio of the tail surface has more effect upon the stability in the usual tractor airplane than any other cause, and this is due not only to the increased slope of the lift curve with increased aspect ratio but also to the fact that a larger amount of area is outside of the slip stream, which of course increases the efficiency. The variation in slope of the lift curve with the change in aspect ratio is shown in figure 10, the results being taken from some of Eiffel's tests. The stabilizing action of the tail is evidently dependent upon the rate of change of lift with a unit change of inclination, so that the slope of the lift curve is a direct criterion of the stabilizing action. In other words, in order to have equal stabilizing

properties in two tails, one with an aspect ratio of 1, the other with an aspect ratio of 6, the latter would need to have only one-third of the area of the former. It should be noted, however, that this only applies to stability and that the small area would in all probability not give a sufficient amount of control.

In order to show the effect of changing the aspect ratio of the tail on the actual flight properties of an airplane, a JN4H was flown with a tail having an aspect ratio of 1.6 and another tail of the same area but with an aspect ratio of 2.5. In figure 11 are plotted the force curves obtained from these tests. The stability is shown by the slope of these curves, the negative slope indicating stability, and it will be noted how greatly the stability is increased by the tail of high aspect ratio even though the center of gravity position has not been changed between the two cases. Another interesting fact observed is that the force curves are closer together with the higher aspect ratio tail for various throttle settings, and this is undoubtedly due to the fact that a larger portion of the area of the high aspect ratio tail is outside of the slip stream. These are the only results available where the aspect ratio has been changed on the same airplane, but the results obtained for the stability on other airplanes seem to show that those airplanes having a tail of high aspect ratio such as the DH4 and the VE7 are stable, while the numerous machines with low aspect ratio tails are in every case unstable.

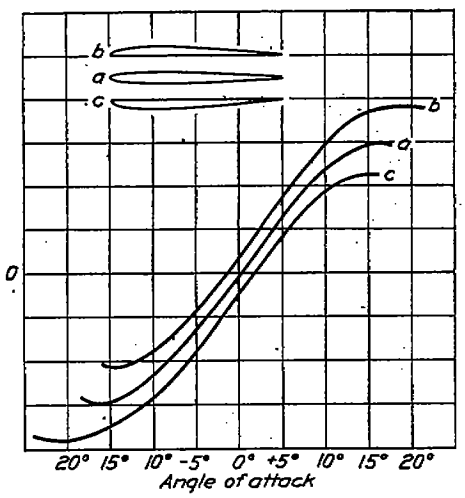

FIG. 12.—Effect of tail surface section on lift.

The characteristics of the airplane previously discussed affected only the degree of stability. The section of the tail plane,[2] however, has apparently the valuable property of changing the speed at which stability occurs. That is, if the camber of the tail plane is on the upper surface the stability will be greatest at low speeds. On the other hand, if the camber is highest on the lower surface the stability will be greatest at high speeds. The reason for this is made clear by referring to figure 12, where there are plotted the lift curves for three sections, the first a flat bottom section with the camber on the upper side, the second a symmetrical section, and the third a section flat on top and with the camber on the lower surface. It will be noted that the lift curve falls off as the burble point is approached and that the burble point is always earlier when the air strikes the cambered surface. As the stability is proportional to the slope of the lift curve it will be evident that varying the section will produce stability at various angles of the tail, which is equivalent to saying at various air speeds, so that by varying the section it is possible to produce stability at any given air speed.

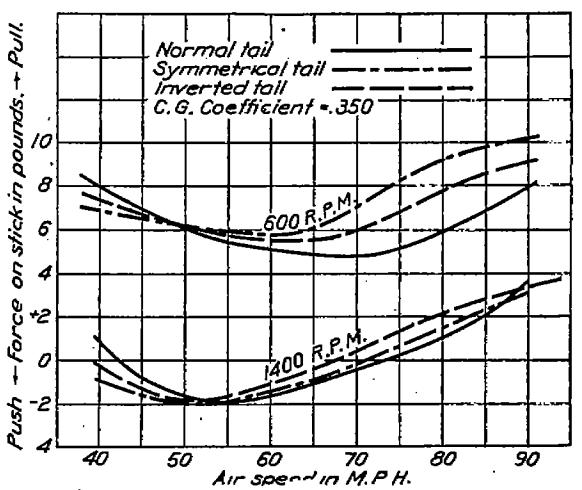

FIG. 13.—Effect of tail surface section on stability.

An actual test was carried out by placing on a JN4H three tails of the symmetrical, flat bottom and inverted section, and control forces and position were taken in the three cases. It was a little difficult to separate the effect of the tail section from the effect of tail setting and center of gravity position, which were necessarily changed somewhat between these different cases, but the tail setting was so placed in each case that the control forces at 60 miles an hour

[2] N. A. C. A. Report No. 96.

were the same for all of the sections. The results from this test, so far as the stability with free controls goes, are shown in figure 13.

There has been very little scientific investigation carried out in full flight on the effect of changing the length of the body or changing the area of the horizontal tail surfaces. This is mainly due to the fact that such alterations in the full-sized airplane are quite expensive. It is necessary, therefore, to fall back on the sizes that have been used in successful airplanes. Although this will undoubtedly give us figures enabling us to design a machine which will be satisfactory, it is simply following someone else and does not allow us to make any marked improvement in the design.

In order to obtain the characteristics of airplanes now in use there has been chosen from each type of airplane 10 successful airplanes and their average areas and lengths have been assembled in the following table. The length is given from the center of gravity to the elevator hinge in terms of the wing chord, and the areas of the control surfaces are all given in percentage of the total wing area, including the ailerons.

Type.	Tailplane area.	Elevator area.	Length.
	Per cent.	*Per cent.*	*Per cent.*
Training biplanes	6.8	5.9	3.2
2-seat service biplanes	6.4	5.8	3.2
1-seat service biplanes	7.8	6.2	2.9
Bombers, biplanes	7.0	3.6	3.7
Flying boats, biplanes	8.4	6.3	3.1
Average biplanes	7.5	5.5	3.2
Monoplanes			2.5
Triplanes			4.3
Airplanes having stability [1]	6.9	5.6	3.1

[1] Average of 5 machines considered to possess good stability: VE7, DH4, SE5, Avro 504K, Bristol fighter.

It will be observed from these figures that the area of the elevator is smaller on the large airplanes than it is on the others, and at the same time the fuselage is longer on these airplanes. This is probably due to the desire to reduce the forces on the controls. The average length of fuselage for the ordinary type of airplane is 3 chord lengths, while for the monoplane it is 2½ chord lengths, and for the triplane about 4.3 chord lengths. The average area of the tailplane is 7½ per cent and the average of the elevator 5½ per cent of the total wing area.

As it is quite impossible to give any definite values to stability without special tests, it was thought that the nearest approach to showing a relation between the longitudinal stability and the control areas would be to average up a group of airplanes which were known to have longitudinal stability. This has been done in the table and it will be observed that the areas of the tail surface and the length of the fuselage are very close to the average for the other airplanes, which shows quite definitely that it is not necessary to increase abnormally the area of the tail surfaces nor increase the length of the body in order to obtain satisfactory longitudinal stability. In fact, I believe that it is quite possible to obtain satisfactory longitudinal stability even when the areas of the horizontal tail surfaces are considerably reduced below the average and the length of the body markedly shortened. The advantages of reducing the length of the body are very great, as it allows a lighter fuselage and a much faster airplane in longitudinal maneuvers.

It has long been believed that the use of monoplanes with large chords would necessitate a longer body and a larger tail, but from actual practice it seems to have been proved that the stability and control are as great with the monoplane as they would be with a corresponding biplane of the same area with the same body and tail surfaces. For example, the Morane monoplane with a tail about 2½ chord lengths back of the center of gravity has most excellent longitudinal stability and can easily be flown without touching the controls. Again, the Stout monoplane seems to have sufficient longitudinal control, although I have no information on its stability, when the elevator hinge is only 1 chord length back of the center of gravity. It is also believed that a construction such as the JL6 (Junkers monoplane), where the wing is considerably below the level of the tail surface, increases the stabilizing efficiency.

The center of pressure travel on the wings may be reduced in a monoplane by varying the wing section, either by using a more nearly symmetrical surface, that is, by using a convex lower surface, or by turning up the trailing edge of the wing. The former method is much the more satisfactory, especially in thick wings, as it does not injure the aerodynamic properties nearly as much as the latter method. In a biplane, however, the center of pressure travel may be improved much more easily by using a large positive stagger or by using a small positive stagger and decalage. The internally braced wing used as a biplane with a large stagger obviously has a great advantage over the usual construction, where the obliquity of the struts materially reduces the structural efficiency.

LATERAL STABILITY.

There are much less available data on lateral stability than there are on longitudinal stability, mainly because the lateral stability is of considerably less importance in respect to the comfort of the pilot. Some work, however, has been done on the JN4H to determine the control forces and positions in circling flight [3] and in side slipping, but few alterations were made on the airplanes in order to determine their effect on the stability. It is evident, however, that any airplane will be moderately stable in straight level flight by the use of small dihedral on the wings, that is, a dihedral of between 2° and 6°. Lateral stability seems to be a much simpler problem than longitudinal stability. There are some airplanes, like the Morane monoplane, for instance, which are stable even in circles, that is, if the airplane is banked into a turn and the controls released it will continue to fly steadily in a circle until brought back to a level course. Just what properties make this stability possible are not known, but there are certainly no radical changes necessary to bring it about.

It may be stated here for those who would predict the lateral stability from mathematical analysis or model tests, that because several factors have been neglected which greatly influence the results, namely, the effect of the slipstream and the varying positions of the controls in full flight (where they have been assumed fixed in the model), the computed stability will have little resemblance to the actual performance of the airplane. The lateral derivatives Y_v, L_v, and N_v have been determined in full flight at Langley Field, and because of the erroneous assumptions mentioned above do not agree with the values obtained from the model.

DIRECTIONAL STABILITY.

Directional stability is exceedingly important, and fortunately is quite easy to obtain. Every airplane is probably directionally stable with locked rudder, but there are a great many airplanes which are unstable with a free rudder, which emphasizes the necessity for testing small models with the hinged part of the control surfaces free or entirely removed. The fore-and-aft position of the center of gravity has a very great effect on the directional stability. It was found in testing the JN4H that only a small change in the center of gravity position would change the airplane from unstable to stable with free rudder, which is due to the increased effectiveness of the fin when the moment arm to the center of gravity is increased, as the center of pressure of the fuselage and fin is very near the center of gravity.[4] Airplanes having large lateral area of the fuselage near the nose must have correspondingly greater fins to obtain directional stability. The Junkers JL6 airplane is directionally unstable because of this type of body. A high aspect ratio is aerodynamically desirable on the rudder and fin, but is structurally awkward.

The principal reason for having directional stability when the controls are free is that an airplane which is unstable in this particular when left to itself will immediately whip into a very rapid spin out of which it is quite impossible to get it without the use of the rudder; so should the rudder wires be broken on an airplane of this type it would be utterly impossible to keep the airplane from crashing. It should be noted that balancing the rudder is approximately equivalent to adding on to the stationary fin twice as much area as the balanced portion,

[3] N. A. C. A. Report No. 112, "Control in Circling Flight."

[4] Applied Aerodynamics, G. P. Thomson, p. 229.

so that by using a balanced rudder the effective fin area is greatly increased, thus increasing the directional stability with a free rudder.

Directional stability is almost as important when on the ground as in the air, for an unstable airplane in landing, losing most of its directional control due to the low air speed, is very apt to make a ground loop. This aspect of directional stability should be kept in mind by designers.

Below is given a table of rudder and fin areas of a number of airplanes in the same way as for longitudinal stability.

	Rudder.	Fin.
	Per cent.	*Per cent.*
Training	3.4	1.0
1-seat service	2.4	1.3
2-seat service	3.1	1.2
Bombers	2.1	1.6
Flying boats	3.2	3.0
Average	2.8	1.6

DYNAMIC STABILITY.

LONGITUDINAL STABILITY.

As dynamic stability can have no significance unless there is static stability, and as there are so few airplanes completely statically stable, there has been very little practical study made of the dynamic stability. Any statically stable airplane may be made to oscillate with its natural period, which ranges between 15 and 30 seconds for various airplanes. If the oscillation decreases in amplitude the airplane is said to be dynamically stable, but if the oscillation increases it is unstable. Of the airplanes that have been studied in this particular it is strange to notice that very few of them have shown any instability; that is, in most cases if the airplane is statically stable it automatically becomes dynamically stable also. A curve is shown in figure 14, the data for which were taken on a JN4H, showing the type of stable oscillation which usually occurs on an airplane. In general, it may be said that increasing the area of the tail or the length of the body will increase the damping and make the airplane more dynamically stable, which are exactly the things that increase the static stability. Extensive full-flight tests now being carried out by the committee show that the dynamic stability in this case does not agree with the theory or model test. At any rate, an airplane that is dynamically unstable in pitch is not at all dangerous; in fact, a pilot would have difficulty in determining whether there was instability or not.

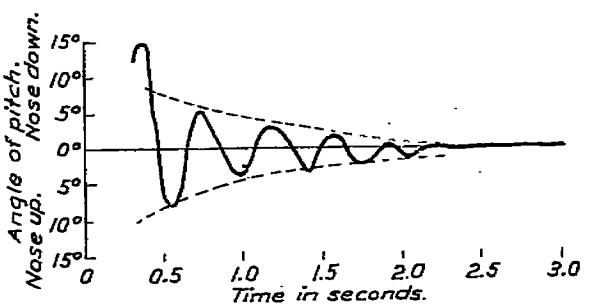

FIG. 14.—Free control oscillation of a JN4H with special tail.

LATERAL AND DIRECTIONAL STABILITY.

Very little is known in full flight of the directional or lateral stability in regard to oscillations, although a certain amount of oscillation has been studied in roll in order to determine the accuracy of bomb dropping.[5]

The spinning of an airplane is an important and much discussed subject, but up to the present there has been very little definitely learned about this matter.[6] It is certain, however, that it is a periodic phenomenon, as shown in the accelerometer record (fig. 15), and it appears as if the oscillation was decreasing in magnitude as the time increased. In some airplanes this dying out of the oscillation is much more marked, and completely disappeared in one or

[5] R. & M. No. 213, "Oscillation of an Airplane in Flight." British Advisory Committee.
[6] N. A. C. A. Report No. 105, "Angle of Attack and Air Speed in Manoeuvers."

two oscillations. The air speed is not at all high in a spin, seldom exceeding 60 to 80 miles per hour, and the angle of attack of the inner wing is often very high, sometimes reaching 90°.

As a large percentage of airplane accidents are due to spins it would be of the greatest value to construct an airplane which would not spin; but this problem is a rather complicated one, as it is connected with both longitudinal and lateral stability. It seems evident, however, from a considerable amount of investigation, that the ability to make an airplane come out of a spin by itself depends upon the area of the vertical fin. There are also some airplanes which can not be spun, but just why this should be is not at all clear.

CONTROLLABILITY.

Controllability is a rather difficult thing to define, as up to the present time there has been no quantitative method for measuring it. It may be logically divided, however, into three parts; the first is the power of the control, that is, the possibility of holding an airplane in any position, even against its natural stability or instability, if sufficient force is applied to the stick; the second, efficiency of control, demands the maximum possible controlling moment about the center of gravity of the airplane with a given force on the stick or rudder bar; and the third, which is quickness of control, demands a large moment about the center of gravity of the machine for a small movement of the control stick or rudder bar and is also of course dependent upon the moment of inertia of the airplane. To illustrate this distinction more completely, let us consider an airplane like the JN4H, which is an airplane with powerful controls, that is, even though the airplane is unstable at high speed and therefore a large force is required to hold the stick back, yet the controls are of sufficient power to pull the airplane out of the steepest dive provided the pilot has sufficient strength. An airplane such as the Salmson biplane is an example of an airplane with efficient control, that is, there are at no time more than 1 or 2 pounds force on the stick, so that it is a very comfortable airplane for the pilot to fly. An airplane that is quick on the controls may be illustrated by the VE7 or the Sopwith-Camel, where even the slightest movement of the controls produces a large angular velocity. It should be noted that the moment of inertia of the control system itself has a considerable influence on the quickness of control and for this reason should be made as light as possible. There seems to be no reason why all of these desirable characteristics may not be combined in one airplane.

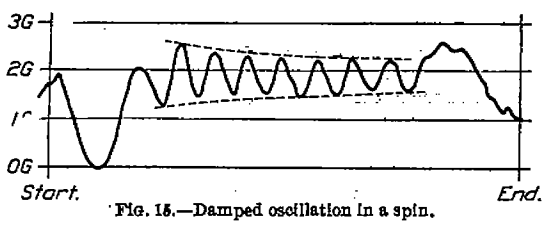

Fig. 15.—Damped oscillation in a spin.

The relation of controllability to stability should be recognized. For instance, it is possible to design an airplane which is so stable and which has so little control that it will be impossible to fly it at more than a small fraction of its normal flight range. In fact, it quite often happens that in stable airplanes it is impossible to reach the minimum speed, due to the fact that the elevator is pulled up as far as possible.[7] Again, an airplane which has powerful controls but is unstable is a rather uncomfortable airplane to fly, especially for commercial use, but is not dangerous. An airplane, however, which lacks both stability and control is extremely dangerous and should be avoided at all costs. In fighting airplanes it is desirable to have great controllability and small or neutral stability, but for commercial airplanes the stability should be considerable and the controllability only sufficient for ordinary flying.

LONGITUDINAL CONTROL.

The British[8] have done considerable work on the best size and shape of elevator, and the results are summarized in figure 16. It will be noticed that fairly close agreement is obtained between the model and the full-scale tests on the hinge moment, but that the results for the normal force on the whole tail surface in full flight show that there is a marked falling off as the size of the elevator is decreased, while the model shows nearly a constant force for any size

[7] The Factors that Determine the Minimum Speed of an Airplane. N. A. C. A. Technical Note No. 54.
[8] British Advisory Committee R. & M. No. 409 and No. 532, T 825.

of elevator, at least down to 30 per cent, so that the erroneous conclusion would be drawn from the latter results that a small elevator would be the best. It is necessary to compromise between efficiency and maximum control, the latter falling off with the size of the elevator, so that it may be concluded that an elevator containing an area of 33 per cent of the total tail surface will be satisfactory for commercial airplanes, which do not need to be stunted and where it is desirable to have an efficient control. On the other hand, for fighting airplanes, where quick maneuvers are essential, the area should be increased to about 42 per cent, which is about the average found in airplanes of this type.

These results are confirmed by some tests which have been made by the N. A. C. A. on a JN4H with two tail planes of the same area, one having an elevator of 33 per cent and one with an elevator of 43 per cent of the total horizontal tail surface. In the first case the airplane would control satisfactorily, but it appeared to the average pilot as sluggish, that is, the stick could be moved rapidly back and forth without producing any violent oscillations of the airplane, and it was very difficult to loop the airplane without having a negative loading at the top of the loop. The force on the stick, however, was quite small at all times, and for ordinary flying the control was considered to be quite satisfactory. The second tail plane, which had an elevator area of 43 per cent, was considerably more powerful, and although the airplane was not nearly as comfortable to fly, it could be stunted with ease.

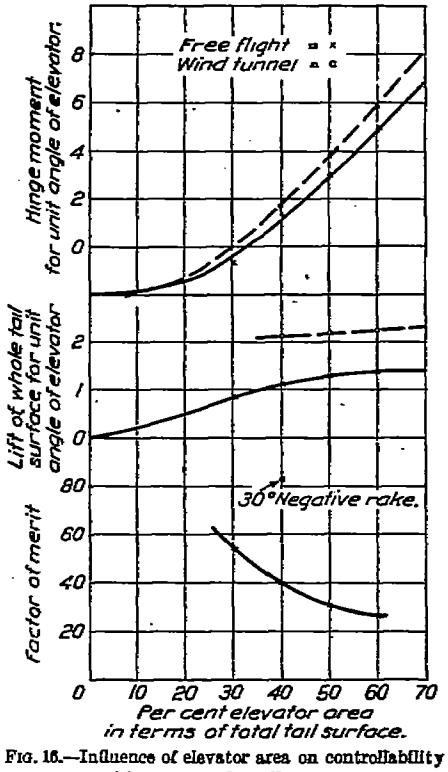

FIG. 16.—Influence of elevator area on controllability with a rectangular tail surface.

The range of elevator movement is quite important in determining the maximum control. The control efficiency can usually be increased by using smaller elevators and greater angular ranges than is now done. The angular ranges of elevator movement for several airplanes are given in the following table as actually measured on the field.

Type.	Elevator up.	Elevator down.
	°	°
JN4h	23	21
VE7	23	25
XB1A	27	19
DH4B	29	25
SE5	37	15
Martin bomber	30	14
Fokker D VII	30	18

Full flight tests were also made by the British to determine the effect of angle of rake at the tips of the tail surface. These results showed that for some inexplicable reason [9] the negative rake of 30°—that is, with the leading edge longest—gave much better results than with the usual positive rake.

LATERAL CONTROL.

There have been no satisfactory quantitative measurements made in free flight of aileron controllability, and it is necessary again to refer to the judgment of the pilot as to the lateral maneuverability of a particular airplane. In order to show what is the usual practice in area for ailerons, the following table gives the areas in percentage of the total wing area for several classes of airplanes.

[9] N. A. C. A. Report No. 119, "Distribution of Pressure Over the Tail Surfaces of an Airplane, II."

Training	11.6
2-seat service	13.8
1-seat service	11.0
Bombers	9.4
Flying boats	11.8
Average	11.5
Machines with good control	10.9

It will be noted that the average area for all of the airplanes is about 11½ per cent, while for the group of airplanes which are considered to be exceptionally controllable the area is only 11 per cent, showing that it is not area of aileron which gives great controllability. In fact, the Fokker, which is considered to have exceptional lateral control, has ailerons of only 5.2 per cent, so that the reason why this airplane should have such good controllability is unknown. As the ailerons on an airplane are out of the wash of the propeller, the results for model tests should give fairly accurate results when applied to the full-sized airplanes; therefore some British tests made on model ailerons may be considered.[10] It was found that the gap between the ailerons and the wings should be as small as possible, as a gap of one-half inch might reduce the effectiveness of the aileron by as much as 30 per cent. Contrary to the general belief, ailerons on the lower wing appear to be fully as effective as ailerons on the upper wing. In the same way as for the tail plane, the negative rake on the wing tip gives greater efficiency to the aileron, although the effect is not quite as marked in this case. As in the case of the elevator, reducing the chord of the aileron, keeping a constant breadth, increases the efficiency of the control and reduces the maximum control, especially at the lower speeds. Both full flight tests and model tests seem to show that the washed-out aileron, that is, ailerons where the tip is turned up, increases the efficiency at the lower speeds, and this method is employed on most of the German airplanes.

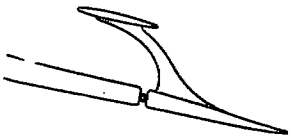

FIG. 17.—Aileron with biplane balance.

There has been a large amount of work done in the wind tunnel on balanced ailerons and some work in full flight, and the conclusion has been reached that satisfactory balances can not be obtained by an extension of the aileron at the wing tip, but that better results are obtained by an auxiliary surface above and ahead of the aileron, as shown in figure 17. From the satisfactory results which have been obtained, however, on the small and medium sized airplanes, which use no balancing, it seems that balancing would be unnecessary if the ailerons are properly designed, except for the larger airplanes.

Below is given a table of the angular range of ailerons on several airplanes.

Type.	Aileron up.	Aileron down.
	°	°
JN4H	19	24
VE7	28	25
XB1A	16	19
DH4B	17	17
SE5	14	12
Martin bomber	20	20
Fokker D VII	23	32

DIRECTIONAL CONTROL.

There can be little said on directional control, for if the rudder has enough power on the ground when taxing it usually has sufficient when in the air. The tendency of some airplanes to ground loop on landing can be attributed to insufficient directional stability and control. In stunting, a powerful rudder is not as essential as the other controls. It may be stated, however, that it is desirable to have the highest aspect ratio possible on the rudder and fin consistent with structural considerations.

[10] British Advisory Committee, T. 1247.

The angular range of rudder movement for several airplanes is given below:

Type.	Right rudder.	Left rudder.
	°	°
JN4H	30	31
VE7	38	36
XB1A	36	33
DH4B	19	20
SE 5	19	19
Martin bomber	30	27
Fokker D VII	43	40

CONCLUSIONS.

In the following paragraphs it is attempted to give as accurately as possible definite data so that the designer may produce an airplane which has the desired amount of stability and controllability. It should be realized, however, that the data on which these conclusions are based is rather meager and applies mainly to tractor airplanes with a single motor and that in some cases the results are obtained from one airplane, so that it can not be expected that this data will apply strictly to any airplane which is designed. Also, the conclusions will be modified as our information is increased. In fact, in the present state of the art it is quite impossible to design at the first trial an airplane which is perfect in stability and control, but it should be possible, however, to design an airplane which is fairly satisfactory and from tests on this airplane to deduce what changes it is necessary to make in order to correct any given faults.

LONGITUDINAL BALANCE.

1. To correct an unbalanced pull on the stick of 1 pound, move the center of gravity back 2 per cent of the chord or set the tail plane to ¼° more positive angle.

LONGITUDINAL STABILITY.

1. The center of gravity may be placed anywhere between 20 per cent and 40 per cent back on the mean chord of the wing, but 30 per cent is probably the most satisfactory.

2. The angle of the tail plane should be set at $-1°$ (zero lift line) to the wing chord for a center of gravity position of 30 per cent and up or down 0.125° for every per cent of the center of gravity from this position.

3. The area of the horizontal tail surfaces should be about 13 per cent of the wing area, and the length from the center of gravity to elevator hinge should be about 3 chord lengths.

4. With the above area and the center of gravity 30 per cent back on the wing chord, an aspect ratio of 2 on the horizontal tail surfaces will give about neutral stability. An aspect ratio of 3 will give great stability.

5. A tail section flat on the bottom will give the greatest stability at low speeds, while if it is flat on top it will give stability at high speeds. To obtain equal stability with free controls at all speeds use two-thirds of the camber above and one-third below.

LONGITUDINAL CONTROL.

1. The power of control is proportional to the area of the elevator. For great controllability use 45 per cent of the tail area in the elevator, for average airplanes 42 per cent, and for commercial airplanes, which require no stunting, and where small forces are desired on the control at all times, use 33 per cent. The efficiency of the elevator as a controlling member is found to be greatly increased by using about a 30 degree negative rake on the tips of the tail surface.

2. For the greatest quickness and lightness of control it is necessary to use small and light elevators with a large gearing between the elevator and the stick and to have a neutral or unstable airplane with locked controls. The quickness of control is also proportional to the longitudinal moment of inertia of the airplane.

LATERAL BALANCE.

1. In balancing a machine laterally, ½° of warp at the outer strut point will be equivalent to an angle of 1° on the aileron.

LATERAL STABILITY.

1. The lateral stability of the airplane does not depend primarily upon the shape or size of the aileron, but can be obtained most easily by using a dihedral angle of 3 to 6°.

LATERAL CONTROL.

1. The size of the aileron to obtain satisfactory lateral control should be about 11 per cent, but areas as low as 5 per cent have been found satisfactory on some airplanes. It is found that washing out the tips of the ailerons helps the controllability at low speeds.

DIRECTIONAL STABILITY.

1. With the usual length of fuselage a fin having an area of 2 per cent of the wings is sufficient to give directional stability with free controls.

DIRECTIONAL CONTROL.

1. It is found that a rudder having an area 2 per cent of the wing area is sufficient for ordinary controls. The rudder should have a high aspect ratio, and for a larger airplane be balanced.

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