LATERAL CONTROL REQUIRED FOR SATISFACTORY FLYING QUALITIES BASED ON FLIGHT TESTS OF NUMEROUS AIRPLANES

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SUMMARY
An analysis has been made of the aileron control characteristics of numerous airplanes tested in flight by the National Advisory Committee for Aeronautics. In the correlation of satisfactory and unsatisfactory characteristics with measured values, it was found that the helix angle $pb/2V$, which expresses the lateral displacement of the wing tip in a given forward travel of the airplane, was the measure of the aileron effectiveness appreciated by the pilots. It was also found that regardless of size or category of the airplanes tested, which included pursuit, transport, training, and bomber types, a value of $pb/2V$ of 0.07 represented a criterion of minimum satisfactory aileron effectiveness.

By the use of previously developed theory, the observed values of $pb/2V$ for the various wing-aileron arrangements were examined to determine the effective section characteristics of the various aileron types.

INTRODUCTION
A few years ago the National Advisory Committee for Aeronautics instituted a program for the study of airplane flying qualities. The primary purpose of the research program was to determine quantitatively what constitutes satisfactory flying qualities and the stability and the control requirements that an airplane can be expected to fulfill. Accordingly, the investigation has consisted mainly in determining these characteristics in flight tests of various airplanes. These airplanes were made available largely by the Army and more recently by private companies through the cooperation of the Civil Aeronautics Authority.

Stability and control characteristics have now been determined for a large number of airplanes of varied types. The data obtained not only show what constitutes satisfactory flying qualities but also, through analysis, show how various design features influence the observed flying qualities.

In the analysis of these data and in the preparation of reports, it has been convenient to consider separately the various phases of control and stability. Thus, the present report is confined to the results of the analysis of aileron control. In addition to the data obtained in tests performed specifically to determine flying qualities, data obtained in previous lateral-control investigations have been included in the analysis. Although this report deals particularly with characteristics of conventional ailerons, some data on spoiler and floating-tip ailerons were used to aid in formulating the criterion of minimum satisfactory aileron effectiveness. Including alterations to the wings and the ailerons of two of the airplanes tested, a total of 28 different wing-aileron combinations was investigated. The data analyzed cover the range of span, aspect ratio, and taper ratio in current use.

SYMBOLS
The symbols used in this report are as follows:

- $p$ rolling velocity, radians per second
- $V$ air speed, feet per second
- $b$ wing span, feet
- $\zeta_a$ average chord of aileron back of hinge line
- $\zeta_b$ average chord of aileron balance
- $\zeta_w$ average total chord of that section of the wing covered by an aileron
- $\Delta \zeta_a$ angular difference between up and down ailerons, degrees
- $k$ aileron effectiveness factor, effective change in angle of attack of wing-ailerons section per unit aileron deflection, $\Delta \alpha/\Delta \delta$
- $C_{b}$ rate of change of rolling-moment coefficient $C_l$ with aileron angle $\delta$
- $C_L$ lift coefficient
- $\alpha$ angle of attack

FLIGHT TESTS
The flight-test procedure for measuring aileron effectiveness consisted in trimming the particular airplane for straight flight at a given air speed and then abruptly applying aileron control, holding the rudder locked. Records were taken of rolling velocity, yawing velocity, air speed, and control position. Aileron control forces were also recorded whenever feasible. This procedure was repeated for various aileron deflections, at various speeds, and for different combinations of flap and power. Standard NACA flight-test instruments were used, the data being recorded photographically and synchronized by means of a timer.
General results for conventional ailerons may be summarized as follows:

(1) The rate of roll for a given airplane at a given control deflection was very nearly a linear function of air speed except for cases where control-cable stretch appreciably limited the available aileron deflections. At a given air speed the rate of roll progressively increased with aileron deflection, the type of variation being dependent on the type of aileron balance. In some instances, with balanced ailerons, a point was reached where further deflection produced no additional rolling moment.

(2) None of the aileron combinations tested exhibited objectionable lag characteristics. Rolling accelerations were great enough in all cases that the rolling velocity furnished the important measure of aileron control from the pilot's viewpoint.

(3) Rates of roll that would have been unsatisfactory for small airplanes were considered entirely adequate for large airplanes.

(4) Rates of roll that were considered inadequate at high speeds were satisfactory at low speeds.

(5) The effectiveness of the aileron control in normal flight had no correlation with the aileron control at the stall. In no case could the completely stalled airplane be controlled by means of the ailerons.

(6) Power or flap position had only very slight effects on the rolling velocities obtained.

(7) Some of the large airplanes tested suffered severely from the effects of control-cable stretch in limiting the available aileron deflections, particularly at high speeds. It would also appear that the large airplanes and some of the small airplanes with fabric-covered wings lost a considerable amount of potential rolling ability through wing warping due to the torsional loads applied by the deflected ailerons.

In the summary of the flight data obtained from the various airplanes tested, it was desirable to use the nondimensional expression $\frac{pb}{2V}$. Interpreted physically, $\frac{pb}{2V}$ represents the lateral displacement of the wing tip in a given forward travel of the airplane or, in other words, the helix angle generated by the wing tip. The characteristics of conventional ailerons are such that, for geometrically similar airplanes regardless of size or air speed, substantially constant values of $\frac{pb}{2V}$ are obtained for a given aileron deflection. Thus, the rolling performance of an airplane may be defined in terms of the numerical value of $\frac{pb}{2V}$ obtained with full control deflection for the case of conventional ailerons that reach full deflection at all speeds under consideration.

This method of presentation has been used in table I where the characteristics of the various airplanes tested have been tabulated. In addition to the values of $\frac{pb}{2V}$ obtained with full available aileron control, the wing span, the wing loading, the pilot's opinion of the control effectiveness, and a sketch of the wing-aileron combination are included for each airplane. Except as indicated in the table, the maximum values of $\frac{pb}{2V}$ given were substantially constant over the speed range tested. Deviation from constant values in the very large airplane (airplane K) resulted from control-cable stretch that also limited aileron power even at low speeds. An average value of $\frac{pb}{2V}$ is given for this airplane. For the airplane U with retractable ailerons, the value given of $\frac{pb}{2V}$ is for low-speed flight.

**CRI TERION FOR ALERON EFFECTIVENESS**

Comparison of the measured values of $\frac{pb}{2V}$ with pilots' opinions of the lateral-control effectiveness suggests a lower limit for the amount of lateral control that is considered satisfactory by pilots. Although the values of $\frac{pb}{2V}$ varied considerably among the various airplanes tested, no case was recorded where control was considered adequate for values of $\frac{pb}{2V}$ less than 0.07 or where inadequate control was reported for airplanes exceeding this limit. The same limit appears to apply to large airplanes as well as small airplanes regardless of wing loading or purpose for which the airplane was intended.

Values of $\frac{pb}{2V}$ much greater than the suggested lower limit of 0.07 were experienced in several cases. These airplanes were not considered by the pilots to be particularly outstanding or to be superior in essential qualities of control to airplanes developing much lower values. On the other hand, none of the ailerons tested were considered as being too effective.

The requirement for satisfactory lateral control indicated by the present analysis is at considerable variance with the criterion previously used by the NACA. Requiring that the maximum value of $\frac{pb}{2V}$ should never be less than 0.07 is the same as specifying that the maximum rolling-moment coefficient should not be less than $0.07C_L$, a value that is constant for any given airplane. On the other hand, the rolling criterion of references 1 and 2 specified that the ratio of rolling-moment coefficient to lift coefficient be a constant. The value of $C_{L}/C_L$ that was suggested was 0.075 although, as stated in reference 2, a value possibly half as great might be used for airplanes not intended to be aerobatic.

The $C_{L}/C_L$ criterion was designed primarily for application to the low-speed conditions for airplanes of the private-owner type. In the light of the present investigation it is considered ultraconservative for all types at low speeds. Comparison of the test results on airplanes of different wing loadings indicates that the rolling-moment coefficient required for satisfactory control is independent of lift coefficient. As the minimum speed and not the lift coefficient is apparent to the pilot, a heavily loaded airplane with a high-lift device should require no greater rolling-moment coefficient, and corresponding helix angle, than is required by a lightly loaded airplane of equivalent minimum speed.
As regards the variation of rolling-moment coefficient with lift coefficient implied by the \( C_l/C_d \) criterion throughout the speed range, the present analysis indicates that no such marked drop in aileron effectiveness can be tolerated with increased speed. Rather, it appears that a rolling-moment coefficient large enough to give the specified value of \( pb/2V \) is desired and is used by pilots up to reasonably high speeds. For large airplanes this amount of control is required chiefly to provide sufficient corrective control for rolling due to atmospheric disturbances. For airplanes of the pursuit category, this amount of control appears to be required in maneuvering at high speeds. In this connection, airplanes with high stick forces may have insufficient aileron control at high speeds because the controls cannot be deflected a sufficient amount.

The rolling requirements of pursuit types, in addition, call for consideration of the actual rolling velocities available, because the maneuverability in roll is dependent on the time required to bank the airplane at maneuvering speeds. As indicated, a value of \( pb/2V \) of 0.07 appears to give adequate rolling velocities at maneuvering speeds for pursuit airplanes of the types tested because of the short span used and the relatively high maneuvering speeds. The use of greater wing spans in airplanes of this type would, of course, require proportionately larger values of \( pb/2V \) unless a reduction of maneuverability in roll could be accepted.

For ailerons of the conventional trailing-edge type, the criterion as expressed in terms of \( pb/2V \) is sufficient to insure satisfactory aileron effectiveness. For lateral controls that depend on spoiler action, however, unsatisfactory characteristics may result from lag or from an incorrect initial response even though the specified value of \( pb/2V \) is obtained. Some of the difficulties experienced with spoilers are discussed in reference 2.
determine \( C_{il}/k \) with sufficient accuracy in practical work for airplanes of aspect ratios other than those given in figure 1. In use, the value of \( C_{il}/k \) is read at a point on the semispan corresponding to the position of the outer end of the aileron, and from this value is deducted the value read at a point corresponding to the inner end of the aileron. The quantity thus obtained is the value of \( C_{il}/k \) used in the formula. The coefficient \( C_{tp} \), of course, does not vary with aileron span.

The values of the aileron effectiveness factor \( k \), when \( \Delta \theta_a = 30^\circ \), were determined from the observed \( \phi b/2V \) values of the various airplanes tested in flight and are presented in figure 3 as a function of the ratio of mean aileron chord \( \bar{c}_a \) to mean wing chord \( \bar{c}_w \). The values of \( k \) determined in flight are considerably lower than those predicted by theory and, in most cases, they are lower than values obtained for comparable aerodynamic arrangements in the wind tunnel. At least part of this effect may be accounted for on the basis of the deflection of the wing in torsion and the deflection of the aileron control system. For example, 1° of wing twist varying uniformly from the wing tip would reduce the apparent aileron effectiveness by about 20 percent. The wing deflections experienced by the various airplanes, however, are unknown. The deflections that occurred between the ailerons and the cockpit control are likewise unknown. Inasmuch as aileron deflections were determined on the basis of the position of the cockpit control, this fact would further tend to reduce the apparent aileron effectiveness. For these reasons, it would seem unwise to draw any final conclusions regarding the relative merits of the aileron types employed.

If the rigidity of the wing and the control system is known, accurate prediction of aileron effectiveness should be possible on the basis of wind-tunnel data for the aileron type employed. If this information is lacking, however, the curves for plain ailerons given in figure 3 should give sufficiently conservative results.

In general, the aileron effectiveness factor \( k \) for plain ailerons did not vary with aileron deflection for angles up to approximately \( \pm 20^\circ \). With the balanced ailerons, however, the effectiveness factor was a maximum at small deflections and usually decreased progressively as the deflection increased so that the values given in figure 3 should be somewhat reduced if a deflection range greater than \( 30^\circ \) is contemplated.

**CONCLUDING REMARKS**

The helix angle \( \phi b/2V \) generated by the wing tip of an airplane in an abrupt aileron roll appears to represent the aileron control effectiveness appreciated by pilots. The lower limit for satisfactory aileron effec-
were unsatisfactory in this respect. In some cases, however, material reduction in stick force has been possible simply by a restriction of the deflection range of the ailerons to that required. The maximum stick force varies as the square of the deflection range, because mechanical advantage of the control system as well as the hinge moments of the ailerons is involved.

The point previously made regarding aileron control at the stall may well be emphasized again. Aileron control here depended upon the symmetry of flow and the rate at which the flow broke down on the wing and had no correlation with the control available in normal flight. In no case was aileron control retained when the wing was completely stalled; roll against the ailerons usually occurred as a result of the adverse yaw developed.

REFERENCES


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