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REQUIREMENTS FOR SATISFACTORY FLYING QUALITIES OF AIRPLANES

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INTRODUCTION

The need for quantitative design criterions for describing those qualities of an airplane that make up satisfactory controllability, stability, and handling characteristics, has been realized for several years. Sometime ago, preliminary studies showed that adequate data for the formulation of these criterions were not available and that a large amount of preliminary work would have to be done in order to obtain the information necessary. It was apparent that flight tests of the flying qualities of numerous airplanes were required in order to provide a fund of quantitative data for correlation with pilots' opinions.

Accordingly, a program was instituted which covered the various phases of work required. The first step involved the development of a test procedure and test equipment which would measure the characteristics on which flying qualities depend. This phase of the work is reported in reference 1, although since that time the test procedure has been expanded and modified on the basis of additional experience and several changes have been made in the equipment used.

Another phase of the investigation has involved the measurement of the flying qualities of a number of airplanes. The procedure used has been in general in accord with that described in reference 1. At the present time, complete tests of this nature have been made of 16 airplanes of varied types. These airplanes were made available largely by the Army and more recently by private companies at the request of the Civil Aeronautics Board. In addition, flying-qualities data of more limited scope have been obtained from time to time on a number of other airplanes, the tests of which covered only particular items of stability and control but which, nevertheless, augment the fund of data now available.

A third phase of the investigation, one which also has been pursued throughout the duration of the project, has involved the analysis of available data to determine what measured characteristics were significant in defining satisfactory flying qualities, what characteristics it was

reasonable to require of an airplane, and what influence the various design features had on the observed flying qualities.

In order to cover this work adequately, a number of papers dealing separately with the various items of stability and control are necessary. Several such papers have been prepared or are in preparation at the present time. Detailed studies of all items will require considerable time for completion, but it is believed that the conclusions reached to date are complete enough to warrant a revision of the tentative specifications set forth in reference 1. As opportunity for additional analysis occurs, it would be desirable to cover the individual requirements at more length than is possible at this time. As a result of further studies, it may also be desirable to revise again the flying-qualities specifications given here.

In addition to the actual specifications, the chief reasons behind the specifications are discussed. Wherever possible, interpretation of the specification is made in terms of the design features of the airplane unless the subject is covered in reports of reference.

In formulating the specifications, every attempt has been made to define the required characteristics in easily measurable, yet fundamental terms. It was necessary to consider all stability and control requirements in arriving at each individual item because of the varied functions of the individual controls and the conflicting nature of many of these functions.

The specifications require characteristics that have been demonstrated to be essential for reasonably safe and efficient operation of an airplane. They go as far toward requiring ideal characteristics as present design methods will permit. Compliance with the specifications should insure satisfactory flying qualities on the basis of present standards, although as additional knowledge is obtained it may be possible to demand a closer approach to ideal characteristics without in any way penalizing the essential items of performance.

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FLYING-QUALITY REQUIREMENTS

It has been convenient to present the flying-quality requirements under the following individual headings. They appear in the report in this order.

I. Requirements for Longitudinal Stability and Control:

A. Characteristics of uncontrolled longitudinal motion.

B. Characteristics of elevator control in steady flight.

C. Characteristics of elevator control in accelerated flight.

D. Characteristics of elevator control in landing.

E. Characteristics of elevator control in take-off.

F. Limits of trim change due to power and flaps.

G. Characteristics of longitudinal trimming device.

II. Requirements for Lateral Stability and Control:

A. Characteristics of uncontrolled lateral and directional motion.

B. Aileron-control characteristics

C. Yaw due to ailerons.

D. Limits of rolling moment due to sideslip.

E. Rudder-control characteristics

F. Yawing moment due to sideslip

G. Cross-wind force characteristics

H. Pitching moment due to sideslip

I. Characteristics of rudder and aileron trimming devices

III. Stalling Characteristics.

These requirements pertain to all flight conditions in which the airplane may be flown in normal or emergency operation, with the center of gravity at any point within the placarded limits. Some of the specifications are based on the behavior of the airplane at some specified air speed. The air speed in such cases shall be taken as the indicated air speed. Where minimum air speed is referred to, unless otherwise stated, it shall be taken as the minimum air speed obtainable with flaps down, power off.

With the exception of part III of the requirements, which deals exclusively with characteristics at or close to the stall, the requirements pertain to behavior of the airplane in the range of normal flight speeds at angles of attack below that at which the stall would occur.

In the specifications which follow, the lower limits of the control-force gradients are specified in terms of the ability of the controls to return to trim positions upon release from deflected positions. This is a very desirable characteristic because it assures a control friction sufficiently low in comparison with the aerodynamic forces to allow the pilot to feel the aerodynamic forces on the controls. However, some additional interpretation of the specifications is necessary, because no control system can be made entirely free of friction and, therefore, there will always be some small deviation from return to absolute trim. At the present time, it is not possible to fix the allowable limits for those deviations. It is known, however, that controls reasonably free from friction, as measured on the ground, have satisfactory self-centering characteristics in the air as long as there is a definite force gradient. For elevators, force gradients as low as 0.05 pound per mile per hour have been satisfactory when the friction was small. For relatively small airplanes such as fighters, trainers, and light airplanes, it appears that about 2 pounds of friction in the elevator control system and 1 pound in the aileron represent an upper limit. In several cases, where push-pull rods with ball bearings were used throughout the control system, friction in both elevator and aileron systems has been found to be under 1/2 pound.

For large airplanes not intended to maneuver where visual or instrument references are always available, self-centering characteristics are not believed to be essential, although they are very desirable. In these airplanes,

control friction should be kept as low as possible, although there is indication that considerably more friction can be tolerated. A representative amount of control friction for a transport or medium bomber would be about 10 pounds in the elevator system and 6 pounds in the ailerons.

Irreversible controls have somewhat similar characteristics to controls with high friction; that is, they are not self-centering and therefore tend to destroy control feel. They are not considered desirable, although on very large airplanes where the rates of deviation from steady flight are slow they have been used successfully on ailerons.

I. Requirements for Longitudinal Stability and Control

Requirement (I-A): Characteristics of uncontrolled longitudinal motion.

When elevator control is deflected and released quickly, the subsequent variation of normal acceleration and elevator angle should have completely disappeared after one cycle.

Reasons for Requirement (I-A): The requirement specifies the degree of damping required of the short-period longitudinal oscillation with controls free. A high degree of damping is required because of the short period of the motion. With airplanes having less damping than that specified, the oscillation is excited by gusts accentuating their effect and producing unsatisfactory rough-air characteristics. The ratio of control friction to air forces is such that damping is generally reduced at high speeds. When the oscillation has appeared at high speeds as in dives and dive pull-outs it was, of course, very objectionable because of the accelerations involved.

The short-period oscillations involve variations of the angle of attack at essentially constant speed and should not be confused with the well-known long-period (phugoid) oscillation, which involves variation of speed at an essentially constant angle of attack. As shown by the tests of reference 2, the characteristics of the latter mode of longitudinal motion had no correlation with the ability of pilots to fly an airplane efficiently, the long period of the oscillation making the degree of damping unimportant. Subsequent tests have not altered this conclusion. The case of pure longitudinal divergence of the airplane (static instability) will be covered later under requirements of the elevator control in steady flight. No

requirement for damping of the long-period phugoid motion appears justifiable at the present time.

Design considerations.- A theoretical analysis of this problem (unpublished) has shown that the damping of the control-free (short-period) oscillation is dependent chiefly on the magnitude of the hinge-moment coefficient of the elevators and on the mass balance and moment of inertia of the control system. The analysis shows that the damping is improved by increasing the hinge-moment coefficient, increasing the mass balance, and reducing the moment of inertia. The introduction of friction damping in the control system should, of course, also be effective although control friction is very undesirable for other reasons.

Requirement (I-B): Characteristics of elevator control in steady flight.

1. The variation of elevator angle with speed should indicate positive static longitudinal stability for the following conditions of flight:

a. With engine or engines idling, flaps up or down, at all speeds above the stall.

b. With engine or engines delivering power for level flight with flaps down (as used in landing approach), landing gear down, at all speeds above the stall.

c. With engine or engines delivering full power with flaps up at all speeds above 120 percent of the minimum speed.

2. The variation of elevator control force with speed should be such that pull forces are required at all speeds below the trim speed and push forces required at all speeds above the trim speed for the conditions requiring static stability in item 1.

3. The magnitude of the elevator control force should everywhere be sufficient to return the control to its trim position.

4. It should be possible to maintain steady flight at the minimum and maximum speeds required of the airplane.

Reasons for Requirement (I-B): Items 1 and 2 require

positive static stability for flight conditions in which the airplane is flown for protracted lengths of time, or where opportunity exists to establish a trim speed so that stable characteristics can be realized. Positive static stability is not considered particularly helpful to a pilot at very low speeds with full power on or with flaps extended with full power on, because of the large trim changes due to power usually experienced. The conditions are classed as emergency conditions because in actual operation they are entered suddenly from approach conditions, where relatively little power is used. In these cases the elevator force and position changes, due to applied power and change of flap setting, are usually far greater than any inherent stable or unstable force or position gradients which exist due to the degree of static stability present. For these reasons, static stability in these conditions is not considered essential, at least not until trim changes due to power are reduced to much lower values than are experienced at the present time. The magnitude of allowable trim change due to power and flaps is covered later in Requirement (I-F).

In other conditions of flight, however, static stability is regarded as an essential flight characteristic. Item 1 pertains to the elevator-fixed condition. This requirement insures that the airplane will remain at a given angle of attack or air speed as long as the elevator is not moved, and provided that disturbed motion of the airplane is not left uncontrolled for long periods of time. Positive stability eliminates the need for constant control manipulation in maintaining given conditions and, furthermore, simplifies the control manipulation when a speed change is desired, because the direction of control movement required to start the rotation in pitch corresponds to that required to trim at the new angle of attack. A negative slope to the elevator-angle curve is a necessary requirement for elevator control feel, and the degree of control feel increases as the variation of elevator angle with angle of attack is increased (reference 3). In general, it may be said that the variation of elevator angle with angle of attack should be negative and as large numerically as is consistent with other requirements of elevator control.

Item 2 requires that the elevator-free static longitudinal stability shall always be positive. This specification insures that the airplane will not depart from a trim speed except as a result of definite action on the part of the pilot.

Item 3 requires that the elevator control be self-centering, a characteristic which is necessary for the attainment of control feel.

The reason for item 4 is obvious.

Design considerations.- A detailed analysis of the static longitudinal stability characteristics of various airplanes and the influence of various design features on the observed characteristics is given in reference 4.

Requirement (I-C): Characteristics of the elevator control in accelerated flight.

1. By use of the elevator control alone, it should be possible to develop either the allowable load factor or the maximum lift coefficient at every speed.

2. The variation of elevator angle with normal acceleration in steady turning flight at any given speed should be a smooth curve which everywhere has a stable slope.

3. For airplanes intended to have high maneuverability, the slope of the elevator-angle curve should be such that not less than 4 inches of rearward stick movement is required to change angle of attack from a C_L of 0.2 to $C_{L_{max}}$ in the maneuvering condition of flight.

4. As measured in steady turning flight, the change in normal acceleration should be proportional to the elevator control force applied.

5. The gradient of elevator control force in pounds per unit normal acceleration, as measured in steady turning flight, should be within the following limits:

a. For transports, heavy bombers, etc., the gradient should be less than 50 pounds per g.

b. For pursuit types, the gradient should be less than 6 pounds per g.

c. For any airplane, it should require a steady pull force of not less than 30 pounds to obtain the allowable load factor.

Reasons for Requirement (I-C): Item 1 of this specification requires that sufficient elevator control should be available to execute maneuvers of the minimum radius inherent in the aerodynamic and structural design of the airplane. Since the curvature of the flight path is directly related to the normal acceleration, it is obvious that the attainment of either the maximum lift coefficient or the allowable load factor is the limiting condition.

Item 2 is a requirement for stability in turning flight. Airplanes that do not meet this requirement tend to "dig in" and overshoot desired accelerations in maneuvers, even though every use is made of visual and instrument references.

Item 3 specifies the amount of stability required of an airplane which must be maneuvered at or close to maximum lift without resort to visual or instrument references. It has been demonstrated by tests of several pursuit airplanes that longitudinal stability and control characteristics as specified are necessary for airplanes that require a high degree of control feel. The provision of such characteristics also reduces the time required to change angle of attack in entering rapid turns or zoons due to the simplified control manipulation associated with a definitely stable airplane.

The linear stick-force gradients specified in item 4 are, of course, very desirable as an aid to the pilot in obtaining the accelerations desired.

The numerical limits specified for the force gradients in item 5 are such that the minimum radius may be readily attained in any airplane. For pursuit types, gradients greater than 6 pounds per g were considered heavy by pilots. For airplanes where the load factor is lower, such as bombers, transports, etc., which are not required to maneuver continuously, a gradient of 50 pounds per g is not excessive. To insure against inadvertent overloading of the structure, the 30-pound lower limit (item 5-c) is necessary. For pursuit airplanes with allowable load factors of 9, this lower limit would correspond to a gradient of about 4 pounds per g. For airplanes with lower load factors, such as bombers, transports, or light airplanes, the gradient in pounds per g would be proportionately higher.

Important design factors.- In turning flight, due to

the curvature of the flight path, a stabilizing effect is obtained which increases the slope of the elevator-angle curve over that obtained in straight flight. The stick forces required to maintain a given lift-coefficient are considerably greater than those for straight flight, however, because the elevator angles are higher and because they are obtained at greater speeds. For this reason, it is necessary to specify the upper limit of elevator-force gradients only for accelerated flight.

A linear relation between stick force and normal acceleration is always obtained provided the elevator-angle curve and hinge-moment coefficient curve have linear variations with angle of attack and deflection, respectively.

Requirement (I-D): Characteristics of the elevator control in landing.

1. (Applicable to airplanes with conventional landing gears only.) The elevator control should be sufficiently powerful to hold the airplane off the ground until three-point contact is made.

2. (Applicable to airplanes with nose-wheel type landing gears only.) The elevator control should be sufficiently powerful to hold the airplane from actual contact with the ground until the minimum speed required of the airplane is attained.

3. It should be possible to execute the landing with an elevator control force which does not exceed 50 pounds for wheel-type controls, or 35 pounds where a stick-type control is used.

Reasons for Requirement (I-D): For airplanes with conventional landing gears, the three-point attitude usually corresponds closely to that for the development of minimum speed for landing. In addition, an airplane alighting simultaneously on main wheels and tail wheel is less likely to leave the ground again as a result of possessing vertical velocity at the time of contact.

The reason for item 2 is obvious.

The limits of allowable control force in landing were determined from considerations of the pilot's capabilities. The limit forces given are 80 percent of those which a pilot can apply with one hand to the different control

arrangements with the control 12 inches from the back of the seat. (See references 3 and 5.)

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Design factors.- The requirements of the elevator in producing three-point or minimum speed landings are by far the most critical from a standpoint of control power. Flight-test data show that low-wing monoplanes with flaps down require about 10° more up elevator to land than to stall in comparable conditions at altitude. Without flaps this increment due to ground effect is not so great, and with high-wing monoplanes without flaps the landing frequently requires less elevator than the power-off stall at altitude.

Requirement (I-E): Characteristics of elevator control in take-off.

During the take-off run, it should be possible to maintain the attitude of the airplane by means of the elevators at any value between the level attitude and that corresponding to maximum lift after one-half take-off speed has been reached.

Reasons for Requirement (I-E): The attitude of an airplane for optimum take-off characteristics depends upon the condition of the runway surface. On smooth, hard surfaces with low-rolling friction the shortest take-off run is obtained with a tail-high attitude. Where rolling friction is high, however, it is advantageous to maintain an attitude which gives high lift.

Design considerations.- Adequate control of the attitude angle during take-off depends more on the proper location of the landing gear with respect to the center of gravity than on the characteristics of the elevators themselves. This requirement certainly is not critical from a standpoint of elevator control. An airplane that has sufficient tail volume to be stable and sufficient elevator control to perform three-point or minimum-speed landings should meet this requirement easily, as long as the main landing-gear wheels are properly located.

Requirement (I-F): Limits of trim change due to power and flaps.

1. With the airplane trimmed for zero stick force at any given speed and using any combination of engine power and flap setting, it should be possible to maintain the given speed without exerting push or pull forces greater than those listed below when the power and flap setting

are varied in any manner whatsoever.

a. Stick-type controls - 35 pounds push or pull.

b. Wheel-type controls - 50 pounds push or pull.

2. If the airplane cannot be trimmed at low speeds with full use of the trimming device, the conditions specified in item 1 should be met with the airplane trimmed full tail-heavy.

Reasons for Requirement (I-F): It is desired that emergency manipulations of flaps or throttles do not require simultaneous adjustments of the trimming device. The force limits specified are approximately 80 percent of the maximum that a pilot can apply with one hand. The one-hand limit is necessary to allow the adjustment of throttles, flaps, or trimming device while complete longitudinal control is maintained. It is, of course, desirable that the trim changes be less than the limiting values given. The ideal condition would be one where the stick forces required for trim were not influenced by the position of the flaps or throttles.

It is also desirable that the control position required to maintain a given speed or lift coefficient be independent of the power and flap position insofar as possible. It is not, however, believed reasonable or necessary to specify any definite limits at this time.

Design factors.- Because of simultaneous changes in downwash, dynamic pressure at the tail, and pitching moment of the airplane less tail, the trim change produced by variations of power and flap setting are very difficult to predict. Several of the effects, however, have opposite signs, so that with sufficient care it should be possible to restrict the trim changes to a reasonably low value. Wind-tunnel tests of a powered model of the design under consideration would be a great help if not an absolute essential in this connection.

Requirement (I-G): Characteristics of the longitudinal trimming device.

1. The trimming device should be capable of reducing the elevator control force to zero in steady flight in the following conditions:

a. Cruising conditions - at any speed between high speed and 120 percent of the minimum speed.

b. Landing condition - any speed between 120 percent and 140 percent of the minimum speed.

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2. Unless changed manually, the trimming device should retain a given setting indefinitely.

Reasons for Requirement (I-G): It is, of course, desirable to be able to reduce the elevator force to zero in conditions where the airplane must be flown for protracted lengths of time. It is also desirable to be able to establish a trim condition within the allowable speed limits of the airplane so that release of the controls will not put the airplane in a dangerous position.

The reasons for item 2 are obvious.

II. Requirements for Lateral Stability and Control.

Requirement (II-A): Characteristics of uncontrolled lateral and directional motion.

1. The control-free lateral oscillation should always damp to one-half amplitude within two cycles.

2. When the ailerons are deflected and released quickly, they should return to their trim position. Any oscillations of the ailerons themselves shall have disappeared after one cycle.

3. When the rudder is deflected and released quickly, it should return to its trim position. Any oscillation of the rudder itself shall have disappeared after one cycle.

Reasons for Requirement (II-A): Because of its relatively short period, the lateral oscillation must be heavily damped. It is not logical to specify limits for the period of the oscillation because the period is dependent on factors covered by other specifications and also because the period is dependent on the size, speed, and weight of the airplane. The amount of damping specified in item 1 has been obtained with all satisfactory airplanes tested.

Items 2 and 3 of the requirement (II-A) are included to insure stability in the behavior of the lateral controls themselves.

Attention is called to the omission of a requirement for spiral stability. Tests have shown that the lack of spiral stability has not detracted from the pilot's ability to fly an airplane efficiently. In fact, it is very difficult to determine whether an airplane is inherently spirally stable or not, because divergence will occur with a spirally stable airplane if perfect lateral and directional trim do not exist or if slight asymmetry in engine power occurs in a multiengine airplane. For these reasons a large amount of inherent spiral stability would be required to insure against lateral divergence under actual conditions.

Since it appears that the degree of spiral stability or instability is inconsequential or at least of doubtful importance under actual conditions, it is desirable to avoid any such requirement because the design conditions for spiral stability conflict with other factors known to be essential in the attainment of satisfactory flying qualities.

Design considerations.- The theory of dynamic stability has been rather extensively developed from a mathematical standpoint. The charts of reference 6 make the calculation of the dynamic characteristics a relatively simple matter, provided the stability derivatives are known. In general, however, the stability derivatives are not known and cannot be estimated to a reasonable degree of accuracy, particularly with power on.

On the basis of experience, however, it appears that the damping requirement is not a critical design condition. There is every indication that when other requirements of fin area and dihedral are met, the uncontrolled lateral motion will be satisfactory.

Items 2 and 3 of the requirement (II-A) are dependent, as was the elevator-free motion (requirement I-A), on the control-hinge moments, mass balance, and moment of inertia of the control systems.

Requirement (II-B): Aileron-control characteristics - (rudder locked).

1. At any given speed, the maximum rolling velocity obtained by abrupt use of ailerons should vary smoothly with the aileron deflection and should be approximately proportional to the aileron deflection.

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2. The variation of rolling acceleration with time following an abrupt control deflection should always be in the correct direction and should reach a maximum value not later than 0.2 second after the controls have reached their given deflection.

3. The maximum rolling velocity obtained by use of ailerons alone should be such that the helix angle generated by the wing tip, $pb/2V$, is equal to or greater than 0.07

where p maximum rolling velocity, radians/second

b wing span

V true air speed, feet per second

4. The variation of aileron control force with aileron deflection should be a smooth curve. The force should everywhere be great enough to return the control to trim position.

5. At every speed below 80 percent of maximum level-flight speed, it should be possible to obtain the specified value of $pb/2V$ without exceeding the following control-force limits:

a. Wheel-type controls: ±80 pounds applied at rim of wheel.

b. Stick-type controls: ±30 pounds applied at grip of stick.

Reasons for Requirement (II-B): Item 1 of this requirement states an obviously desirable condition for any control; i.e., that the response shall be proportional to deflection.

Item 2 is designed to eliminate controls that are unsatisfactory from a standpoint of lag in the development of the rolling moment, or controls in which the initial rolling action is in the wrong direction.

Item 3 was obtained by correlation of pilots' opinions and measured characteristics for some 20 different airplanes of various types and sizes (reference 7). It was found that pilots judged the adequacy of their lateral control on the basis of the helix angle generated by the

wing tip of the airplane. Airplanes giving values of $pb/2V$ less than 0.07 were always considered unsatisfactory.

Item 4 is a requirement for self-centering characteristics of the lateral control. This is a necessary condition for satisfactory control feel.

The specification of item 5 was determined by the limitations of pilots in applying forces to the lateral controls. Lower forces are, of course, desirable.

Design considerations for Requirement (II-B): Item 1 represents a normal characteristic of conventional flap-type ailerons, provided they are not deflected beyond the range where their effectiveness is linear. Certain spoiler-type ailerons, however, have been unsatisfactory because of their failure to meet this requirement. In these cases, the variation of effectiveness with deflection was either markedly nonlinear or such that appreciable movements of the control about the neutral point were required before the ailerons became effective.

Item 2 also is met by all conventional flap-type ailerons. Again, however, certain arrangements of lateral controls that depend on spoiler action have proved unsatisfactory because of lag or incorrect initial development of the rolling moment. Detail information on various satisfactory and unsatisfactory spoiler types may be found in reference 8 and later reports on the subject.

The specification of the helix angle, $pb/2V \geqq 0.07$ of item 3, corresponds approximately to requiring a rolling moment coefficient, C_l, of 0.035 or greater. Actually since $pb/2V$ is equal to the ratio of the rolling-moment coefficient to the damping-moment coefficient, C_l/C_{l_p}, a criterion in terms of C_l alone is not strictly applicable. The damping-moment coefficient tends to decrease with increased taper of the wing and to increase with increased aspect ratio. However, for the aspect ratios and taper ratio likely to be used, the criterion considered in terms of rolling-moment coefficient alone, $C_l \geqq 0.035$, should be satisfactory. In several types tested, particularly the very large airplanes, control-cable stretch resulted in a very serious loss of aileron effectiveness. There is also indication that wing twist under the torsional loads applied by ailerons, should be considered in an interpretation of the rolling-moment coefficient required to obtain the specified value of $pb/2V$.

Item 4 sets the upper limit for aileron control friction since the ability of a control to center itself depends on the ratio of the inherent force gradient to the frictional force.

The control-force limits of item 5 are, of course, critical at the high speed specified. This requirement can be met by using existing design methods without servo control or mechanical booster systems except, perhaps, for the very largest airplanes that appear at this time.

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Requirement (II-C): Yaw due to ailerons.

With the rudder locked at 110 percent of the minimum speed, the sideslip developed as a result of full aileron deflection should not exceed 20°.*

Reasons for Requirement (II-C): Aileron yaw is responsible not only for annoying heading changes as a result of the use of ailerons but also for a reduction of aileron effectiveness unless the rudder is carefully manipulated to eliminate the sideslip induced. This latter effect is also dependent on the rolling moment due to sideslip (dihedral effect).

The requirement for aileron yaw expressed in this manner clearly separates satisfactory characteristics from those considered unsatisfactory by pilots and, moreover, has the merit of relating the factors responsible for aileron yaw in a fundamental manner. The limiting condition of 20° sideslip seems surprisingly high, but the number of satisfactory airplanes that develop sideslip angles substantially this great cannot be ignored. The requirement, however, is written to cover the critical low-speed conditions. At cruising speeds, comparable tests would give sideslip angles of the order of 5°.

Design considerations.- The sideslip due to ailerons is chiefly dependent on the aileron yawing moment, the yawing moment due to rolling, the dihedral effect, and the directional stability of the airplane. Compliance with the requirement depends mainly on the provision of sufficient directional stability, since the aileron yawing moment and the yawing moment due to rolling are determined by the aileron power. Of course, the designer has some

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*The measured sideslip angle on which this and subsequent specifications are based should not be confused with the angle of bank of the airplane. The angle of sideslip is simply that given by a vane free to pivot about a vertical axis and aline itself with the relative wind.

control over the adverse aileron yawing moment through the use of differential in the control system and by increasing the profile drag of the up aileron. These effects, however, are generally small in comparison with inherent yawing moments due to ailerons and rolling velocity, which are always adverse in sign.

The required amount of directional stability is simply that which will give an equilibrium of the yawing moments at or below the angle of sideslip specified. The adverse aileron yawing moments can, of course, be determined in the wind tunnel. The yawing moment due to rolling for wings of various plan forms is given in the charts of reference 9.

Requirement (II-D): Limits of rolling moment due to sideslip (dihedral effect).

1. The rolling moment due to sideslip as measured by the variation of aileron deflection with angle of sideslip should vary smoothly and progressively with angle of sideslip and should everywhere be of a sign such that the aileron is always required to depress the leading wing as the sideslip is increased.

2. The variation of aileron stick force with angle of sideslip should everywhere tend to return the aileron control to its neutral or trim position when released.

3. The rolling moment due to sideslip should never be so great that a reversal of rolling velocity occurs as a result of yaw due to ailerons (rudder locked).

Reasons for Requirement (II-D): Item 1 insures that the roll due to rudder will always be in the correct direction and that any lateral divergence will not be of a rapid type. It is also a necessary but not a sufficient condition for the ability to raise a wing by means of the rudder.

Item 2 is required to insure that the rolling moment due to sideslip will be of the correct sign with controls free. The ability of the control to self-center here again is a requirement for control feel.

The reason for item 3 is obvious.

Design considerations.- Wind-tunnel data showing the effects of flaps, wing plan form, and fuselage-wing arrangement on the rolling moment due to sideslip are given in references 10 and 11. These results are generally sub-

stantiated by flight test. With single-engine, low-wing airplanes, however, the dihedral effect in sideslips made to the left sometimes became negative at low speeds with power on, even though it was satisfactory with power off or with power on at higher speeds. Low-wing monoplanes generally required from 4° to 8° more geometric dihedral angle than high-wing monoplanes to obtain the same effective dihedral effect. On airplanes with the trailing edges of the wing swept forward, flaps reduced the effective dihedral and where the trailing edge of the wing was a continuous straight line, flaps had little or no effect on the dihedral effect.

In order to meet item 2, the friction in the aileron control system must be low and the aileron required to overcome the rolling tendencies in the sideslip (dihedral effect) must exceed that at which the ailerons would tend to float due to the spanwise angle-of-attack variation.

The upper limit of the rolling moment due to sideslip (item II-D-3) is dependent on the yaw due to ailerons (item II-C-1) and the power of the aileron control (item II-B-3).

Requirement (II-E): Rudder-control characteristics.

1. The rudder control should everywhere be sufficiently powerful to overcome the adverse aileron yawing moment.

2. The rudder control should be sufficiently powerful to maintain directional control during take-off and landing.

3. On airplanes with two or more engines, the rudder control should be sufficiently powerful to provide equilibrium of yawing moments at zero sideslip at all speeds above 110 percent of the minimum take-off speed with any one engine inoperative (propeller in low pitch) and the other engine or engines developing full rated power.

4. The rudder control in conjunction with the other controls of the airplane should provide the required spin-recovery characteristics.

5. Right rudder force should always be required to hold right rudder deflections, and left rudder force should always be required to hold left rudder deflections.

6. The rudder forces required to meet the above rudder-control requirements should not exceed 180 pounds (trim tabs neutral).

Reasons for Requirement (II-E): The reasons for these various items are obvious. Item 1 must, of course, be met if satisfactory turns are to be made at low speeds unless, of course, the directional stability is very great. Item 2 represents one of the most important functions for rudder control, although if a tricycle landing gear is used it becomes much less important.

Items 3 and 6 should insure adequate control over asymmetric thrust following engine failure subsequent to take-off. It does not seem necessary to retain directional control below the speed specified because of the probability that lateral instability due to stalling would set in first. The 180-pound force limit specified is about 90 percent of the maximum that an average pilot can apply.

Design considerations.- The rudder power needed to meet item 1 of the above requirement can be determined in the same manner that the directional stability required by aileron yaw was found (requirement II-C).

In at least one instance, item 2 of the above requirements was met without any rudder control. This was accomplished by using a tricycle landing gear and by eliminating the rudder-position variation with speed and power. However, due to the inherent instability of conventional landing gears, a certain amount of rudder control during take-off and landing will always be required when this arrangement is used, even though the rudder-trim change due to power or speed were eliminated. Just how much rudder is needed here is not known. The efficiency of the brakes, type of tail wheel (lockable or free-swiveling), and the magnitude of the inherent ground-looping tendency undoubtedly enter into the problem. Also, in landing, the stalling characteristics of the airplane may have an important

bearing. On the basis of data on hand, however, it appears that a rudder control that is sufficiently powerful to meet the other requirements outlined should generally be satisfactory from a standpoint of ground handling.

Items 3, 4, and 5 do not appear to require additional discussion.

Requirement (II-F): Yawing moment due to sideslip (directional stability).

1. The yawing moments due to sideslip (rudder fixed) should be sufficient to restrict the yaw due to ailerons to the limits specified in requirement (II-C-1).

2. The yawing moment due to sideslip should be such that the rudder always moves in the correct direction; i.e., right rudder should be required for left sideslip and left rudder should be required for right sideslip. For angles of sideslip between $\pm 15^{\circ}$, the angle of sideslip should be substantially proportional to the rudder deflection.

3. The yawing moment due to sideslip (rudder free) should be such that the airplane will always tend to return to zero sideslip regardless of the angle of sideslip to which it has been forced.

4. The yawing moment due to sideslip (rudder free with airplane trimmed for straight flight on symmetric power) should be such that straight flight can be maintained by sideslipping at every speed above 140 percent of the minimum speed with rudder free with extreme asymmetry of power possible by the loss of one engine.

Reasons for Requirement (II-F): The reasons for item 1 are covered in discussion under requirement (II-C).

Item 2 of this requirement states a desirable characteristic for any control; i.e., the response should be proportional to the deflection.

Item 3 is designed to insure satisfactory directional stability, particularly at large angles of sideslip where vertical tail stalling has frequently led to trouble. This requirement follows directly from the results of reference 12.

Item 4 is included to prevent the directional diver-

gence following an engine failure from being excessively rapid. Although the ability to fly with rudder free on asymmetric power is probably not in itself important, it is undoubtedly strongly related to the rate of divergence and therefore the required quickness of action on the part of the pilots when this emergency occurs.

Design considerations.- The directional stability required to fulfill item 1 has been discussed under requirement (II-C).

General discussion of the factors that determine the fin area required to meet items 2 and 3 of this requirement is given in reference 12. However, the interference effects of wing-fuselage position, vertical tail arrangement, etc., are so great that wind-tunnel tests would appear a necessary aid to design for these requirements. Since the directional stability at large angles of sideslip, however, is related to the manner in which the flow breaks down on the vertical surfaces and on its effect on the floating characteristics of the rudder, the scale of the test should be kept as great as possible.

Requirement (II-G): Cross-wind force characteristics.

The variation of cross-wind force with sideslip angle, as measured in steady sideslips, should everywhere be such that right bank accompanies right sideslip and left bank accompanies left sideslip.

Reasons for Requirement (II-G): Under normal conditions in a sideslip or skid, a force is produced which acts toward the backward-lying wing tip. Since the actual angle of sideslip cannot be observed by the pilot, the cross-wind force developed allows appreciation of the fact that sideslip exists because of the lateral acceleration which occurs. In steady sideslips the cross-wind force is balanced by a component of the weight of the airplane, so that an angle of bank results. The greater the cross-wind force the greater is the angle of bank. An approximate relation between angle of bank ϕ and the cross-wind force may be written as follows:

$$\phi = \sin^{-1} \frac{\text{cross-wind force}}{\text{weight of airplane}}$$

In addition to providing the pilot with "feel" of the sideslip or skid, the lateral attitude from which it is

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possible to recover with the rudder alone (without permitting a heading change) is directly related to the magnitude of the cross-wind force. Obviously, a positive dihedral effect is also necessary for the performance of this maneuver, but the fact remains that turning toward the low wing will always occur if the lateral attitude from which recovery is attempted exceeds that which can be held in steady sideslip with full rudder.

For these and other reasons, large values of cross-wind force are desirable and more rigid specification than that given would lead to better flying qualities. On the other hand, it is not known whether this could be done without increasing the drag of the airplane.

None of the airplanes tested to date has failed to meet the requirement as written. It is included, however, because there is indication on the basis of wind-tunnel tests that some future designs may actually develop cross-wind force of opposite sign to that normally experienced. Obviously, this condition could not be tolerated.

Requirement (II-H): Pitching moment due to sideslip.

As measured in steady sideslip, the pitching moment due to sideslip should be such that not more than 1° elevator movement is required to maintain longitudinal trim at 110 percent of the minimum speed when the rudder is moved 5° right or left from its position for straight flight.

Reasons for Requirement (II-H): A pitching-moment change due to sideslip is undesirable because it requires that the elevator as well as the rudder must be coordinated with the ailerons. Also, since sideslip of considerable amounts may be carried inadvertently, a marked variation of pitching moment with sideslip will tend to produce inadvertent angle-of-attack changes. The condition is critical at high lift coefficients, so compliance with the specifications given should automatically insure satisfactory characteristics at higher speeds.

Design considerations.- It is believed that the change in pitching moment with sideslip occurs as a result of the downwash change experienced by the horizontal tail as it moves from behind the wing center. In most cases, the moment produced is a diving moment because of the relatively high concentration of downwash at the wing center due to

the propeller or partial-span flaps. It has also been noted that the magnitude of the pitching moment due to sideslip progressively decreased as the angle of attack was reduced, presumably because of the corresponding reduction of downwash angles.

Requirement (II-I): Power of rudder and aileron trimming devices.

1. Aileron and rudder trimming devices should be provided if the rudder or aileron forces required for straight flight at any speed between 120 percent of the minimum speed and the maximum speed exceed 10 percent of the maximum values specified in requirements (II-B-5) and (II-E-6), respectively, and unless these forces at cruising speed are substantially zero.

2. Multiengine airplanes should possess rudder and aileron trimming devices sufficiently powerful in addition to trim for straight flight at speeds in excess of 140 percent of the minimum speed with maximum asymmetry of engine power.

3. Unless changed manually, the trimming device should retain a given setting indefinitely.

Reasons for Requirement (II-I): The reasons for the items listed above are obvious.

Requirement (III): Stalling characteristics.

1. The approach of the complete stall should make itself unmistakably evident through any or all of the following conditions:

a. The instability due to stalling should develop in a gradual but unmistakable manner.

b. The elevator pull force and rearward travel of the control column should markedly increase.

c. Buffeting and shaking of the airplane and controls produced either by a gradual breakdown of flow or through the action of some mechanical warning device should provide unmistakable warning before instability develops.

2. After the complete stall has developed, it should

be possible to recover promptly by normal use of controls.

3. The three-point landing attitude of the airplane should be such that rolling or yawing moments due to stalling, not easily checked by controls, should not occur in landing, either three-point or with tail-first attitude 2° greater than that for three-point contact.

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Reasons for Requirement (III): The items of this requirement are in keeping with all others given; i.e., it demands all that can be obtained with existing knowledge and yet is sufficiently rigid so that any airplane that complies with the specification will be reasonably safe in terms of our present standards. Since there is never occasion in the normal operation of an airplane for a pilot to stall intentionally, such characteristics that provide warning of the stall are given first importance. If the warning is unmistakable, the relative violence of the actual stall loses much of its significance because it would then occur only as an intentional act on the part of the pilot and at a safe altitude. Item 2 is included to insure that recovery from an intentional stall can be promptly made.

Item 3 is an outgrowth of some experience in studying ground-handling problems. In most cases, poor stalling characteristics are troublesome in landing because of wing dropping either during the actual landing flare or after the airplane has alighted during the landing run. In other cases the wing stall has influenced the flow at the vertical tail in such a manner that powerful yawing moments have developed. Unless the stall itself can be made to develop in a gentle manner, the cure for these characteristics can be effected by preventing the occurrence of the stall altogether in the landing maneuver.

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