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A FLIGHT DETERMINATION OF THE TOLERABLE RANGE OF EFFECTIVE DIHEDRAL ON A CONVENTIONAL FIGHTER AIRPLANE

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SUMMARY

The results of an investigation to determine the tolerable (safe for normal fighter operation) range of effective dihedral on a conventional fighter airplane are presented. The test airplane was equipped with a special device for varying the effective dihedral in flight over a large range of positive and negative values. The results of quantitative flight measurements of the effective dihedral and the dynamic-lateral-stability characteristics are shown. A survey of pilots' opinions was made to determine which values of effective dihedral were intolerable. It was found that small amounts of negative dihedral (of the order of -5°) could be tolerated by the pilots at both landing-approach and cruising speeds and that values of positive dihedral greater than 20° could be tolerated. It was found, in fact, that at landing-approach speeds, an effective dihedral high enough (28.4°) to produce oscillatory instability could be tolerated. The occurrence of rolling velocity reversals during rudder-fixed aileron rolls with high positive values of dihedral did not adversely affect the pilots' opinions of the over-all lateral handling characteristics. The relation between the findings of this investigation and the present Air Force-Navy stability and control specifications is discussed.

INTRODUCTION

It is well known that wings with high-speed plan forms, such as highly swept-back and triangular wings, exhibit unusual lateral-stability and -control characteristics. The designer who wishes to make use of such plan forms is inevitably confronted with the question of how unconventional he can allow his airplane to be, with respect to the lateral-stability and -control characteristics, in order to gain the advantages offered by such plan forms. The NACA has under way a broad flight-research investigation of this problem.

The first phase of the program has been a determination, on a conventional fighter airplane with otherwise normal stability derivatives, of the range of tolerable effective dihedral. The test airplane was equipped with a special device for varying the effective dihedral in flight, the development of which has been reported in reference 1. Quantitative flight measurements were made to determine the range of effective dihedral produced by the apparatus, and then a survey of pilots' opinions was made among several experienced pilots to determine the tolerable range of effective dihedral. The results of this investigation are reported herein.

SYMBOLS

Γ_e	effective dihedral, degrees
b	wing span, feet
S	wing area, square feet
q	dynamic pressure, pounds per square foot
C_l	rolling-moment coefficient $\left(\frac{\text{rolling moment}}{qSb}\right)$
β	sideslip angle, degrees
φ	bank angle, degrees
C_{l_β}	$\frac{\partial C_l}{\partial \beta}$, per degree
P	period of oscillation, seconds
$T_{\frac{1}{2}}$	time to damp to half amplitude, seconds
T_2	time to double amplitude, seconds
p	rolling velocity, radians per second
V	true airspeed, feet per second
$\frac{\lvert p \rvert}{\lvert \beta \rvert}$	ratio of amplitude of rolling velocity to amplitude of sideslip angle of the oscillatory mode as measured in lateral oscillations excited by returning the controls to wings-level position from a steady sideslip, per second
$\frac{\lvert \varphi \rvert}{\lvert \beta \rvert}$	ratio of amplitude of angle of bank to amplitude of sideslip angle of the oscillatory mode as measured in lateral oscillations excited by returning the controls to wings-level position from a steady sideslip

EQUIPMENT AND INSTRUMENTATION

A conventional single-engine fighter airplane, equipped with a special apparatus for varying the effective dihedral in flight, was used for the investigation. A three-view drawing and a photograph of the airplane are shown in figures 1 and 2, respectively.

The special dihedral apparatus is described in detail in reference 1. Essentially, it is a servomechanism which deflects the ailerons, through a differential arrangement, in response to a signal from a sideslip vane, and thereby changes the variation of rolling-moment coefficient with sideslip angle. An aileron tab is deflected in response to the servo-applied aileron angle so that the stick-free effective dihedral is changed as well as the stick-fixed. Three positive increments and three negative increments of effective dihedral can be produced by the apparatus. Since the tests of reference 1, the range of effective dihedral which the apparatus is capable of producing has been extended, and the aileron tab has been enlarged to improve the relation between stick-fixed and stick-free dihedral effect.

Standard NACA photographically recording instruments were used to measure indicated airspeed, pressure altitude, aileron stick force, aileron angle (pilot-applied and servo-applied), rudder angle, sideslip angle, and rolling and yawing velocities.

PROCEDURE

The flight conditions chosen for the investigation were as follows:

<u>Landing-approach condition</u>.- In this condition the indicated airspeed was 90 knots, the flaps were extended, and the landing gear was retracted. Ninety knots was about the lowest speed at which the servo-applied aileron angle caused by the wings-level sideslip angle was sufficiently small to allow reasonable maneuvers without exceeding the limits of the apparatus. The gear was retracted in order to keep the drag, the propeller loading, and hence the wings-level sideslip angle to a minimum.

<u>Cruising condition</u>.- The indicated airspeed was 180 knots for this condition; flaps and gear were up. This speed was not so high as to require diving or high engine power for level flight, but it was sufficiently high that further increases in speed would mean only small changes in lift and thrust coefficients.

All flights were made at a pressure altitude of approximately 7000 feet. Because of its experimental nature the apparatus was not used in flight close to the ground. The engine power used was that necessary for level flight.

Quantitative data were gathered during steady, straight sideslips, rudder-fixed aileron rolls, and lateral oscillations. In order to excite the oscillations the pilot first put the airplane in a steady sideslip, the recording instruments were then turned on, and the controls were abruptly returned to approximately the wings-level-equilibrium position. The instruments were turned off after several cycles or after the oscillations were damped.

A survey of pilots' opinions was made among five pilots in a series of flights separate from those during which quantitative measurements were made. Four were NACA test pilots and one was a service pilot; all were highly experienced with fighter-type aircraft. The pilots were requested to report their opinions (in the form of answers to specific questions) with regard to the damping and period of the oscillations, the response to gusts in rough air, their ability to coordinate during turn entries and exits, and the general flying qualities.

RESULTS AND DISCUSSION

Measurement of the Effective Dihedral

Figures 3 and 4 are presentations of the pertinent data obtained during steady, straight sideslips in the landing-approach and cruising conditions, respectively. Pilot-applied total aileron deflection and aileron stick force are shown as functions of sideslip angle. (The term, "pilot-applied aileron deflection from trim," as used in these figures, means the contribution of the pilot to the change, from the wings-level value, in the sum of the angles of the two ailerons.) The variations of pilot-applied aileron deflection with sideslip, together with the aileron effectiveness obtained from wind-tunnel data on the test airplane, made possible the computation of C_{l_β} for each servo setting. A value of C_{l_β}/Γ_e of −0.000225 per degree squared was obtained from reference 2 and was used to compute the values of Γ_e.

It is seen in figures 3 and 4 that in the landing-approach condition Γ_e was varied from -18.2° to 28.4°, and in the cruising condition from -12.4° to 24.4°. The corresponding values of C_{l_β} are noted in the figures. The wider range of Γ_e covered in the approach condition as compared with that covered in the cruising condition was caused by a higher aileron effectiveness in the approach condition.

Oscillatory Characteristics of the Airplane

Time histories of typical control-fixed oscillations in the landing-approach condition with the apparatus set for effective dihedrals of 28.4°, 5.3° (normal airplane, apparatus inoperative), and -3.1° are shown in figure 5. Figure 6 shows similar time histories for the cruising condition with effective dihedrals of 24.4°, 6.2° (normal airplane), and zero. It is seen that, with Γ_e=28.4° in the approach condition, the airplane exhibited slight oscillatory instability.

The period and damping of oscillations such as those shown in figures 5 and 6 were measured for other dihedral settings, and the average values are shown as functions of effective dihedral in figure 7. The time to double amplitude of 38 seconds for the landing-approach condition with 28.4° dihedral is arbitrarily shown in a region of approximately neutral stability. No points are shown for negative Γ_e because, as seen in figure 5, the damping was so high that evaluation of period and damping was virtually impossible.

Characteristics in Rudder-Fixed Aileron Rolls

Time histories of typical rudder-fixed aileron rolls for the landing-approach condition with the apparatus set for effective dihedrals of 28.4°, 22.7°, 14.2°, and 5.3° (normal airplane with apparatus inoperative) are shown in figure 8. Similar time histories for the cruising condition with effective dihedrals of 24.4°, 18.2°, 12.9°, and 6.2° are shown in figure 9. It is seen that rolling-velocity reversals occurred in the landing-approach condition with effective dihedrals greater than that of the normal airplane and in the cruising condition with 24.4° effective dihedral.

Reduction of these data to the conventional plots of the aileron-effectiveness criterion $pb/2V$ against aileron deflection was not done, because the dihedral apparatus is effective over only a limited range of sideslip angle, and the usable aileron deflection during rolls is thereby limited. However, it was estimated from the available data that the $pb/2V$ for full aileron deflection would be well below the required value (reference 3) of 0.07 with the high positive dihedrals in the landing-approach condition.

Pilots' Opinions

Figure 10 is a graphic summary of the pilots' opinions of the over-all lateral handling characteristics in which pilots' opinions are shown as a function of effective dihedral.

The term "intolerable" as used here means something worse than "objectionable," but does not necessarily mean "unflyable." It describes a condition which would be considered dangerous in normal fighter operation.

The term "tolerable" describes a condition which would not be dangerous in normal fighter operation, but which is not necessarily "desirable" or "pleasant."

A "good" condition is not only safe but is also a desirable or pleasant condition.

The rolling-velocity reversals which occurred in rudder-fixed aileron rolls with high values of effective dihedral (figs. 8 and 9) did not adversely affect the pilots' opinions of the over-all lateral handling characteristics shown in figure 10, although such reversals are unacceptable according to reference 3. As for lateral controllability, one feature of high dihedral which was very desirable to the pilots in the landing-approach condition was the effectiveness of the rudder in producing roll. Thus, for this airplane, the high rate of roll due to the rudder more than offset the low values of and reversal in rolling velocity due to aileron deflection. The requirements of reference 3 would, therefore, seem too stringent in this case.

Figure 11 shows how the various configurations compare with the period-damping requirements of reference 3. The data of figure 7 were used to plot time to damp to half amplitude against period, and the points were labeled with the opinions shown in figure 10 and the corresponding effective dihedrals.

The maximum tolerable effective dihedral in the landing-approach condition was not reached. Although the highest dihedral used (28.4°) produced oscillatory instability in the approach condition, the oscillations were relatively easy to control because, according to the pilots, the period was long and the rolling velocities were not too high. In fact, the pilots considered an effective dihedral of 22.7° to be good in the approach condition, although the period-damping combination produced by this dihedral (fig. 11) was well within the unsatisfactory area as defined by reference 3. It would appear, then, that the period-damping requirements of reference 3 are too severe in this case.

The maximum tolerable effective dihedral in the cruising condition is seen in figure 10 to be about 22°. Figure 11 shows that, for the cruising condition, the good configurations satisfied the requirements of reference 3, but the intolerable configuration did not. With 24.4° effective dihedral in the cruising configuration, the oscillations set up in rough air were difficult to control. Some of the pilots attributed this difficulty to the short period in combination with the low damping. The measurements showed the natural period to be about 3.0 seconds for $\Gamma_e = 24.4^\circ$ in the cruising condition and 3.6 seconds for $\Gamma_e = 28.4^\circ$ in the landing-approach condition. The 3.0-second period in the cruising condition was intolerable, and the 3.6-second period in the approach condition was tolerable - yet the latter was oscillatorily unstable. When presented with the results of the measurements, the pilots agreed that they probably could not detect the difference between a 3.0-second period and a 3.6-second period, at least not definitely enough to enable them to classify one as tolerable and the other intolerable. The difficulty in controlling the oscillations in the cruising condition was finally attributed by the pilots to the high rolling velocities. These higher rolling velocities are apparent when figure 6(a) is compared with figure 5(a). It seems, then, that a period-damping relationship cannot, in itself, define all of a pilot's concepts of the lateral-dynamic-stability characteristics, at least when extreme values of effective dihedral are considered. It would seem that a limitation should be placed on the rolling response to some form of yawing or sideslipping disturbance. The reduction of these pilots' concepts to a concrete, numerical criterion is a problem which deserves considerable effort in future work.

A possible criterion on which a limitation might be placed is the ratio of the amplitude of the rolling velocity to the amplitude of the sideslip angle in the oscillatory mode as measured in lateral oscillations such as were made for this investigation. Another possible criterion worthy of future study is the ratio of the amplitude of angle of bank to that of the angle of sideslip, perhaps as a function of period. For purposes of future reference, the above-mentioned quantities were evaluated from the data gathered during this investigation and are presented in table I together with the periods, the effective dihedrals, and the pilots' opinions of the over-all lateral handling characteristics.

The minimum tolerable effective dihedral in the landing-approach condition is seen in figure 10 to be about -7°. With $\Gamma_e = -10.7^\circ$ the adverse rolling response to rudder control (left roll with right rudder) was considered by the pilots to be intolerably rapid for a landing approach. It should be noted here, however, that, although all flights were made at altitude, the pilots based their opinions on the consideration of the use of the airplane for field landings. It is believed that, due to lower approach speeds and the necessity for rapid maneuvers during wave-off, the minimum tolerable effective dihedral for carrier landings would be less negative.

The minimum tolerable effective dihedral in the cruising condition is shown in figure 10 to be about -5°. With $\Gamma_e = -7.1^\circ$ the rolling response to gusts and the adverse rolling response to rudder control when corrections were made were so rapid that the pilot had to be constantly on the controls, a situation which, the pilots believed, would be intolerable from the standpoint of fatigue on flights of normal duration.

It was the opinion of the pilots that the optimum values of effective dihedral investigated were 6.2° (normal airplane without apparatus) for the cruising condition and 14.2° for the landing-approach condition. They thought more than normal amounts of dihedral were desirable in the approach condition because of the good response in roll to rudder control. It is noteworthy that this is the direction of the variation of effective dihedral with lift coefficient for swept-back wings; that is, increasing lift coefficient results in increasing effective dihedral.

Consideration of the Results with Respect to the Flying Qualities Specifications

Examination of reference 3 indicates that the requirements which probably limit the designer's choice of effective dihedral in most cases are, for the lower limit, the requirement that static effective dihedral be positive, and, for the upper limit, the prohibition of rolling-velocity reversal during aileron rolls and the oscillation period-damping requirement (fig. 11). Information gathered during this investigation has indicated that, if these requirements are met with an airplane similar to the test airplane, the resultant lateral-stability characteristics will certainly be satisfactory. The investigation has further indicated, however, that, if necessary, small negative values of effective dihedral can be tolerated and that the upper limit of dihedral is determined by some criterion other than a restriction against rolling-velocity reversal during aileron rolls or a period-damping relationship. The tolerable amount of negative dihedral is apparently related to the growth of rolling motion following a yawing-moment disturbance.

The specific values of the limits of tolerable effective dihedral determined in the present investigation, of course, cannot be applied generally to all airplanes. It is believed that future tests should be conducted with control over other stability parameters, such as directional stability and directional damping, as well as control over effective dihedral. With such additional control, it would be possible to vary the characteristics of the airplane motion (period, damping, response, spiral divergence) which seem to be important to the pilots over a much wider range than is possible at present. The formulation of more generally applicable conclusions should thereby be made possible.

CONCLUSIONS

A flight investigation to determine the tolerable (safe for normal fighter operation) limits of effective dihedral at landing-approach and cruising speeds for a conventional fighter airplane resulted in the following conclusions, with respect to the test airplane:

1. An effective dihedral as high as 28.4° did not cause the airplane to exhibit intolerable stability and control characteristics at landing-approach speed, even though it caused rolling-velocity reversals in rudder-fixed aileron rolls and even though the airplane was oscillatorily unstable. It appears that this was because the period was long, the rolling velocities experienced in rough air were low, and the rudder was very effective in producing roll.

2. The maximum tolerable effective dihedral at cruising speed was indicated to be about 22°. With higher values of dihedral the large and poorly damped rolling motions caused by rough air made the lateral oscillations difficult to control.

3. The minimum tolerable effective dihedral at landing-approach speed was indicated from pilots' opinions formed during flights at altitude to be about -7° for field landings. With more negative values the adverse rolling response to rudder control (left roll with right rudder) was considered to be dangerously high for an approach.

4. The minimum tolerable effective dihedral at cruising speed was indicated to be about -5°. With more negative values the rolling response to gusts and the adverse rolling response to rudder control was so rapid that, in rough air, the pilot had to be constantly on the controls, a situation which was considered dangerous from the standpoint of fatigue for flights of normal duration.

Ames Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Moffett Field, Calif., June 16, 1949.

REFERENCES

1. Kauffman, William M., Smith, Allan, Liddell, Charles J., Jr., and Cooper, George E.: Flight Tests of an Apparatus for Varying Dihedral Effect in Flight. NACA TN 1788, 1948.

2. Pearson, Henry A., and Jones, Robert T.: Theoretical Stability and Control Characteristics of Wings with Various Amounts of Taper and Twist. NACA Rep. 635, 1938.

3. Anon.: Flying Qualities of Piloted Airplanes. U.S. Air Forces Spec. No. 1815-B, June 1, 1948.

TABLE I.– VALUES OF POSSIBLE CRITERIA FOR LIMITATION OF POSITIVE EFFECTIVE DIHEDRAL AS MEASURED ON THE TEST AIRPLANE

Γ_e (deg)	P (sec)	$T_{\frac{1}{2}}$ (sec)	$\frac{\|p\|}{\|\beta\|}$ (per sec)	$\frac{\|\varphi\|}{\|\beta\|}$	Pilot opinion
Landing–approach condition					
28.4	3.6	(Unstable, T_2=38)	3.8	2.3	Tolerable
22.7	3.9	11.5	3.2	2.0	Good
14.2	4.4	5.2	2.1	1.4	Good
5.3	5.2	2.4	.5	.4	Good
Cruising condition					
24.4	3.0	8.3	11.2	5.4	Intolerable
18.2	3.3	5.2	9.1	4.7	Tolerable
12.9	3.6	3.5	5.8	3.3	Good
6.2	4.0	2.6	2.3	1.5	Good

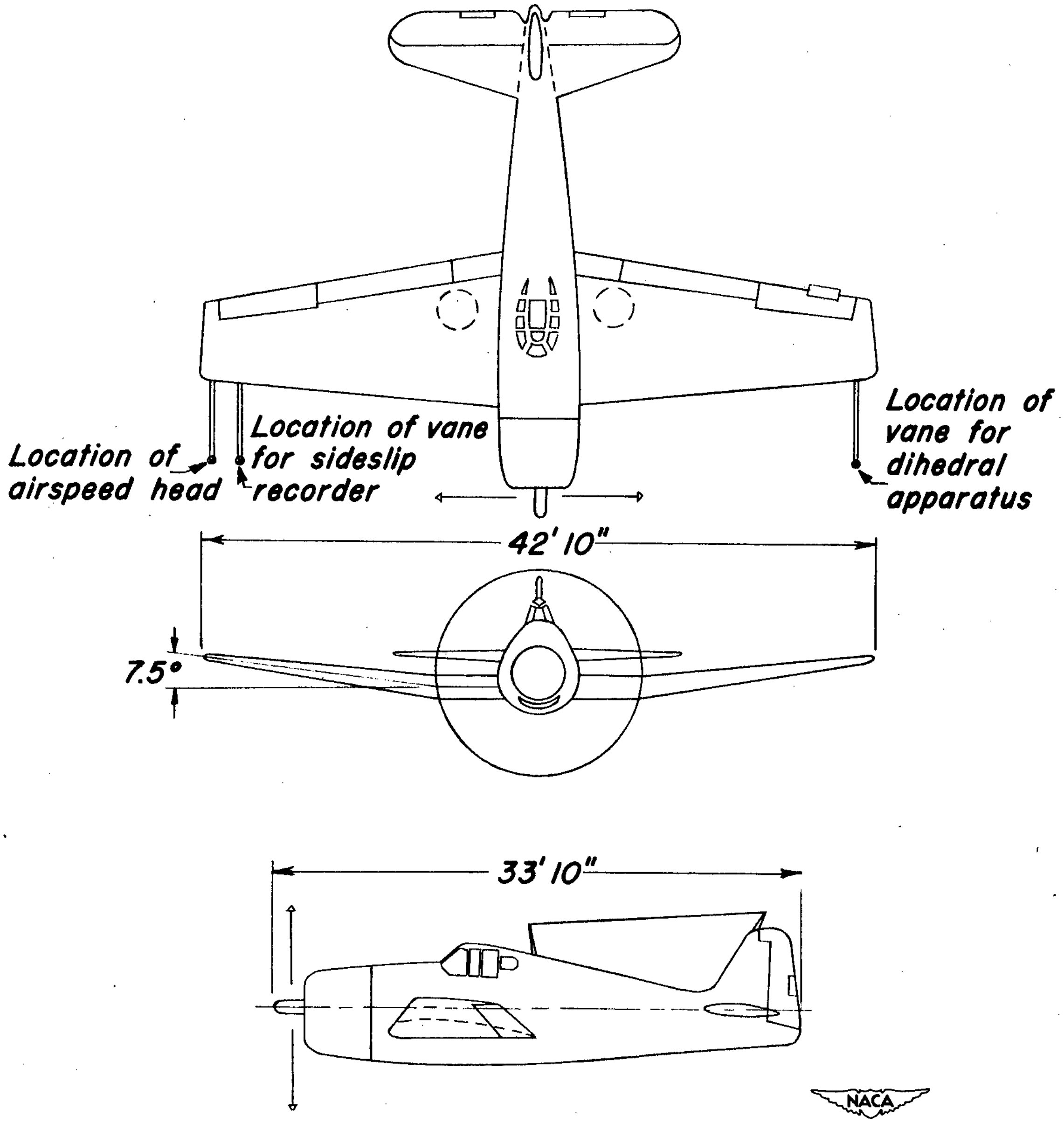


Figure 1.- Three-view drawing of the test airplane.

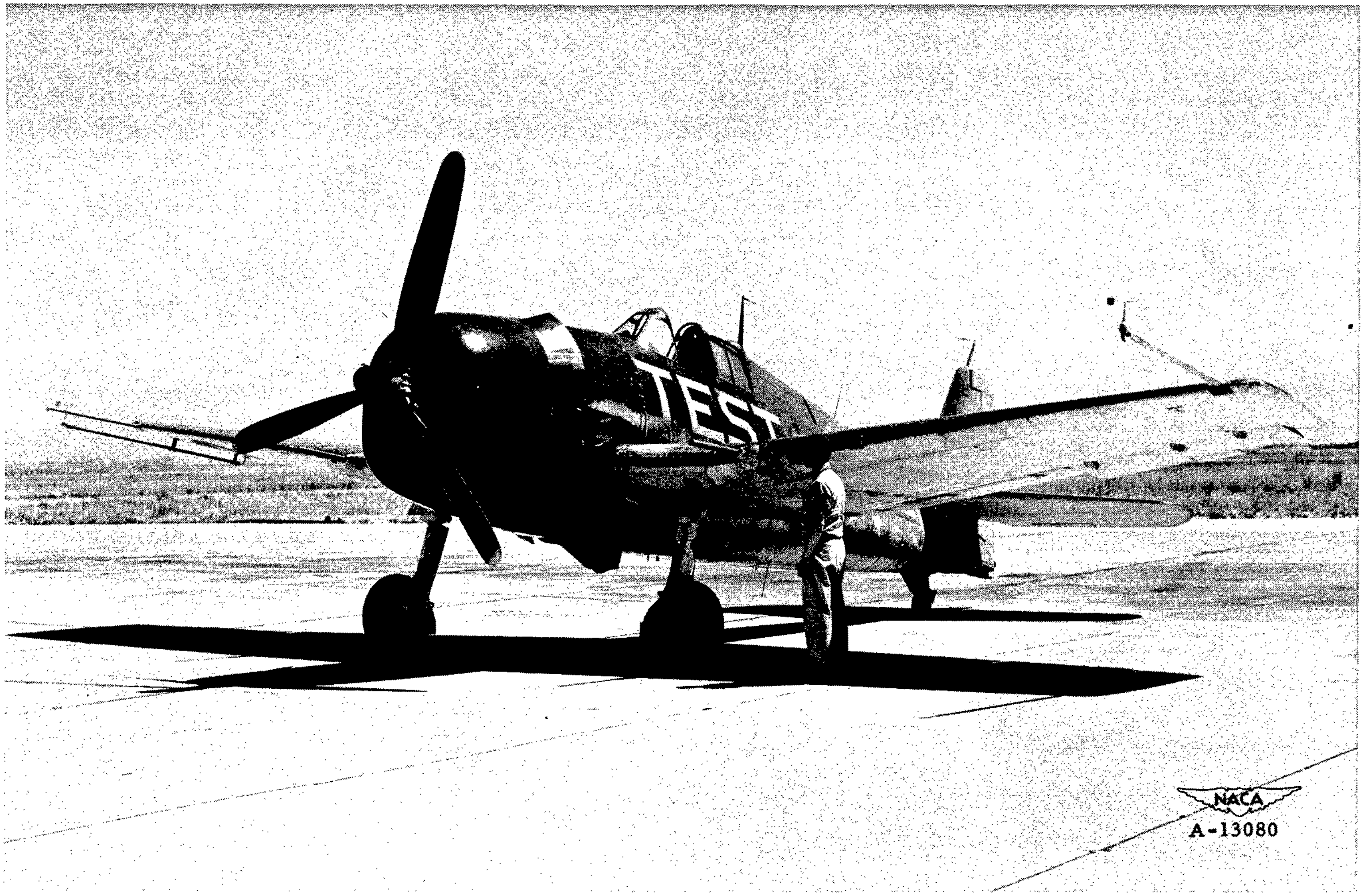
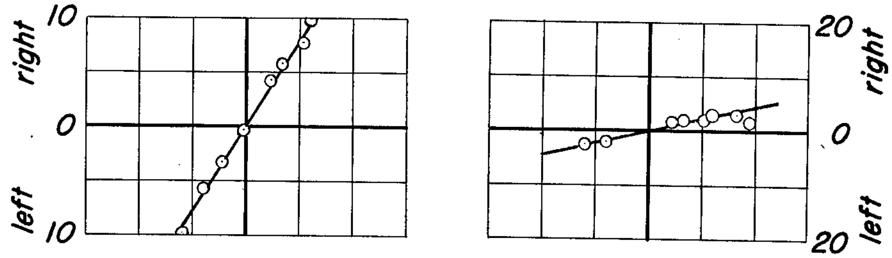
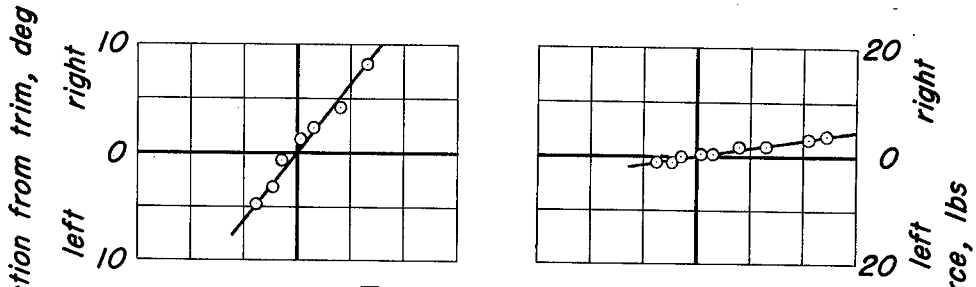


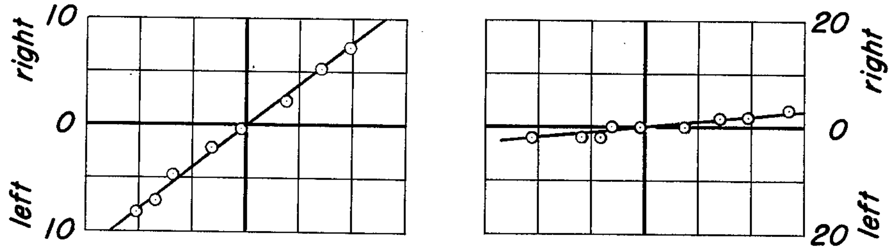
Figure 2.- Three–quarter front view of airplane instrumented for flight.



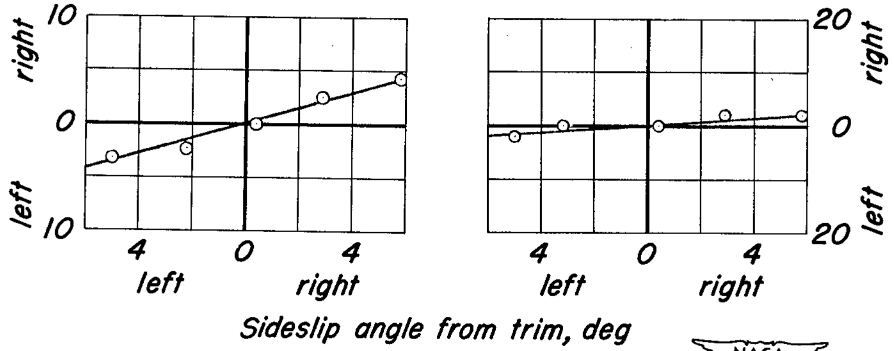
(a) Γ_e, 28.4° (C_{l_β}, -0.0064).



(b) Γ_e, 22.7° (C_{l_β}, -0.0051).

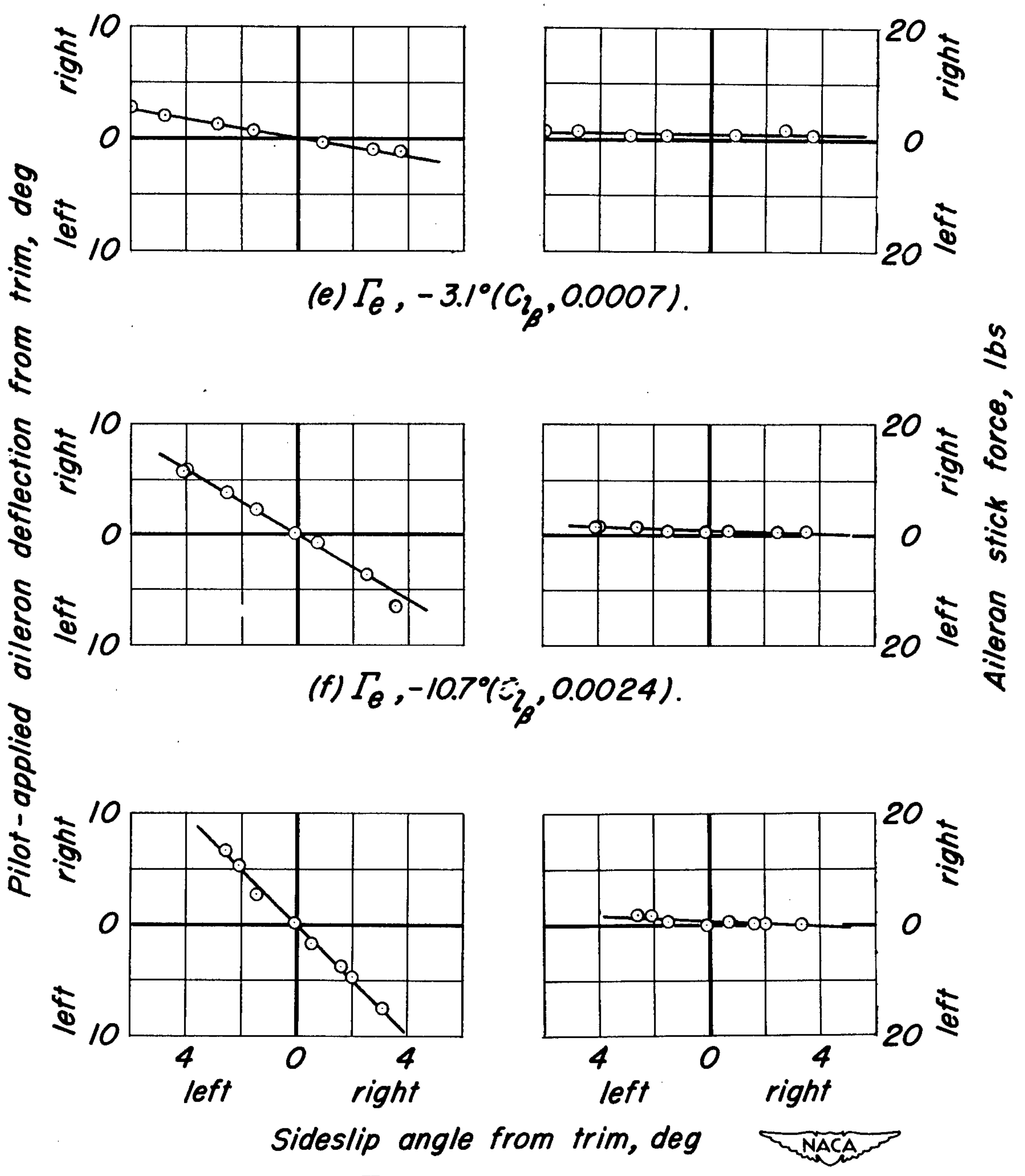


(c) Γ_e, 14.2° (C_{l_β}, -0.0032).



(d) Γ_e, 5.3° (C_{l_β}, -0.0012).

Figure 3.- Lateral stability and control characteristics during steady, straight sideslips. Landing approach condition.

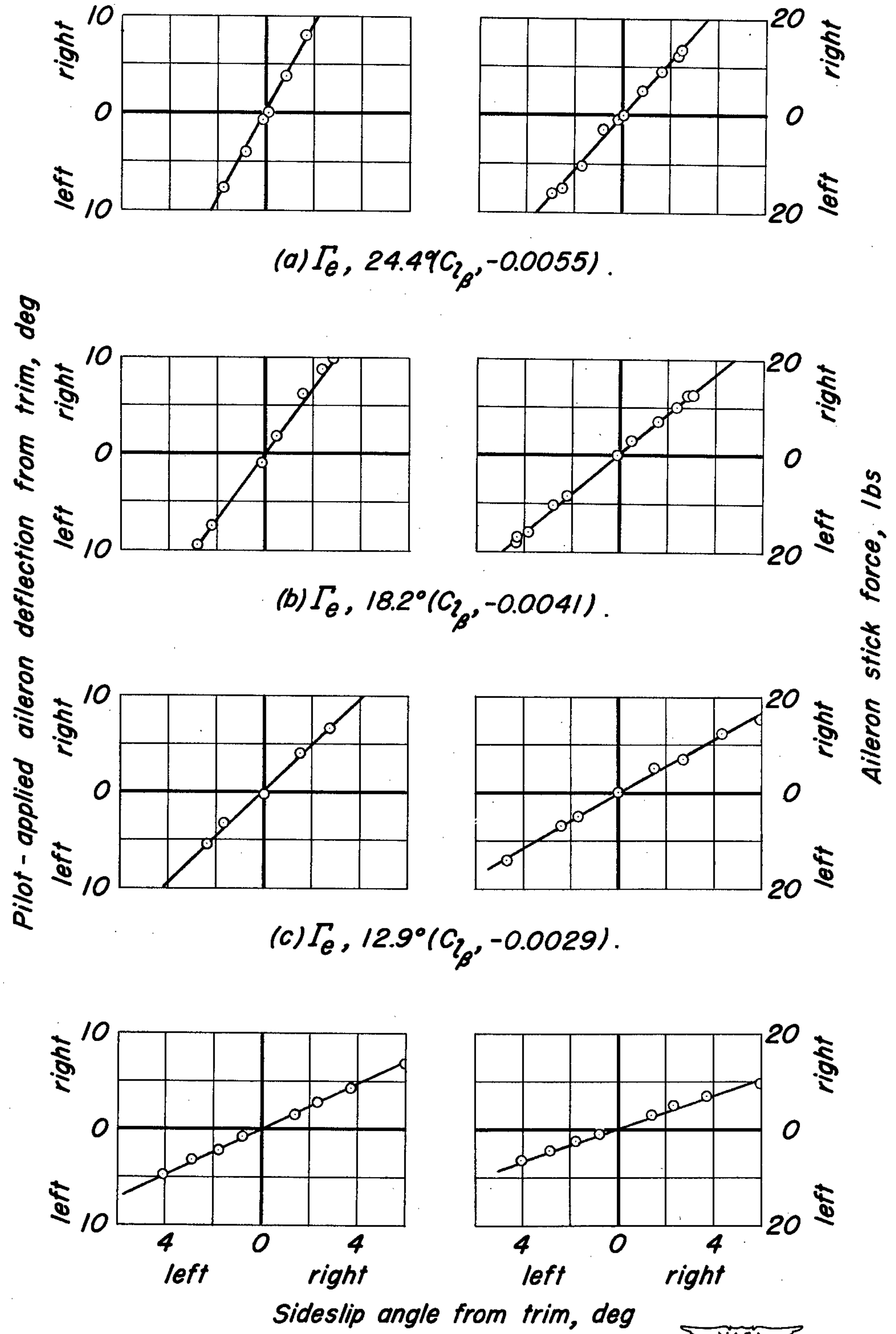


(e) Γ_e, -3.1° (C_{l_β}, 0.0007).

(f) Γ_e, -10.7° (C_{l_β}, 0.0024).

(g) Γ_e, -18.2° (C_{l_β}, 0.0041).

Figure 3.- Concluded.



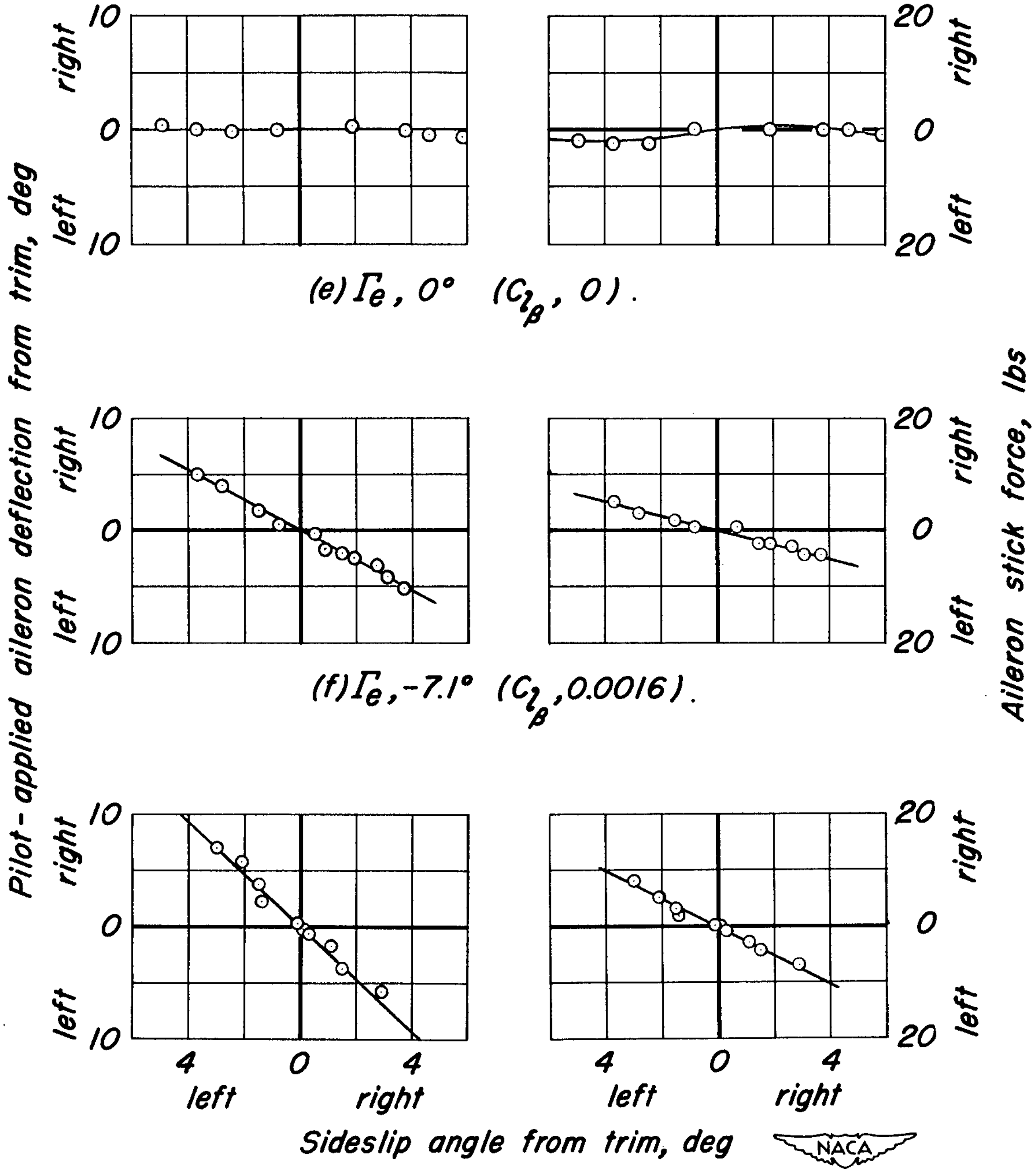
(a) Γ_e, 24.4° (C_{l_β}, -0.0055).

(b) Γ_e, 18.2° (C_{l_β}, -0.0041).

(c) Γ_e, 12.9° (C_{l_β}, -0.0029).

(d) Γ_e, 6.2° (C_{l_β}, -0.0014).

Figure 4.- Lateral stability and control characteristics during steady, straight sideslips. Cruising condition.



(e) Γ_e, 0° (C_{l_β}, 0).

(f) Γ_e, -7.1° (C_{l_β}, 0.0016).

(g) Γ_e, -12.4° (C_{l_β}, 0.0028).

Figure 4.- Concluded.

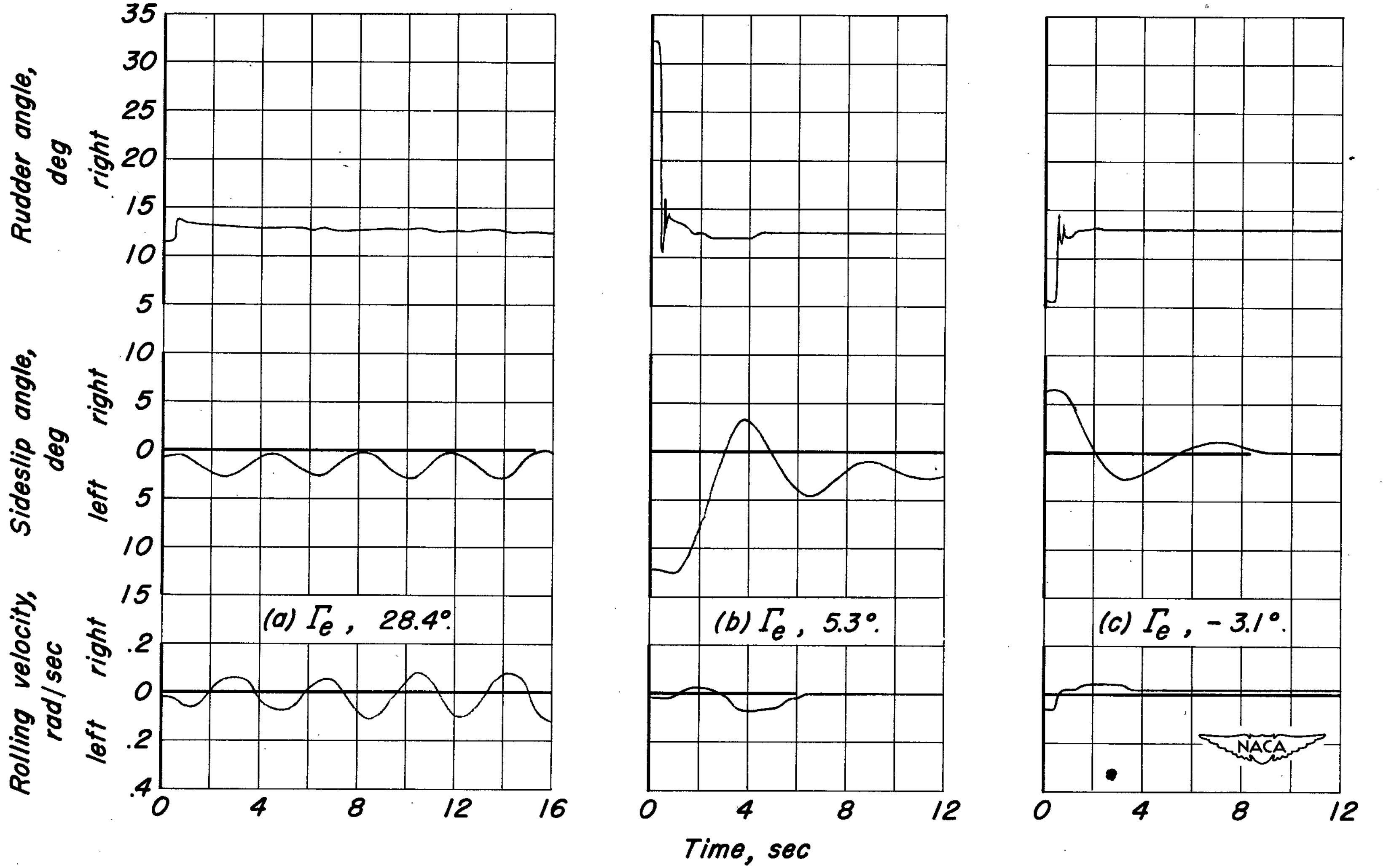


Figure 5.- Time histories of typical controls - fixed lateral oscillations. Landing-approach condition.

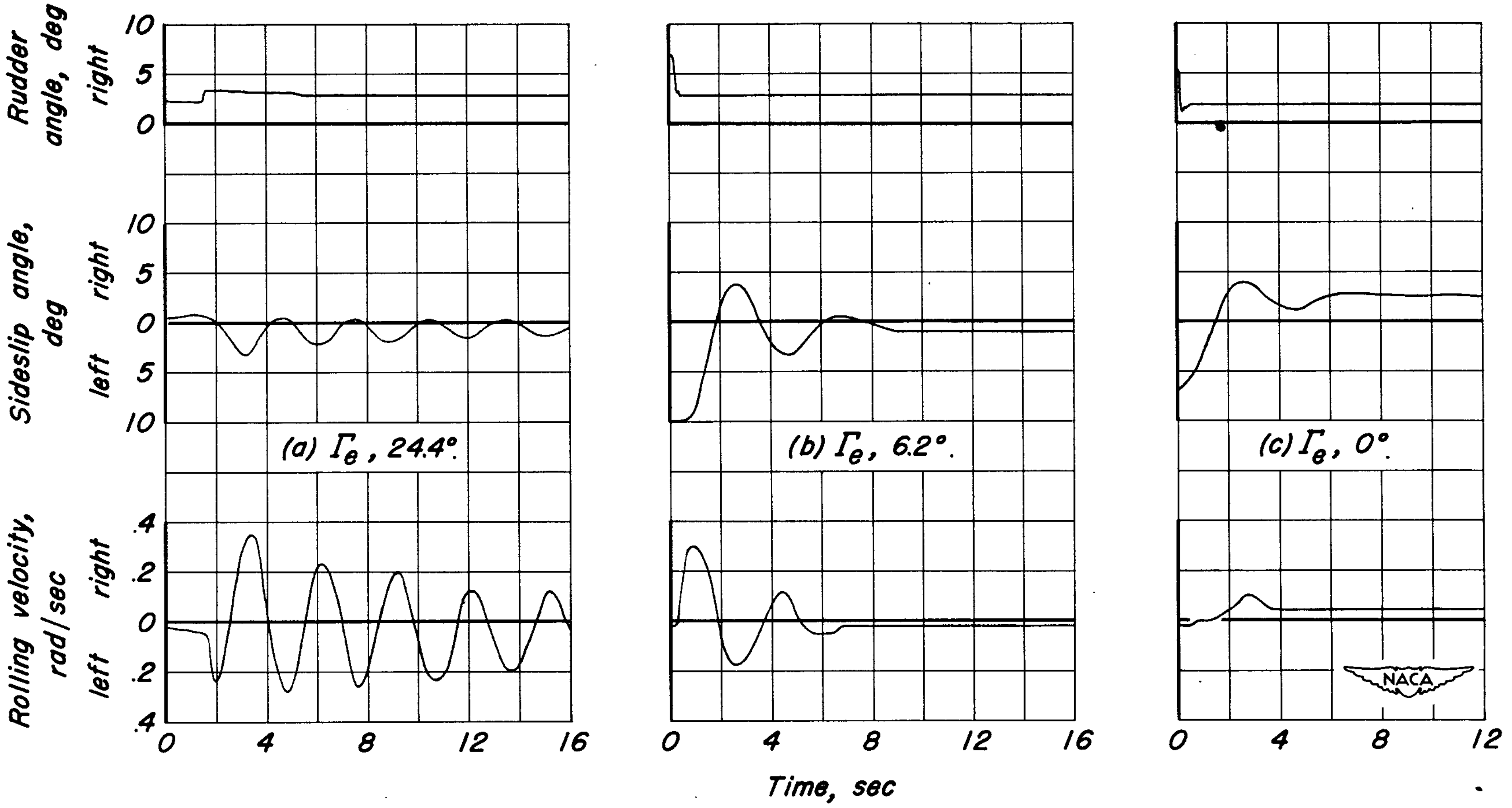


Figure 6.- Time histories of typical controls-fixed lateral oscillations. Cruising condition.

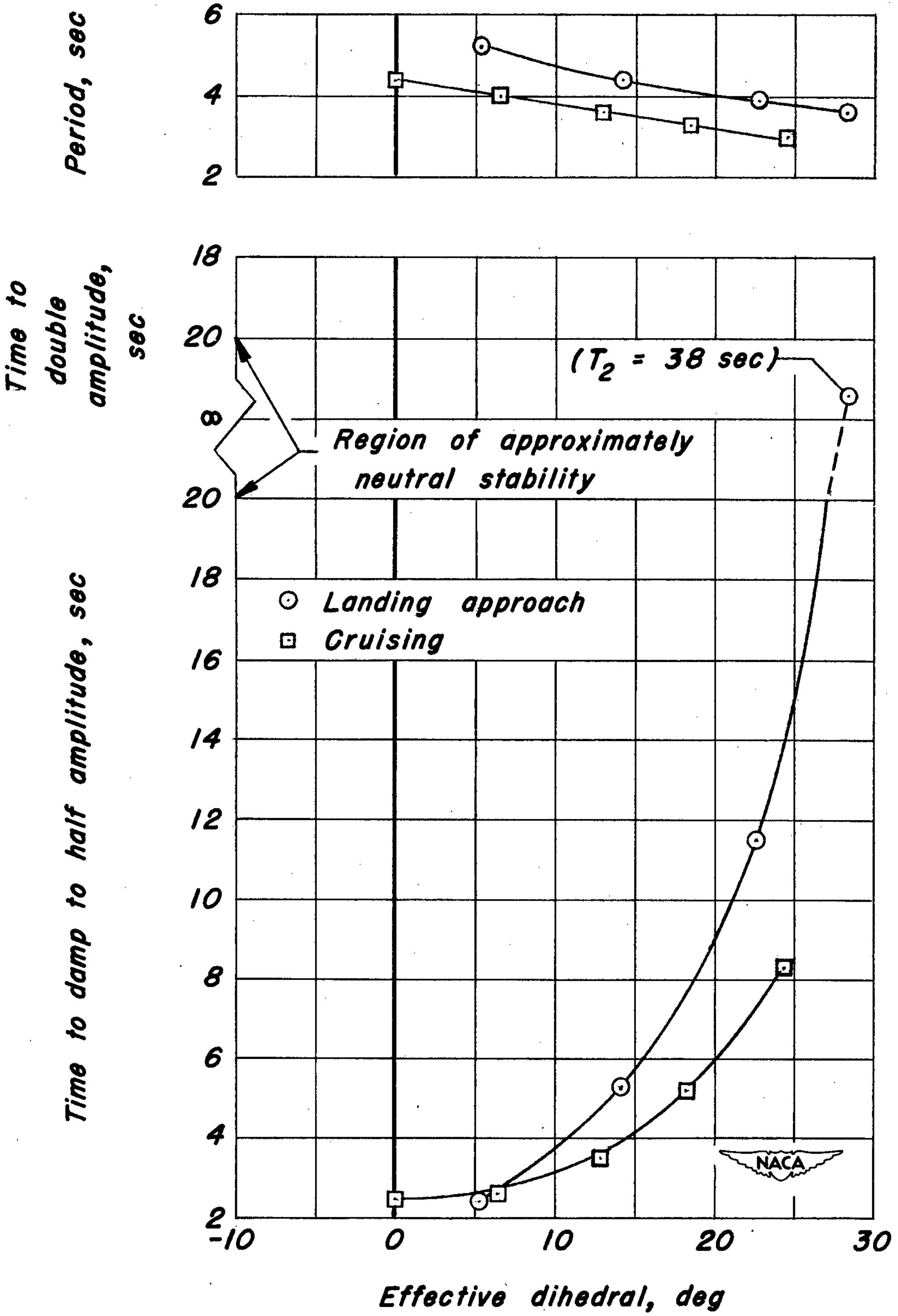


Figure 7.- Variation of period and damping of the lateral oscillations with effective dihedral.

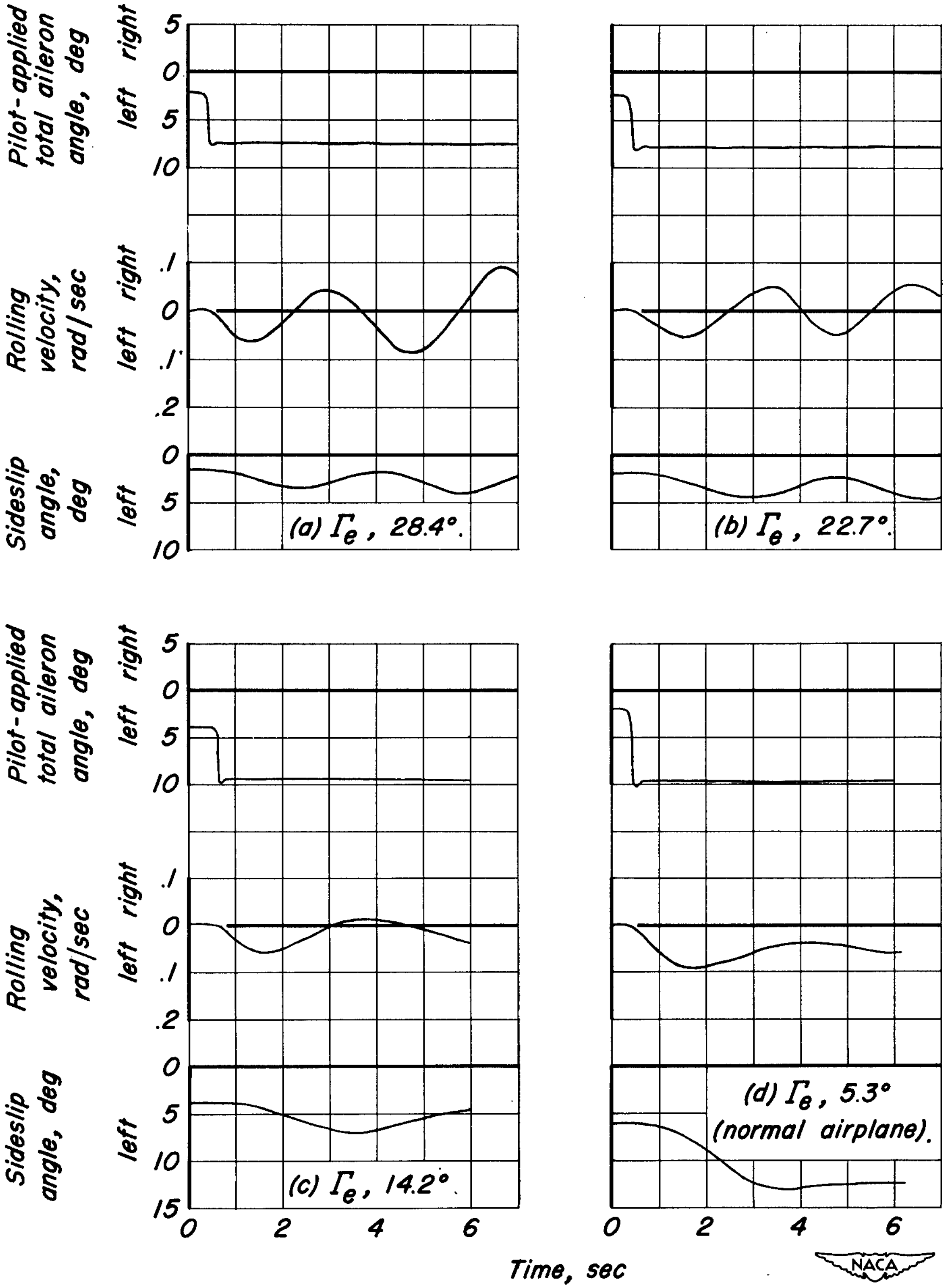


Figure 8.- Time histories of typical rudder-fixed aileron rolls. Landing-approach condition.

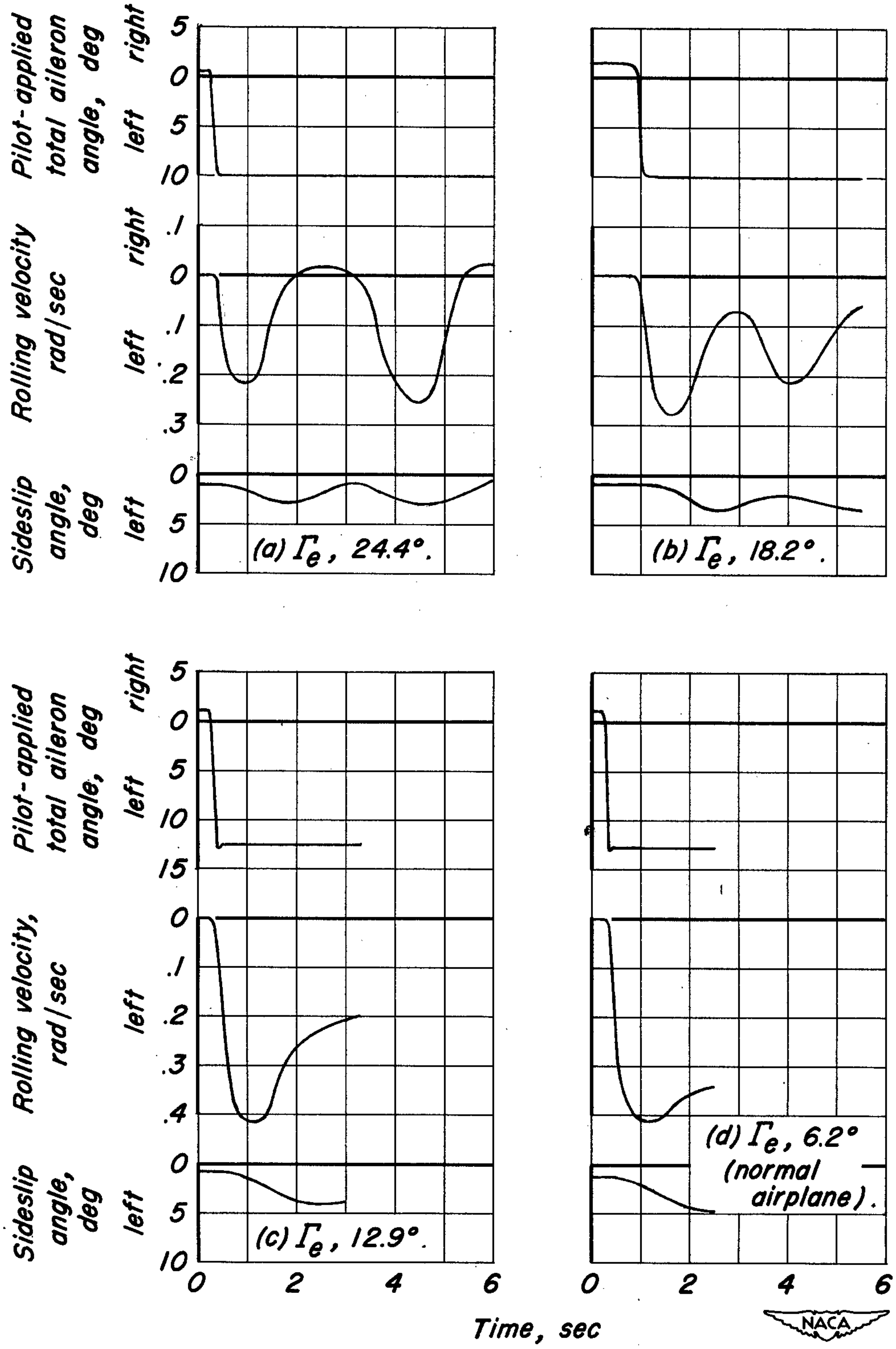


Figure 9.- Time histories of typical rudder-fixed aileron rolls. Cruising condition.

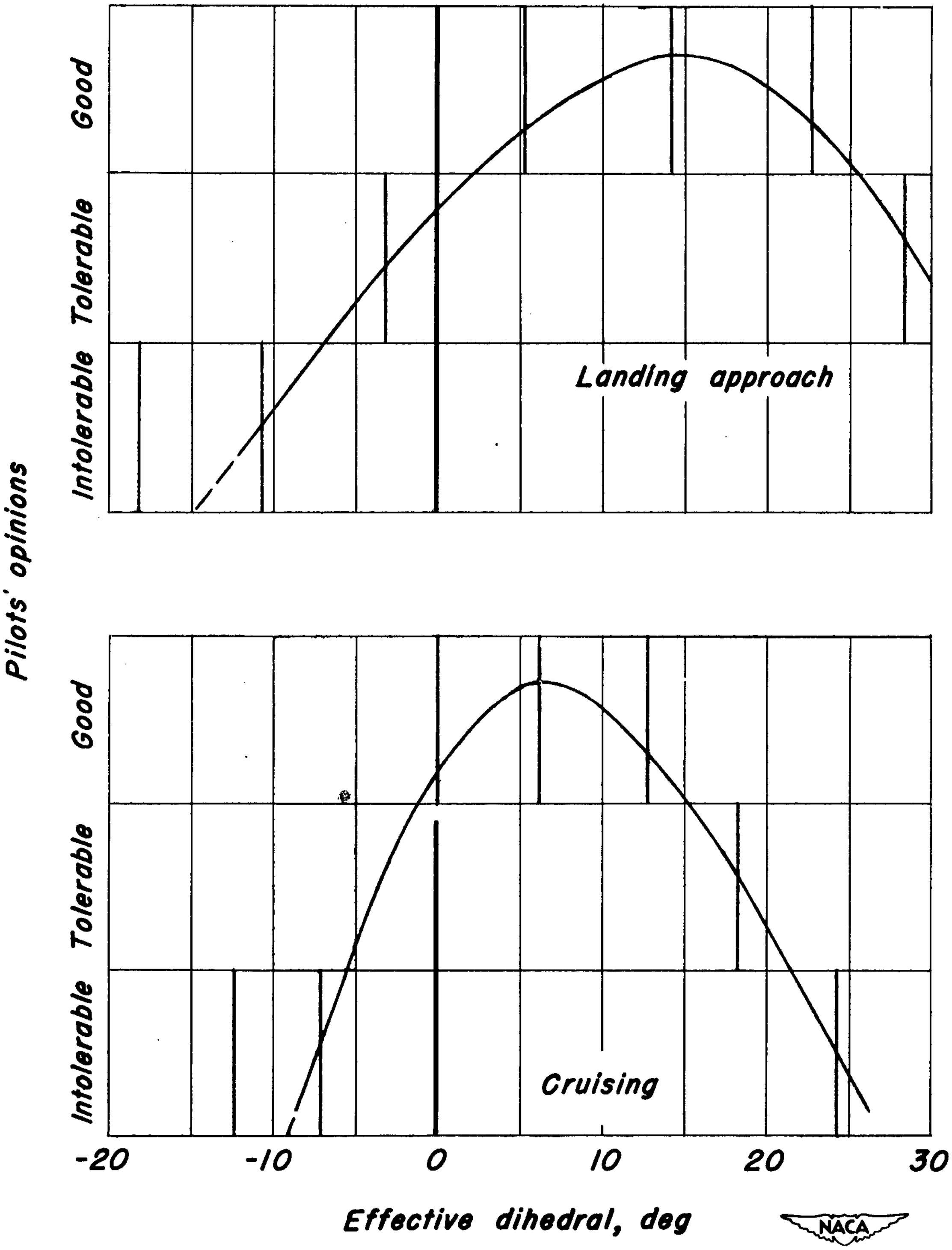


Figure 10.- Variation of pilots' opinions of lateral handling characteristics with effective dihedral.

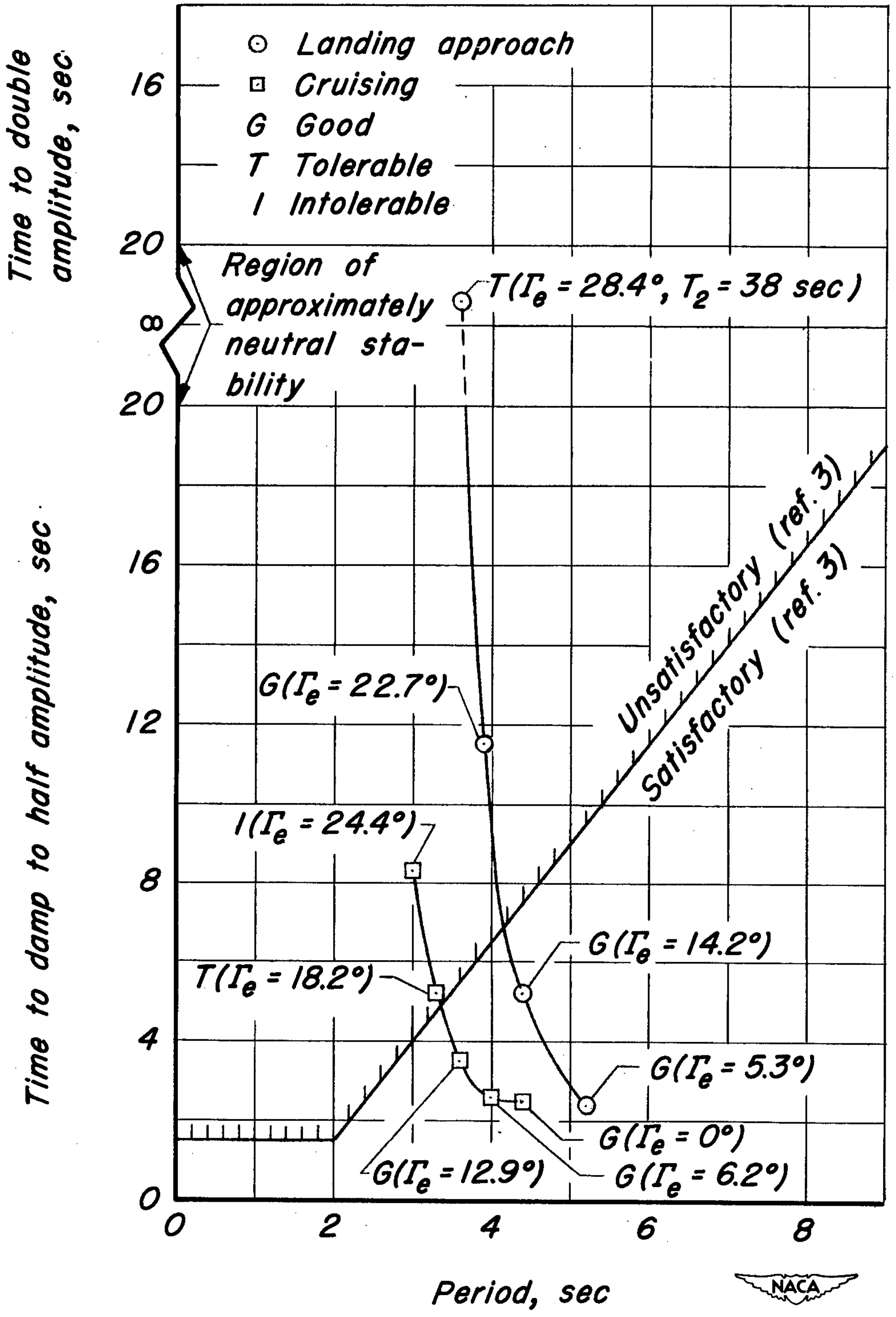


Figure 11.-Comparison of pilots' opinions of over-all lateral characteristics with period-damping requirements of reference 3.