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EXPERIMENTAL DETERMINATION OF THE EFFECT OF NEGATIVE DIHEDRAL ON LATERAL STABILITY AND CONTROL CHARACTERISTICS AT HIGH LIFT COEFFICIENTS

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WASHINGTON

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EXPERIMENTAL DETERMINATION OF THE EFFECT OF NEGATIVE DIHEDRAL ON LATERAL STABILITY AND CONTROL CHARACTERISTICS AT HIGH LIFT COEFFICIENTS

By Marion O. McKinney, Jr.

SUMMARY

The effects of negative dihedral on lateral stability and control characteristics at high lift coefficients have been determined by flight tests of a model in the Langley free-flight tunnel. The geometric dihedral angle of the model wing was varied from 0° to -20° and the vertical-tail area, from 0 to 35 percent of the wing area. The model was flown with various combinations of dihedral angle and vertical-tail area at lift coefficients of 1.0, 1.4, and 1.8.

As the effective dihedral was decreased from 0° to -15°, the model became increasingly difficult to fly. With an effective dihedral of -15° the flying characteristics were considered to be dangerous because, when there was only a slight lag in the application of corrective control following a disturbance, the unstable moments resulting from spiral instability became sufficiently large to overpower the moments of the controls so that return to straight flight was impossible. Inasmuch as full-scale airplanes because of their greater size will diverge at a slower rate than free-flight models, the amount of negative effective dihedral that would constitute a dangerous condition is expected to be greater for full-scale airplanes.

Increasing the directional stability reduced the magnitude of the sideslip and improved the general flight behavior. In the negative effective-dihedral range, increasing the lift coefficient from 1.0 to 1.8 had a slightly detrimental effect on the general flight behavior of the model at any given value of effective dihedral and directional stability.

INTRODUCTION

Tests of modern military airplanes have indicated that large changes in dihedral effect may occur over the speed range of an airplane operating under high-power conditions. This change in dihedral effect may cause an airplane that has a normal amount of positive effective dihedral in the high-speed condition to have large negative effective dihedral in the flaps-down, low-speed, high-power condition (wave-off, landing-approach, or take-off condition).

Previous tests (reference 1) have indicated that slightly negative dihedral effect is not objectionable and that spiral stability is not important. It was desired to extend the previous work to higher lift coefficients and to determine how much negative dihedral could be tolerated without excessive detrimental effects on flying characteristics. Flight tests of a model with variable dihedral have therefore been conducted in the Langley free-flight tunnel in order to determine experimentally the effects of various amounts of negative dihedral on the lateral stability and control characteristics of an airplane at high lift coefficients. The results of this investigation are presented herein. These results are part of a more comprehensive investigation being made to determine the effects of large variations of dihedral angle, vertical-tail area, and lift coefficient on the lateral stability characteristics of an airplane.

The present investigation consisted in power-off flight tests of a model on which the geometric dihedral angle was varied from 0° to -20° for vertical-tail areas from 0 to 35 percent of the wing area and for lift coefficients of 1.0, 1.4, and 1.8. Sufficient combinations of dihedral angle and tail area were tested at each of the three lift coefficients to determine the effect of dihedral, tail area, and lift coefficient on the lateral stability and control characteristics over the range of the variables. The results of the flight tests of the model are presented in the form of qualitative ratings of the general flight behavior of the model for each test condition.

SYMBOLS

m	mass of model, slugs
S	wing area, square feet
S_t	vertical-tail area, square feet
b	wing span, feet
V	free-stream velocity, feet per second
q	dynamic pressure, pounds per square foot $\left(\frac{1}{2}\rho V^2\right)$
T	time to damp to one-half amplitude for spiral divergence, seconds (negative values indicate time to increase to double amplitude)
k_X	radius of gyration of model about longitudinal axis, feet
k_Z	radius of gyration of model about vertical axis, feet
R	Routh's discriminant
D	coefficient in stability quartic equation, given in reference 2
E	coefficient in stability quartic equation, given in reference 2
λ	roots of stability quartic equation
r	yawing angular velocity, radians per second
ρ	mass density of air, slugs per cubic foot
β	angle of sideslip, degrees except where otherwise specified
p	rolling angular velocity, radians per second
γ	flight-path angle, degrees
Γ	geometric dihedral angle of mean-thickness line, degrees

μ	airplane relative-density factor $\left(\frac{m}{\rho S b}\right)$
τ	time-conversion factor $\left(\frac{m}{\rho S V}\right)$
C_L	lift coefficient $\left(\frac{\text{Lift}}{qS}\right)$
C_Y	lateral-force coefficient $\left(\frac{\text{Lateral force}}{qS}\right)$
C_l	rolling-moment coefficient $\left(\frac{\text{Rolling moment}}{qSb}\right)$
C_n	yawing-moment coefficient $\left(\frac{\text{Yawing moment}}{qSb}\right)$
C_{Y_β}	rate of change of lateral-force coefficient with angle of sideslip, per radian $(\partial C_Y/\partial \beta)$
C_{l_β}	rate of change of rolling-moment coefficient with angle of sideslip, per degree except where otherwise specified $(\partial C_l/\partial \beta)$
C_{n_β}	rate of change of yawing-moment coefficient with angle of sideslip, per degree except where otherwise specified $(\partial C_n/\partial \beta)$
C_{l_p}	rate of change of rolling-moment coefficient with rolling-angular-velocity factor $\left(\frac{\partial C_l}{\partial \frac{pb}{2V}}\right)$
C_{n_p}	rate of change of yawing-moment coefficient with rolling-angular-velocity factor $\left(\frac{\partial C_n}{\partial \frac{pb}{2V}}\right)$
C_{l_r}	rate of change of rolling-moment coefficient with yawing-angular-velocity factor $\left(\frac{\partial C_l}{\partial \frac{rb}{2V}}\right)$
C_{n_r}	rate of change of yawing-moment coefficient with yawing-angular-velocity factor $\left(\frac{\partial C_n}{\partial \frac{rb}{2V}}\right)$

APPARATUS

The investigation was carried out in the Langley free-flight tunnel, which is equipped for testing free-flying dynamic airplane models. A complete description of the tunnel and its operation is given in reference 3. Force tests to determine the static lateral stability derivatives were made on the Langley free-flight-tunnel six-component balance, described in reference 4. This balance rotates with the model in yaw, so that all forces and moments are measured with respect to the stability axes. The stability axes are an orthogonal system of axes having its origin at the center of gravity in which the Z-axis is in the plane of symmetry and perpendicular to the relative wind, the X-axis is in the plane of symmetry and perpendicular to the Z-axis, and the Y-axis is perpendicular to the plane of symmetry.

The control used on free-flight-tunnel models is a "flicker" (full-on or full-off) system. During any one particular flight the control deflections in the full-on positions are constant and the amount of control applied to the model is regulated by the length of time the controls are held on rather than by the control deflections used.

A three-view drawing of the model used in the tests is shown as figure 1 and photographs of the model are presented as figures 2 to 4. Figure 5 is a photograph of the model, with a geometric dihedral angle of -15°, flying in the test section of the tunnel. Although the model used in the tests was not a scale model of any particular airplane, it approximately represented a $\frac{1}{10}$-scale model of any current fighter airplane.

For all tests the model was equipped with a duplex flap arrangement consisting of a 40-percent-chord double slotted flap located inboard over 40 percent of the semispan and a 20-percent-chord balanced split flap located outboard over 42 percent of the semispan. The front and rear portions of the double slotted flap were deflected 30° and 70°, respectively, with respect to the airfoil chord. The balanced split flap was deflected 40°.

The effective dihedral was changed by altering the geometric dihedral angle of the wing. Four geometrically similar vertical tails and two end-plate vertical tails were used on the model to produce changes in directional stability. (See fig. 1.)

The model relative-density factor and radii of gyration varied slightly during the test program between the following limits:

μ . . . . 8.10 to 8.92

$\frac{k_X}{b}$ . . . . 0.161 to 0.181

$\frac{k_Z}{b}$ . . . . 0.241 to 0.290

The data presented in references 1, 5, and 6 indicate that changes of weight and moment of inertia of the magnitudes involved in the present investigation would make no pronounced difference in the stability or flying characteristics of the model.

TESTS

Scope of Tests

Flight tests of the model were made at lift coefficients of 1.0, 1.4, and 1.8 with the following combinations of dihedral angle and vertical-tail area:

Vertical tail	Vertical-tail area, S_t/S	Geometric dihedral angle, Γ (deg)
Off	0	-5, -10, -20
1	.03	0, -5, -10, -15, -20
2	.05	0, -5, -10
3	.10	0, -5
4	.15	0, -5, -10, -15, -20
4, 5, 6	.35 (total)	0, -5, -10, -15, -20

The values of C_{l_β} and C_{n_β} corresponding to the various test conditions were determined from force-test data and are presented in figure 6. These data show that the tests covered a range of C_{l_β} from 0.0032 to -0.0018 and a range of C_{n_β} from 0.0001 to 0.0066. The test range is considered representative of present-day limits, as shown by the data presented in figure 7. These data show that the variation of C_{n_β} and C_{l_β} of two high-powered (2000 bhp) airplanes over their speed range falls almost within the range of values covered by the tests.

Testing Procedure

The model was flown at each test condition by means of ailerons alone and ailerons coupled with rudder. The rudder travels used were selected by visual observation of flight tests as the amount necessary to eliminate the yawing due to aileron deflection and rolling. For tests in which the rudder control was crossed (that is, left rudder applied with right aileron and right rudder applied with left aileron), the rudder travel was the same as that used for the coordinated rudder and aileron control at the same test condition. For the tail-off condition the ailerons were rigged up 12° in order to eliminate the adverse yawing due to aileron deflection. The stability and control characteristics of the model were noted by the pilots from visual observation, and motion pictures were made of some flights in order to supplement the pilots' observations.

The spiral stability of the model was determined by the pilot from the rate at which the model, with controls fixed, sideslipped and rolled from level flight. An increasing rate of rolling and inward sideslip was judged as spiral instability.

The general oscillatory stability characteristics were judged by the pilot from the damping of the lateral oscillations of the model after a disturbance. The model could never be allowed to fly with controls fixed for sufficient time to allow measurement of period and damping from the motion-picture records.

Flight-behavior ratings based on the pilot's opinion of the general stability and control characteristics of the model were recorded for each test condition. Each rating was based on a number of separate flights. Although the accuracy of these ratings depended upon the pilot's ability to recognize unsatisfactory conditions, it is believed that the ratings give a qualitative indication of the effect of changes of the variables involved.

CALCULATIONS

Boundaries for neutral spiral stability $(E = 0)$, neutral oscillatory stability $(R = 0)$, and neutral directional stability $(D = 0)$ were calculated over the test range by means of the stability equations of reference 2 and are shown in figure 6. Lines of constant damping of the spiral mode were also calculated for the model by determining the root of the stability quartic λ that would give the desired value of damping by the formula (from reference 2)

$$\lambda = \frac{-0.693\tau}{T}$$

and by determining various values of C_{l_β} and C_{n_β} that would give this root λ from substitution of the root in the stability quartic. The calculated lines of constant damping are shown in figure 8.

Values of the static-lateral-stability derivative C_{Y_β} used in the calculations were obtained from force tests of the model. The value of the rotary derivative C_{n_r} was obtained from free-oscillation tests of the model by the method described in reference 7. The other rotary derivatives C_{l_p}, C_{n_p}, and C_{l_r} were estimated from the charts of reference 8 and the formulas of reference 9. The values of the mass characteristics m, k_X, and k_Z were measured for the model. Values of the stability derivatives used in the calculations are given in table I.

RESULTS AND DISCUSSION

The variations of effective-dihedral parameter C_{l_β} and directional-stability parameter C_{n_β} were obtained in the present investigation by changing the geometric dihedral angle and vertical-tail area. The flying characteristics, however, depend on the values of the stability derivatives, not on the method by which they were obtained; hence the flying characteristics of the model may be applied to conditions - such as wave-off, take-off, and landing-approach - in which negative effective dihedral is often caused by the high power and high lift coefficient.

The principal results of the present investigation are given in figure 8 in the form of ratings of the general flight behavior. All flight ratings not in parentheses were obtained with a total aileron deflection of 30°; those in parentheses were obtained with a total aileron deflection of 50°. The maximum values of $pb/2V$ corresponding to the aileron deflections of 30° and 50° were determined to be about 0.08 and 0.12, respectively, from roll-offs at a geometric dihedral angle of 0°, with the vertical tail having $\frac{S_t}{S} = 0.15$, and with coordinated rudder. It was, perhaps, not necessary to use an aileron deflection of 50° for all the test points at which this increased travel was used. When it was found necessary to use 50° travel with a certain combination of dihedral angle and vertical-tail area at a lift coefficient of 1.8, the same travel was used at lower lift coefficients.

Effect of Dihedral

Although the model was observed to be spirally unstable for all conditions tested, the flight data of figure 8 show that very satisfactory flights were obtained at positive values of effective dihedral. The rate of spiral divergence for the conditions of positive effective dihedral was observed to be small and the controls-fixed lateral motion was characterized by a slow gentle roll-off and sideslip from the steady state. The divergence could be controlled readily by occasional application of a total aileron deflection of 30°. Under these conditions, the model was as easy to fly as if it had been spirally stable and in the normal gusty air of the tunnel did not seem to require more frequent control than in a spirally stable condition.

At small values of negative effective dihedral, flight characteristics were not much different from those at small values of positive effective dihedral and the slow spiral divergences were readily controlled by application of the aileron and rudder controls. The rate of spiral divergence, however, was found to become increasingly rapid with increasing negative effective dihedral until, at an effective dihedral of about -15°, the divergence was quite violent. As in the case of small positive effective dihedral, the motions were characterized by a roll-off and sideslip from steady flight. As the negative effective dihedral was increased, the rate of the divergence increased until, for the conditions having the larger negative dihedral angles, the motion appeared to be as rapid as a fast aileron roll. As the negative effective dihedral was increased, the controls had to be applied sooner after the divergence was noticed because, when there was only a slight lag in the application of corrective control following a disturbance, the unstable moments resulting from spiral instability became sufficiently large to overpower the moments of the controls so that return to straight flight was impossible.

It was found impossible to fly the model with negative effective dihedral angles greater than about -10° ($C_{l_\beta} = 0.002$) with a total aileron deflection of 30°. The rate of spiral divergence apparently had become great enough by the time the pilot applied opposite control to make recovery impossible. The rate of divergence was observed to be retarded with aileron application, but the model continued to diverge.

In order to obtain data for the whole test range, the total aileron deflection was increased from 30° to 50° for all test conditions having a value of $C_{l_\beta} > 0.002$. It was therefore possible to control the spiral divergence over the complete range of negative dihedral angles. Flight under conditions of $C_{l_\beta} > 0.002$ was difficult, however, because flying the model required constant attention to the controls. The largest negative effective dihedral angles ($C_{l_\beta} \approx 0.003$) seemed to be the maximum for which the model could be flown with a total aileron deflection of 50°, inasmuch as even slight delays in applying lateral control allowed the model to continue to diverge. Many crashes therefore occurred during the tests at values of C_{l_β} of about 0.003.

The general flight-behavior ratings in figure 8 were given when the rudder was coordinated with the ailerons in the normal manner (right rudder with right aileron). The flight tests, however, showed that using the ailerons alone for control or even crossing the rudder control improved the flying characteristics of the model throughout the negative dihedral range and made the model slightly easier to control. This improvement evidently took place because the sideslip resulting from adverse yawing opposed the inward angle of sideslip caused by spiral divergence and, in spite of the adverse effect of rolling due to yawing, reduced the rolling divergence. This reduction of inward sideslip caused the response to the controls to be improved. The large amplitude of the yawing motions caused by crossing rudder control, however, was objectionable to the free-flight-tunnel pilots. Applying opposite rudder with ailerons would probably be objectionable to the pilot of an airplane inasmuch as it is an unnatural motion and would cause a loss of altitude. In a crucial moment, the pilot's reaction would probably be to apply coordinated rudder and aileron control rather than to think to apply rudder opposite to the ailerons. A pilot might, however, be trained to apply no rudder with aileron control when flying an airplane in conditions that are known to give negative dihedral effect and thus obtain some improvement in the control response for recovery.

The wave-off, take-off, and landing-approach conditions are believed to be dangerous for airplanes that have large negative effective dihedral because, when these conditions are encountered, there is only a limited altitude in which to apply corrective control. To fly with as much negative effective dihedral as was encountered in the present tests should be possible if the airplane ailerons are as powerful as those of the model tested and if careful attention is given to controlling the airplane. To fly airplanes with greater negative effective dihedral angles than were encountered in the present tests might be possible inasmuch as the rate of divergence of the airplane would be $1/\sqrt{N}$ times as fast as that of the model, where N is the scale of the model as 10, 15, etc. No information is available, however, concerning the relative reaction time and the time to deflect the controls for free-flight-tunnel and airplane pilots. Inasmuch as there has been no correlation of the boundaries of the region in which flight is possible in the Langley free-flight tunnel with time to damp, extension of the results to more negative dihedral angles has not been attempted.

Effect of Directional Stability

Increasing the directional stability C_{n_β} improved the general flight behavior of the model over the range of dihedral angles and lift coefficients tested, as shown in figure 8.

The tests showed that for the range of positive effective dihedral angles tested adequate directional stability was more desirable than the slightly lower rate of spiral divergence associated with lower directional stability, because excessive yawing was encountered with low directional stability. The rates of spiral divergence encountered in the positive dihedral range were, as previously discussed, quite slow even with a high degree of directional stability.

When the effective dihedral was negative, however, increasing the directional stability was observed to cause a slight reduction of the rate of spiral divergence. This reduction is in agreement with the calculations of the spiral stability, as shown by the increase in time for the motion to increase to double amplitude as C_{n_β} increases. An analysis of the general flight-behavior ratings and the calculated lines of constant damping of the spiral divergence indicates that the general flight behavior within the negative effective-dihedral range is primarily influenced by the spiral stability.

The motions of the model with a geometric dihedral angle of -20°, with tails off, and at lift coefficients of 1.4 and 1.8 appeared to be directional divergences. Immediately after taking off, the model commenced a divergence in yaw that was followed by rapid rolling in the opposite direction caused by the negative dihedral. No recoveries from the initial divergence could be obtained.

Effect of Lift Coefficient

The flight ratings of figure 8 show that increasing the lift coefficient from 1.0 to 1.8 at constant values of C_{l_β} and C_{n_β} had a slightly detrimental effect on the general flight behavior of the model over the negative effective-dihedral range. This detrimental effect is believed to be caused by the increase in the rate of spiral divergence indicated by the calculated lines of constant damping shown in figure 8.

CONCLUSIONS

The following conclusions were drawn from free-flight-tunnel tests to determine the effect of negative dihedral on the lateral stability and control characteristics of a free-flying dynamic model at high lift coefficients:

1. As the effective dihedral was decreased from 0° to -15°, the model became increasingly difficult to fly. With an effective dihedral of -15° the flying characteristics were considered to be dangerous because, when there was only a slight lag in the application of corrective control following a disturbance, the unstable moments resulting from spiral instability became sufficiently large to overpower the moments of the controls so that return to straight flight was impossible. Inasmuch as full-scale airplanes because of their greater size will diverge at a slower rate than free-flight-tunnel models, the amount of negative effective dihedral that would constitute a dangerous condition is expected to be greater for full-scale airplanes.

2. In addition to reducing the amount of sideslipping over the range of dihedral angles tested, increasing the directional stability was found to reduce the spiral stability for positive effective dihedral angles and to increase the spiral stability for negative effective dihedral angles. The net result of increasing directional stability, however, was to improve the general flight behavior over the entire dihedral range.

3. In the negative effective-dihedral range, increasing the lift coefficient from 1.0 to 1.8 had a slightly

detrimental effect upon the general flight behavior of the model at any given value of effective dihedral and directional stability.

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TABLE I.- STABILITY DERIVATIVES OF MODEL USED IN CALCULATIONS

[Values were arbitrarily assigned to C_{n_β}, the independent variable; C_{l_β} was used as the dependent variable. $\mu = 8.12$; $k_X/b = 0.165$; $k_Z/b = 0.245$]

C_{Y_β} (1)	C_{n_β} (1)	C_{l_p}	C_{n_p}	C_{l_r}	C_{n_r}	γ (deg)
$C_L = 1.0$						
-0.102	0	-0.49	-0.060	0.246	-0.040	-11.6
-.114	.005	-.49	-.058	.248	-.048	-11.6
-.128	.010	-.49	-.056	.250	-.055	-11.6
-.166	.025	-.49	-.050	.255	-.078	-11.6
-.230	.050	-.49	-.040	.265	-.115	-11.6
-.294	.075	-.49	-.031	.274	-.153	-11.6
-.358	.100	-.49	-.021	.284	-.190	-11.6
-.486	.150	-.49	-.002	.303	-.265	-11.6
-.614	.200	-.49	.015	.320	-.340	-11.6
-.742	.250	-.49	.032	.337	-.413	-11.6
-.870	.300	-.49	.048	.353	-.491	-11.6
$C_L = 1.4$						
-0.108	0	-0.49	-0.086	0.340	-0.040	-11.6
-.121	.005	-.49	-.085	.342	-.048	-11.6
-.135	.010	-.49	-.084	.343	-.055	-11.6
-.175	.025	-.49	-.080	.347	-.078	-11.6
-.242	.050	-.49	-.073	.354	-.115	-11.6
-.308	.075	-.49	-.067	.360	-.153	-11.6
-.375	.100	-.49	-.060	.367	-.190	-11.6
-.508	.150	-.49	-.047	.380	-.265	-11.6
-.642	.200	-.49	-.036	.392	-.340	-11.6
-.775	.250	-.49	-.025	.402	-.413	-11.6
-.909	.300	-.49	-.015	.412	-.491	-11.6
$C_L = 1.8$						
-0.114	0	-0.49	-0.114	0.436	-0.040	-13.5
-.128	.005	-.49	-.113	.436	-.048	-13.5
-.142	.010	-.49	-.112	.437	-.055	-13.5
-.184	.025	-.49	-.110	.439	-.078	-13.5
-.254	.050	-.49	-.106	.443	-.115	-13.5
-.322	.075	-.49	-.103	.446	-.153	-13.5
-.392	.100	-.49	-.099	.450	-.190	-13.5
-.532	.150	-.49	-.092	.457	-.265	-13.5
-.670	.200	-.49	-.085	.463	-.340	-13.5
-.810	.250	-.49	-.082	.468	-.413	-13.5
-.958	.300	-.49	-.078	.471	-.491	-13.5

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[1] β is measured in radians.

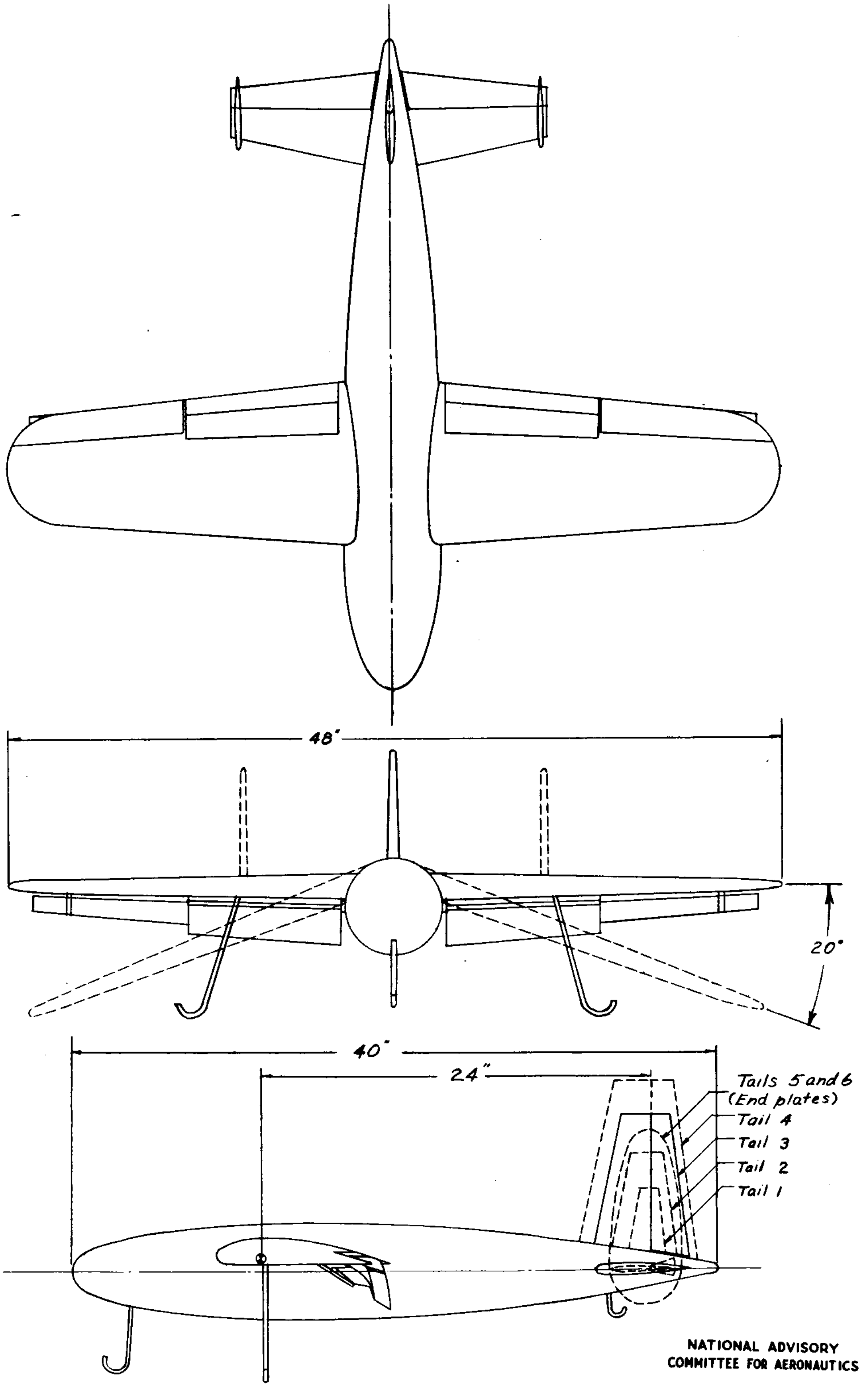


Figure 1. - Three-view sketch of model tested in Langley free-flight tunnel showing range of dihedral adjustment and alternate vertical-tail arrangements.

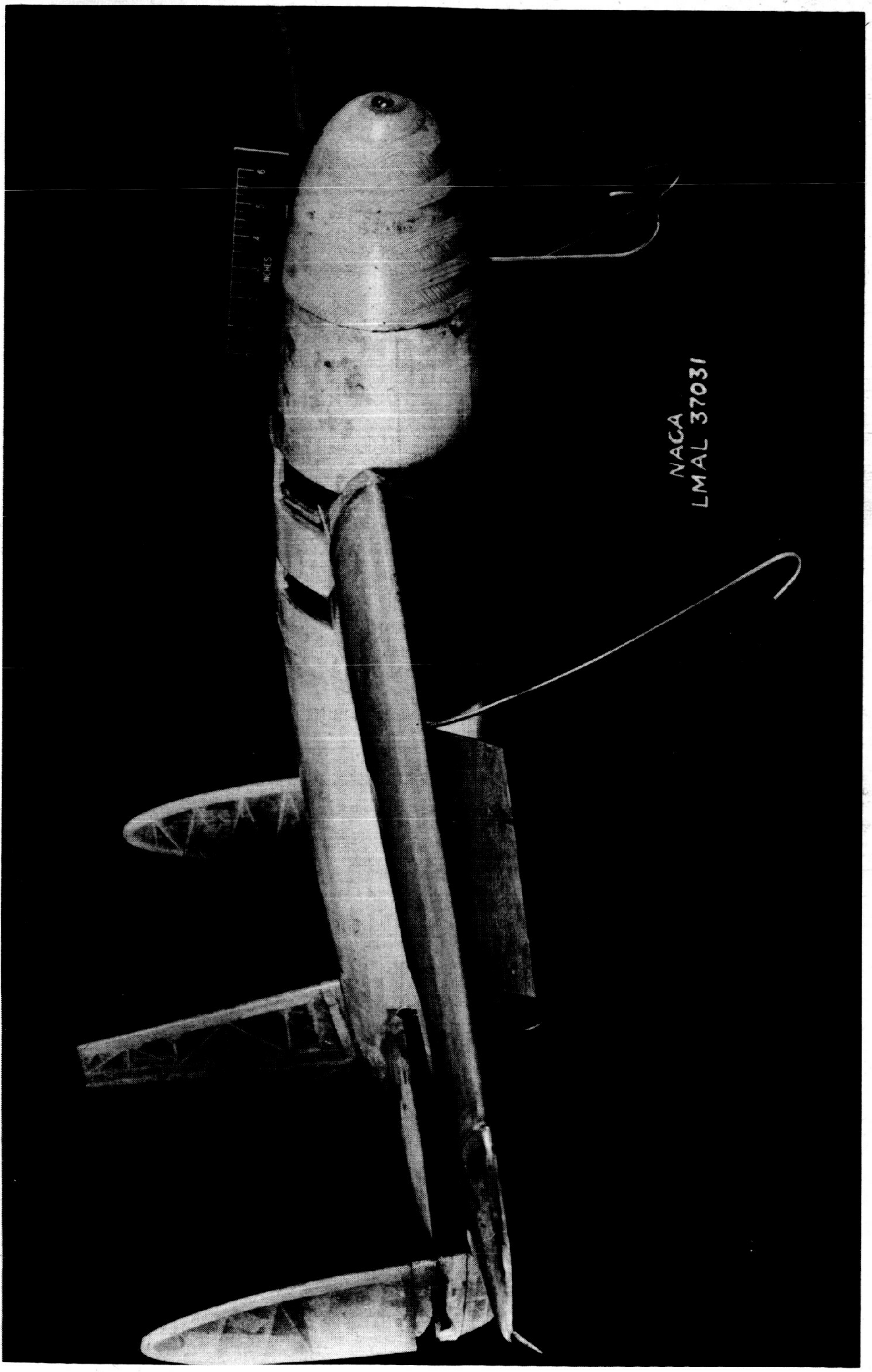


Figure 2.- Three-quarter front view of model with vertical-tail area 30 percent of wing area.

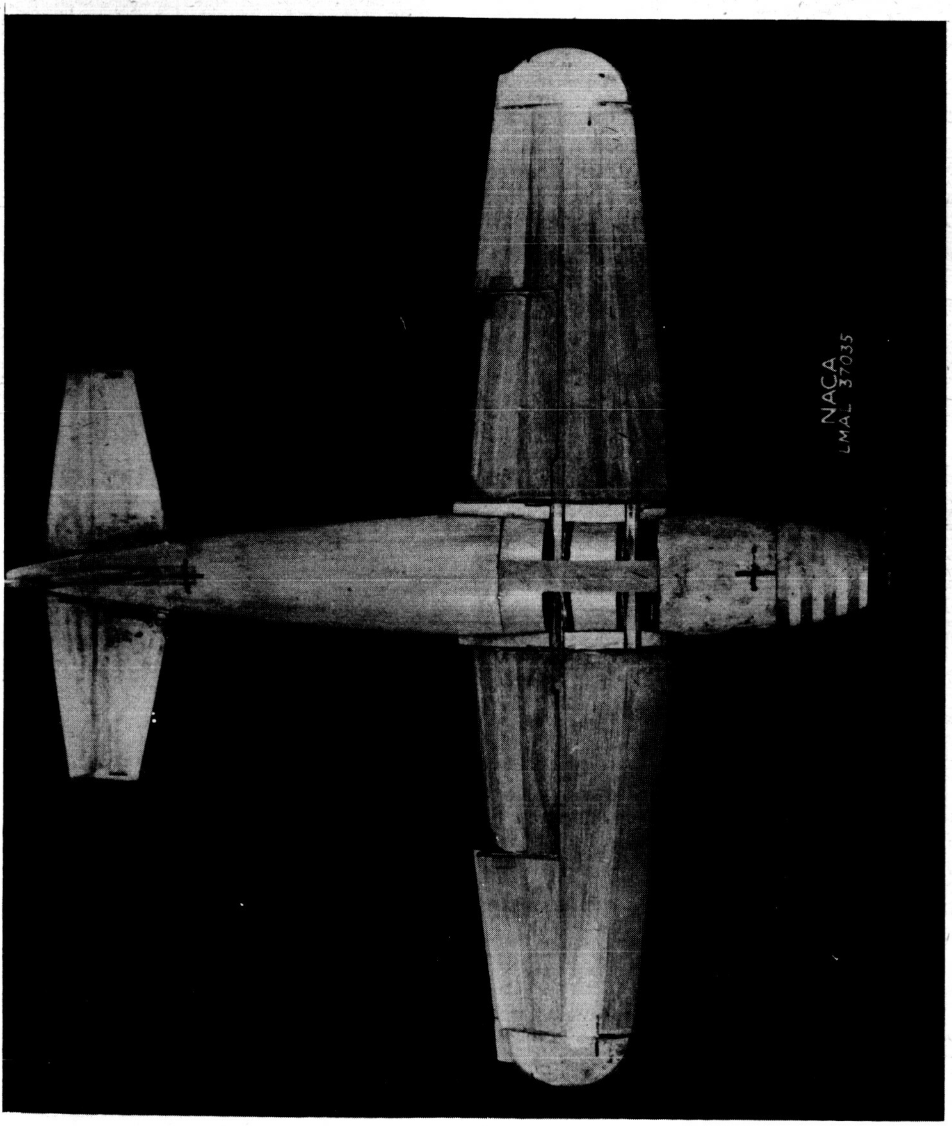


Figure 3.- Plan view of model.

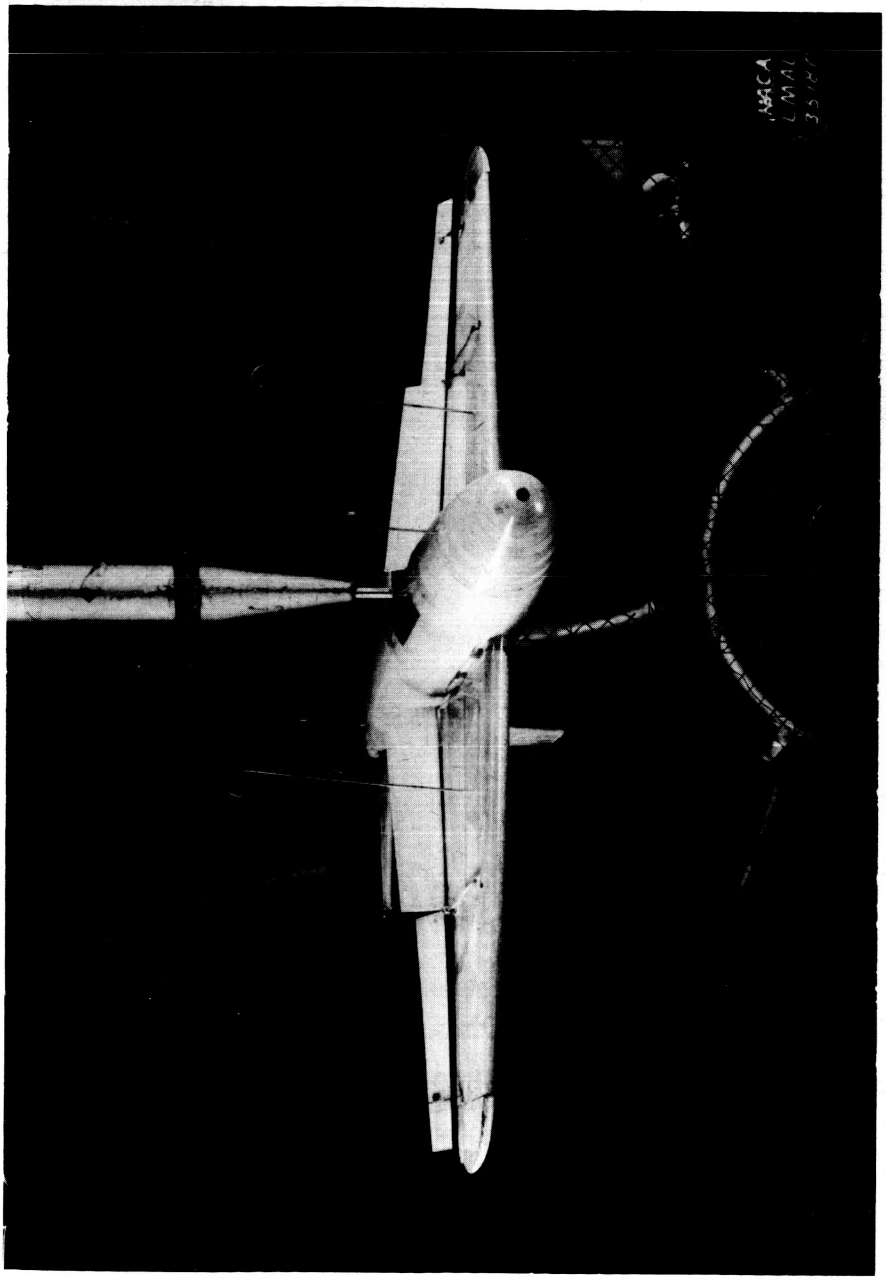


Figure 4.- Model mounted on balance strut in Langley free-flight tunnel.

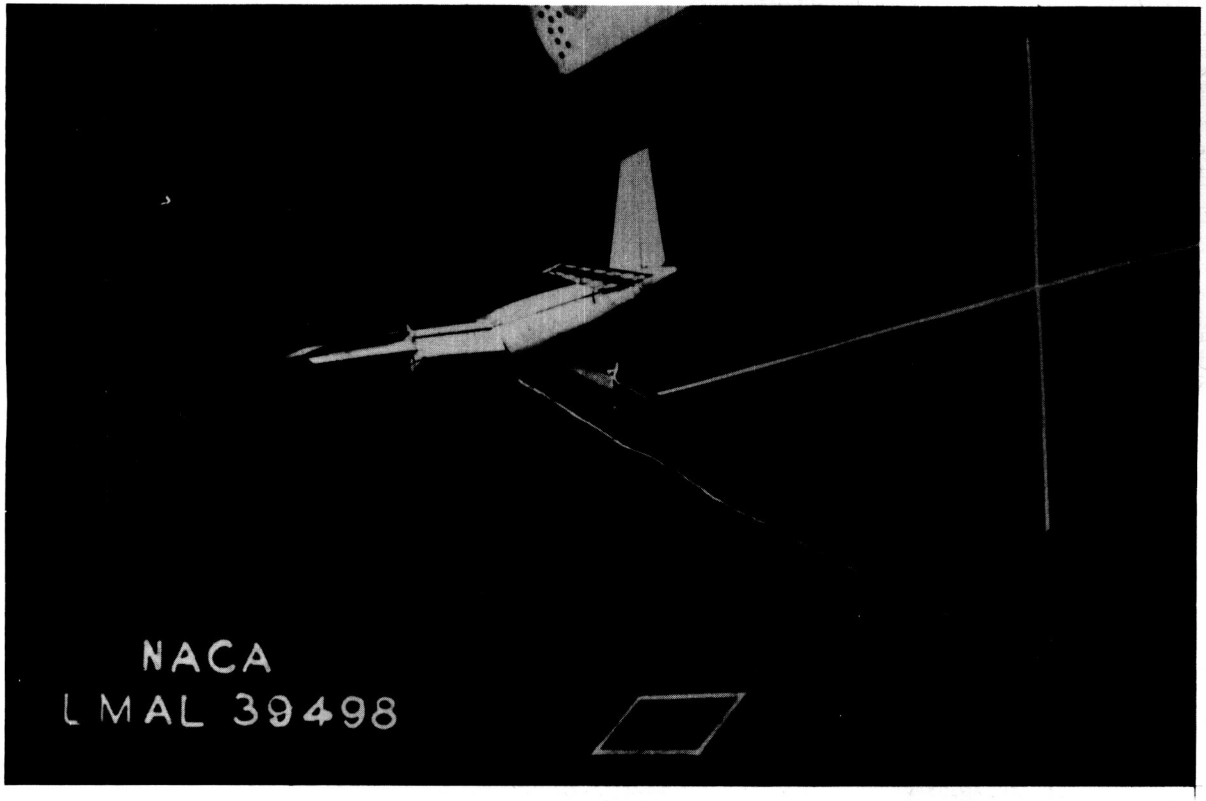
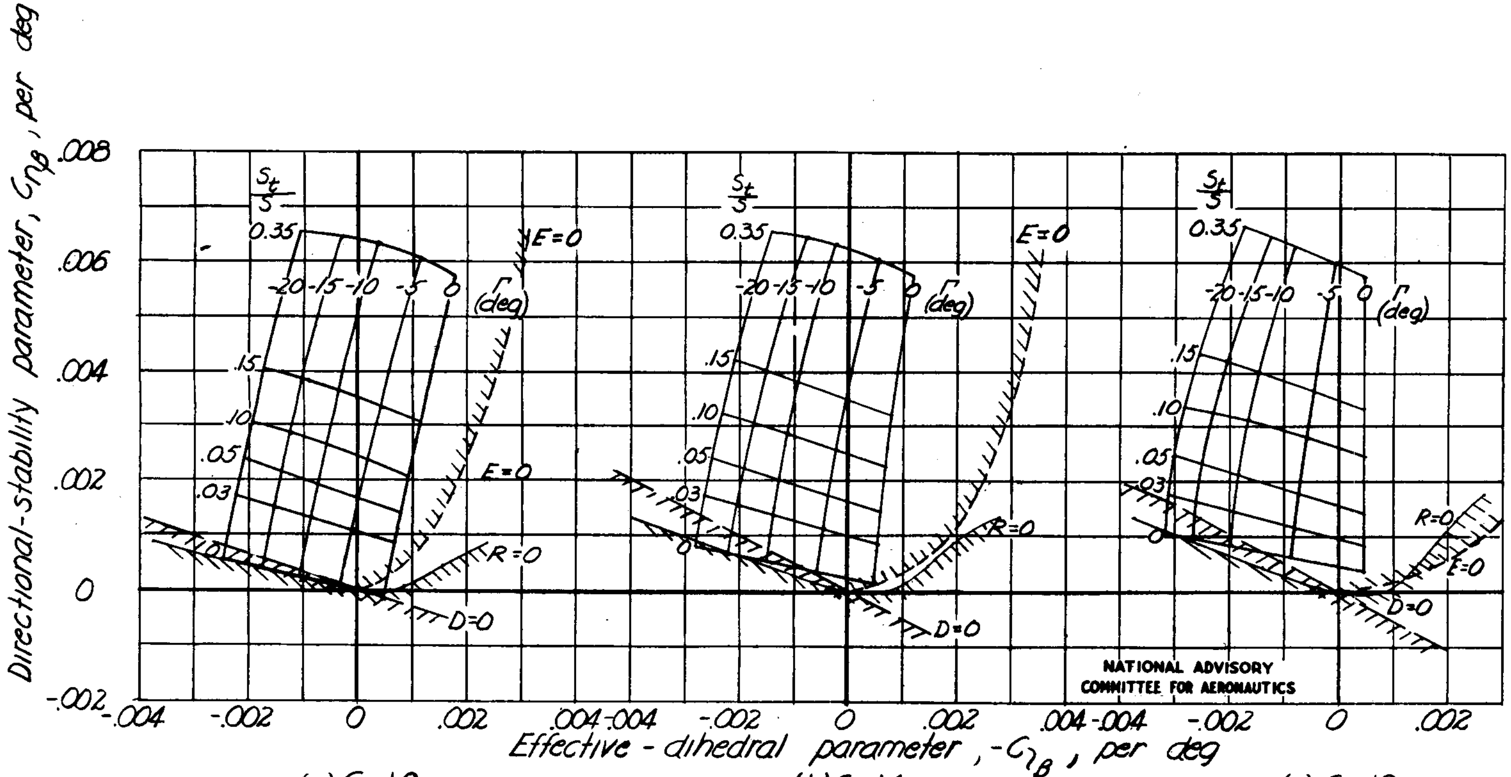


Figure 5.- Model, with dihedral angle of -15°, flying in Langley free-flight tunnel.



(a) C_L=1.0. (b) C_L=1.4. (c) C_L=1.8.

Figure 6 .- Values of C_{l_β} and C_{n_β} for the model with various combinations of dihedral angle and vertical-tail area compared with the calculated lateral-stability boundaries.

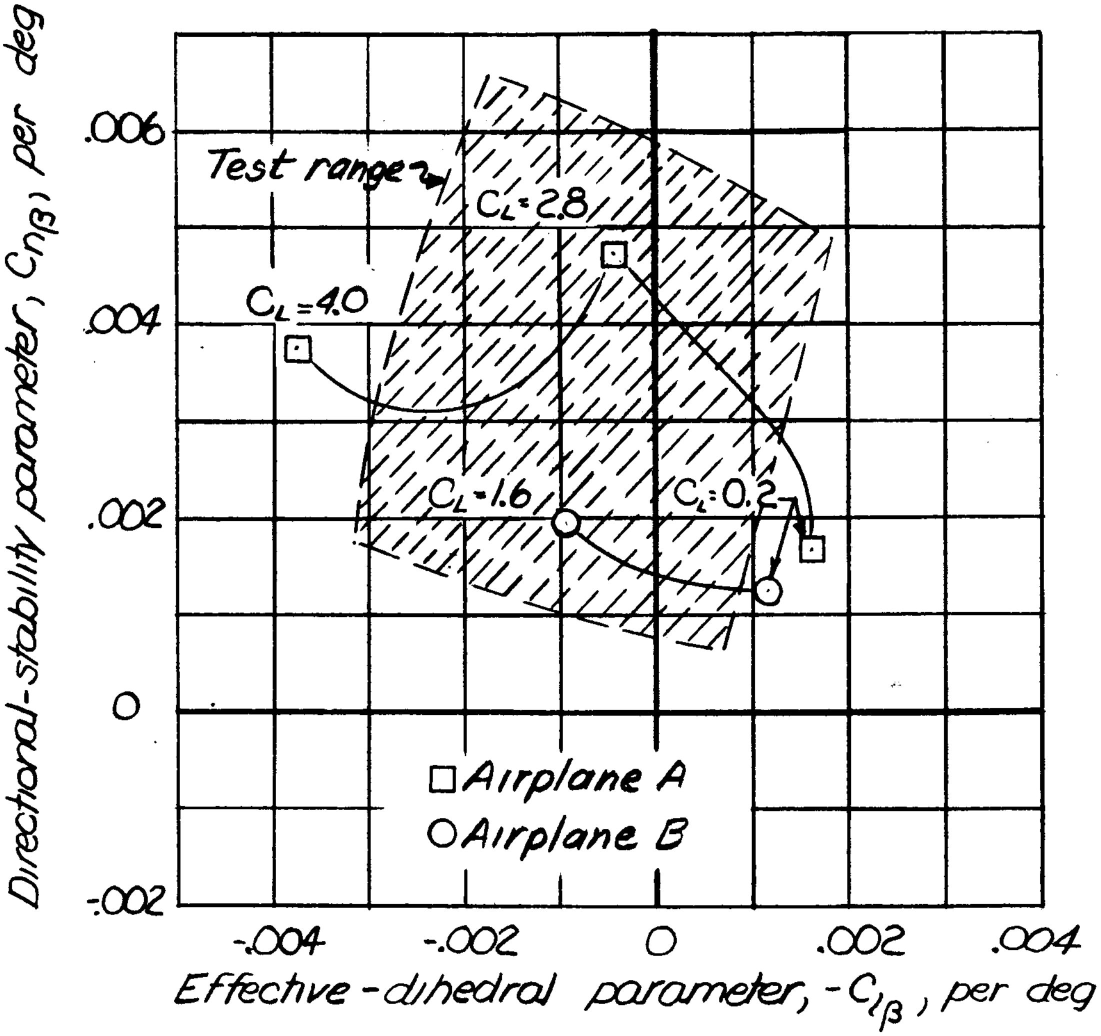


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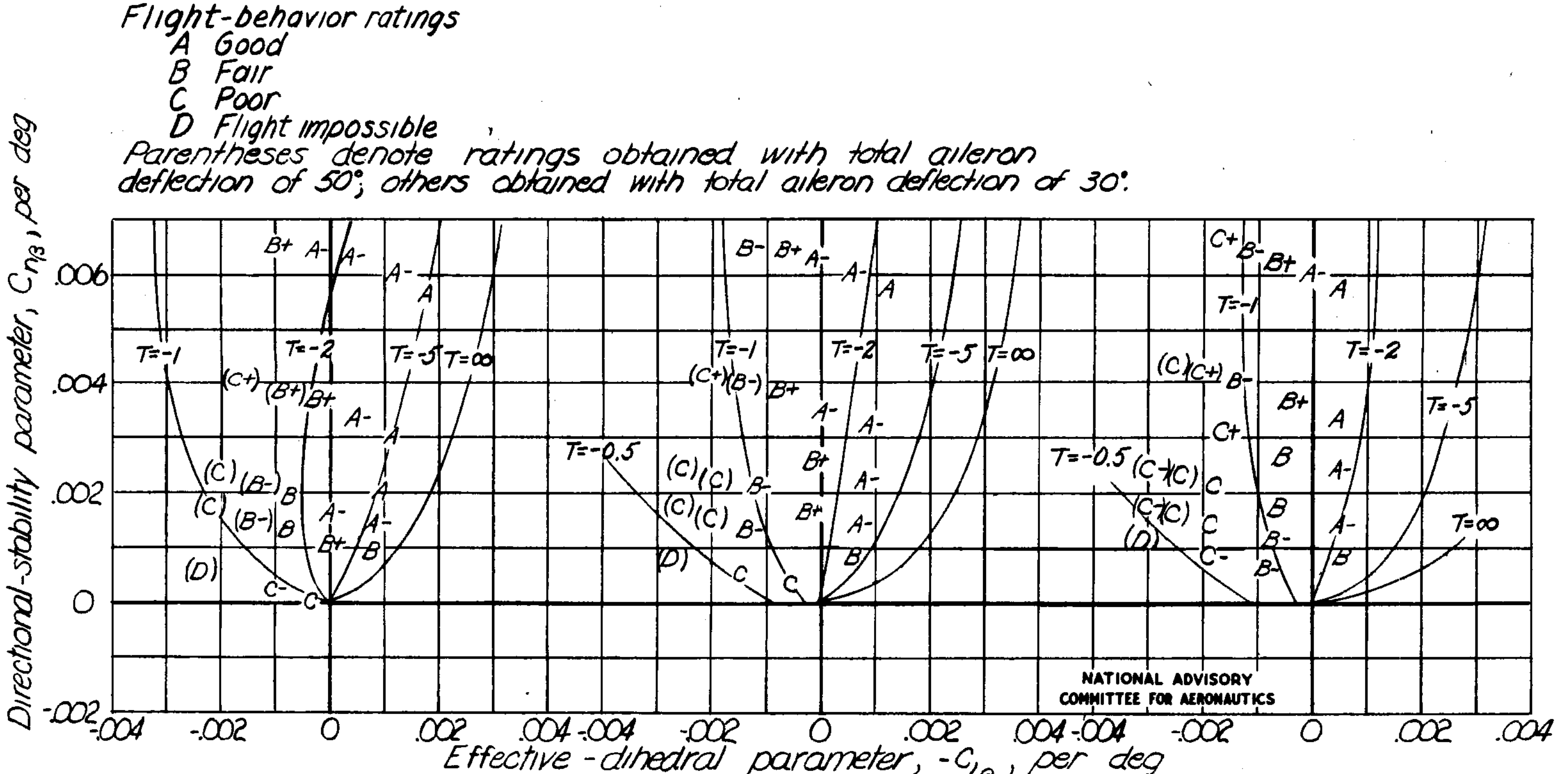
Figure 7.- Values of C_{l_β} and C_{n_β} for two modern high-powered airplanes as compared with the range tested.



(a) C_L=1.0.

(b) C_L=1.4.

(c) C_L=1.8.

Figure 8 .- General flight-behavior ratings with calculated lines of constant damping of the spiral divergence.