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TECHNICAL NOTE

D-1141

THE EFFECT OF LATERAL-DIRECTIONAL CONTROL COUPLING ON PILOT CONTROL OF AN AIRPLANE AS DETERMINED IN FLIGHT AND IN A FIXED-BASE FLIGHT SIMULATOR

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Moffett Field, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON November 1961

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SUMMARY

A flight and fixed-base simulator study was made of the effects of aileron-induced yaw on pilot opinion of aircraft lateral-directional controllability characteristics. A wide range of adverse and favorable aileron-induced yaw was investigated in flight at several levels of Dutch-roll damping.

The flight results indicated that the optimum values of aileron-induced yaw differed only slightly from zero for Dutch-roll damping from satisfactory to marginally controllable levels. It was also shown that each range of values of aileron-induced yawing moment considered satisfactory, acceptable, or controllable increased with an increase in the Dutch-roll damping. The increase was most marked for marginally controllable configurations exhibiting favorable aileron-induced yaw.

Comparison of fixed-base flight simulator results with flight results showed agreement, indicating that absence of kinesthetic motion cues did not markedly affect the pilots' evaluation of the type of control problem considered in this study.

The results of the flight study were recast in terms of several parameters which were considered to have an important effect on pilot opinion of lateral-directional handling qualities, including the effects of control coupling.

Results of brief tests with a three-axis side-arm controller indicated that for control coupling problems associated with highly favorable yaw and cross-control techniques, use of the three-axis controller resulted in a deterioration of control relative to results obtained with the conventional center stick and rudder pedals.

INTRODUCTION

Several current aircraft and proposed supersonic and hypersonic designs exhibit undesirable lateral-directional control-coupling characteristics. One problem of particular concern is associated with the conversion of angle of attack to sideslip angle as the airplane is rolled about a highly inclined longitudinal axis. Excessive aileron-induced yaw may have a number of adverse effects on the lateral-directional handling qualities, including the large sideslip angles and the associated large uncomfortable yawing accelerations developed in rolling maneuvers, undesirably large increases or decreases in roll performance, precise control of bank or sideslip angle may be difficult, and cross-controlling techniques may be needed for coordinating maneuvers. Although previous flight and simulator studies bearing on these problems have been made (refs. 1 through 4), few systematic data are available upon which to base design criteria or to establish the extent to which simulator studies of control-coupling problems can be extrapolated to flight.

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As part of a general program being conducted at the Ames Research Center to investigate the basic vehicle flying or handling qualities of advanced vehicle designs (see refs. 2, 5, and 6), a flight and fixed-base simulator study was made of the effects on pilot opinion of a wide range of favorable and adverse yawing moments due to aileron deflection.

This report has three main objectives:

1. To define the maximum acceptable levels of aileron-induced yawing moments.

2. To assess the effect of lack of kinesthetic motion cues in evaluating the problem.

3. To evaluate several lateral-directional handling qualities parameters and compare them with flight experience.

NOTATION

b	wing span, ft
C_l	rolling-moment coefficient
C_n	yawing-moment coefficient
g	acceleration due to gravity, ft/sec^2
h	altitude, ft
I_X	rolling moment of inertia, slug-ft^2

I_{xz}	product of inertia, slug-ft^2
I_z	yawing moment of inertia, slug-ft^2
K_p	pilot gain, deg/deg
L	rolling acceleration due to externally applied torques, $\frac{C_l qSb}{I_x}$
L_i	variation of L with input or motion quantity, $i = p, r, \beta, \delta_a,$ or δ_r
L_i'	$\frac{L_i + r_x N_i}{1 - r_x r_z}$
L_p	$\frac{\partial L}{\partial p}$, per sec
L_r	$\frac{\partial L}{\partial r}$, per sec
L_β	$\frac{\partial L}{\partial \beta}$, per sec^2
L_{δ_a}	$\frac{\partial L}{\partial \delta_a}$, per sec^2
L_{δ_r}	$\frac{\partial L}{\partial \delta_r}$, per sec^2
N	yawing acceleration due to externally applied torques, $\frac{C_n qSb}{I_z}$
N_i	variation of N with input or motion quantity, $i = p, r, \beta, \delta_a,$ or δ_r
N_i'	$\frac{N_i + r_z L_i}{1 - r_x r_z}$
N_p	$\frac{\partial N}{\partial p}$, per sec
N_r	$\frac{\partial N}{\partial r}$, per sec
N_β	$\frac{\partial N}{\partial \beta}$, per sec^2
N_{δ_a}	$\frac{\partial N}{\partial \delta_a}$, per sec^2

N_{δ_r}	$\frac{\partial N}{\partial \delta_r}$, per sec^2
p	rolling velocity, radians/sec
$\frac{\lvert p \rvert_1}{\lvert p_{ss} \rvert}$	ratio of the amplitude of the oscillatory roll rate at first overshoot to the steady-state roll rate, percent
q	dynamic pressure, lb/sq ft
r	yawing velocity, radians/sec
r_x	$\frac{I_{xz}}{I_x}$
r_z	$\frac{I_{xz}}{I_z}$
S	wing area, ft^2
s	Laplace transform variable
T_R	roll subsidence time constant, sec
t	time, sec
V	velocity, ft/sec
W	weight of airplane, lb
Y	dimensionless lateral acceleration due to externally applied forces, $\frac{\text{lateral acceleration}}{V}$
Y_β	$\frac{\partial Y}{\partial \beta}$, per sec
Y_{δ_r}	$\frac{\partial Y}{\partial \delta_r}$, per sec
α	angle of attack, deg
β	angle of sideslip, radians
δ_a	total aileron deflection, radians (except as noted)
δ_r	rudder deflection, radians

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ζ_d	damping ratio of the Dutch-roll oscillation
ζ_{CL}	closed-loop Dutch-roll damping ratio appearing in the bank-angle response to aileron transfer function
σ	ratio of air density at test altitude to that at sea level
φ	bank angle, radians
φ_c	command bank angle, deg
$\frac{\lvert\varphi\rvert}{\lvert v_e\rvert}$	$\frac{\lvert\varphi\rvert 57.3}{\lvert\beta\rvert V\sqrt{\sigma}}$, ratio of bank-angle amplitude to equivalent side velocity amplitude, $\frac{\text{deg}}{\text{ft/sec}}$
ω_d	undamped natural frequency of the Dutch-roll oscillation, 1/sec
ω_φ	undamped natural frequency appearing in the numerator of the bank-angle-response-to-aileron transfer function, 1/sec
$(\dot{\ })$	derivative with respect to time

TEST APPARATUS AND EQUIPMENT

Variable-Stability Airplane

The flight portion of the present study was conducted in a variable-stability F-86E airplane. The airplane has a servo-driven rudder and ailerons through which the apparent stability and control characteristics may be varied. This vehicle is fully described in reference 7.

Flight Simulator

The simulator used in this study consisted of a fixed cockpit with instruments and controls, a servo-driven horizon projector, a projection screen, and an analog computer. The simulator gave the pilot a visual impression of flying above a layer of clouds. See figure 1. In this figure the horizon is situated so as to indicate a diving right turn. The cockpit layout is similar to that of the variable-stability airplane and contains the conventional rudder pedals and center stick, and a three-axis side-arm controller (fig. 2). Force and deflection characteristics of the center stick and rudder pedals were approximately the same as those of the test airplane. The only flight instrument present in the simulator cockpit was a sideslip-angle indicator similar to the one mounted above the instrument panel in the variable-stability airplane. No other instruments were required since the simulation represented the aircraft maneuvering about a 1g flight path with the airspeed held constant.

A two-axis servo-driven (in roll and in pitch) horizon projector was employed. The projector lamp and lense arrangement was such that the lower portion of the projection screen was illuminated for level flight. The projector was servo driven through an analog computer so that the projected image appeared to be a brightly illuminated layer of clouds several thousand feet below the simulator cockpit.

The projection screen was the inner surface of a 20-foot-diameter sphere, the base of which was truncated below the pilot's field of view. The projector was located at the center of the sphere formed by the screen.

The analog computer was used to solve the equations of motion and to generate appropriate signals for the projector servos and the sideslip indicator. The lateral set of equations used in the simulator study is given in appendix A.

TEST CONDITIONS

Three NASA research pilots participated in the study. In both flight and simulator tests the pilots (referred to as A, B, or C) evaluated test configurations and assigned to each a numerical rating according to the pilot-opinion rating scale of reference 5 which is reproduced in table I. The basis for the numerical rating values of pilot opinion obtained in this investigation and presented in the figures of this report was the degree of lateral-directional controllability of each test condition when over-all operation of current fighter-type aircraft was considered.

The maneuvers executed by pilot A in rating each configuration generally form the basis for results presented in this report and are as follows:

(a) Abrupt 45° to 60° bank-angle turn entries using rudder to minimize sideslip.

(b) Abrupt aileron reversals to effect rolling oscillations of ±20°, ±30°, and ±45° bank-angle amplitudes using rudders to minimize sideslip.

(c) Rolling through ±360° bank angle with rudder pedals fixed and with rudder pedals controlling sideslip.

In the discussion that follows, the words "coordinated" and "uncoordinated" refer to coordination of rudder with aileron to prevent sideslipping and no rudder manipulation during rolling maneuvers, respectively.

Flight Tests

All flight tests were performed at 170 knots indicated airspeed and 10,000 feet altitude. The variable stability equipment in the airplane was adjusted to give the dynamic response characteristics shown in table II. Estimated stability derivatives and other pertinent information for the test conditions are also given in table II. Pilots A and B participated in the flight tests but only pilot A evaluated characteristics at all damping conditions shown in table II, while pilot B performed evaluations only at 0.10 damping ratio.

Simulator Tests

All three pilots participated in the simulator tests. The simulator investigation was conducted only at a damping ratio of 0.10. The stability and control derivatives shown in table II were used in the analog computer to provide simulator response characteristics approximately the same as those for the flight tests. In table II, values of ζ_d, ω_d, and $|\varphi|/|v_e|$ derived from the flight tests and from the estimated stability derivatives are presented.

RESULTS AND DISCUSSION

Flight Results

Pilot ratings based on lateral-directional handling characteristics obtained in the flight tests are presented in figure 3. In this figure, it is shown that the handling characteristics deteriorate with reduction of damping and with variation of the aileron coupling parameter N_{δ_a}' from an optimum value. Fairings presented in the left-hand part of the figure are based on the flight data points shown, on pilot comments of optimum N_{δ_a}', and on data of reference 7. During the tests the period of Dutch-roll oscillation varied with changes of damping between 3.4 seconds ($\zeta_d = 0.22$) and 4.0 seconds ($\zeta_d = -0.13$).

Comparison of the pilot opinion data of pilot A ($\zeta_d = 0.10$) with that of pilot B (see fig. 3) shows good agreement. The greatest difference, one, in ratings of the two pilots occurs at the most positive value of N_{δ_a}'. Figure 3 shows a preference for increasingly positive N_{δ_a}' with decreasing damping which may be attributed to the associated increase in the closed-loop Dutch-roll damping ratio relative to the open-loop Dutch-roll damping. It is shown in reference 8 and in appendix A, that a negative product $N_{\delta_a}'L_\beta'$ (which holds for the test conditions when

N_{δ_a}' is positive) is generally associated with an increase in closed-loop damping (relative to the open-loop damping) and, conversely, a positive product is associated with a decrease in closed-loop damping.

In order to illustrate, in terms of the open-loop response characteristics, the nature of the control problems encountered at highly favorable and highly adverse N_{δ_a}' conditions, typical simulator time histories, for the test conditions, of roll-rate response to aileron step inputs are presented in figure 4. Shown are response characteristics corresponding to a near optimum N_{δ_a}' (-0.70) and two conditions near the unsatisfactory-unacceptable boundary (1.92 and -2.31). A fourth case not investigated in this study (see ref. 6) is also presented in figure 4. The latter case is the response of an uncoupled aircraft ($N_{\delta_a}' = 0$) with the same T_R and L_{δ_a}' as in the present tests.

The excessively favorable N_{δ_a}' (-2.31) is characterized by an increased and oscillatory roll-rate response relative to the near optimum N_{δ_a}' (-0.70) or to the single degree of freedom case. In addition, if the pilot attempts to maintain small sideslip angles while maneuvering, he must cross-control which further aggravates the control problem.

The response for highly adverse N_{δ_a}' (1.92) is characterized by a marked decrease in steady-state rolling velocity and an oscillatory response resulting in rolling velocity reversals. The response characteristics of two current high-performance aircraft, which have undesirable lateral-directional coupling characteristics and which will be discussed later, are similar to those for the excessively favorable and highly adverse N_{δ_a}' cases illustrated in figure 4.

The basic data of figure 3 (pilot A) are replotted in figure 5 showing constant pilot-opinion contours as a function of N_{δ_a}' and Dutch-roll damping ratio. Also presented in this figure are the flight data points and ratings of pilot A. It can readily be seen in this figure that a pilot will tolerate increasing levels of N_{δ_a}', either positive or negative, as the damping is increased. For marginally controllable conditions, this effect is more pronounced for favorable than for adverse N_{δ_a}' values.

Simulator Results

Center stick.- The data obtained in the simulator tests, conducted only at the Dutch-roll damping ratio of 0.10, are presented in figure 6 in the form of pilot rating versus the aileron-yaw parameter N_{δ_a}'. In this figure a difference in optimum N_{δ_a}' between pilots can be seen. Pilot A prefers a condition of slightly favorable N_{δ_a}' while pilots B and C show a preference for a slightly adverse N_{δ_a}'.

Side-arm controller.- Because of interest in the use of side-arm controllers in current and proposed vehicles, a brief simulator study of effects of aileron-induced yaw on pilot opinion was made using a three-axis wrist-pivoted type. The simulated characteristics were identical to those of the conventional center-stick tests previously described.

Figure 7 presents a comparison of the data obtained in the side-arm controller tests with the center-stick results (fig. 6). There is good correlation between center-stick and side-arm controller results except in the region where cross-controlling techniques are required for coordinated maneuvering (N_{δ_a}' negative). Where cross controlling was required, the pilots criticized the side-arm controller because of awkwardness of coordination of rudder and aileron.

Comparison of Flight and Simulator Results

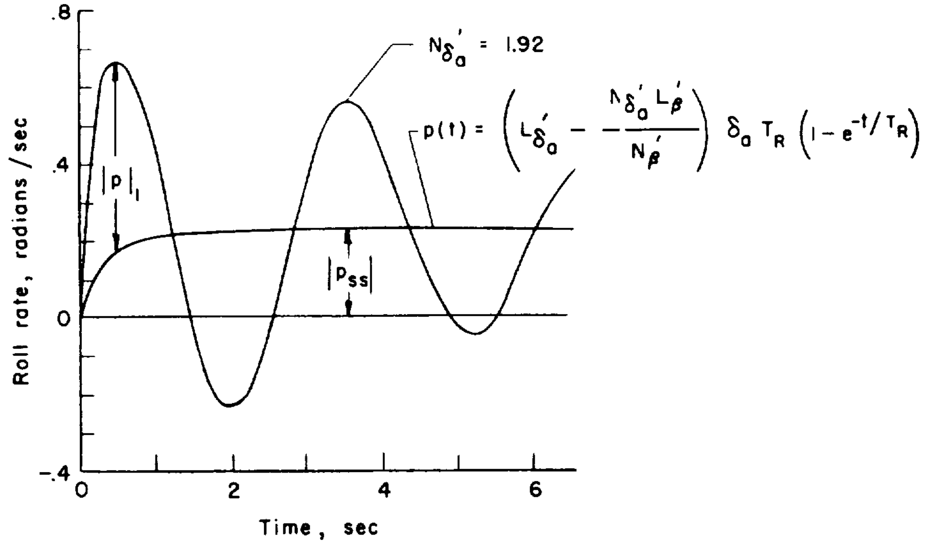
In figure 8, the fairings and data points of the flight results (fig. 3) of pilot rating versus N_{δ_a}' are compared with the simulator results. Excellent agreement is shown between flight and simulator results for the pilots who participated in both phases of the study, with a maximum spread in pilot ratings of approximately one. The largest difference between simulator and flight ratings occurred for the more negative values of N_{δ_a}' where both pilots gave more conservative ratings in the simulator than in the flight tests. The pilots' flight experiences may have had some influence on the simulator results; however, the flight ratings of pilot A were obtained some time previous to those obtained in the simulator tests while the simulator tests of pilot B were performed shortly before the flight tests. The good agreement shown in figure 8 indicates that the absence of kinesthetic motion cues in the simulator tests did not markedly affect pilot opinion possibly because of the strong visual cues present.

Comparisons of Data With Various Lateral-Directional Handling Qualities Parameters

In this section, the data of the present study are examined and compared with several parameters that have been considered for prediction of pilot opinion of lateral-directional characteristics, including the effects of aileron coupling (N_{δ_a}'). The present flight-test results for approximately optimum N_{δ_a}' are plotted in figure 9 in terms of the conventional Dutch-roll handling qualities criterion, the ratio of bank angle to side velocity $|\varphi|/|v_e|$, and Dutch-roll damping ζ_d. Also shown are boundaries from reference 7 delineating satisfactory, unsatisfactory, and unacceptable boundaries. As expected, the two sets of data for near optimum values of N_{δ_a}' are in good agreement. However, it is clear from the data of figure 5 that even though the reference boundaries in terms of $|\varphi|/|v_e|$ and ζ_d may be satisfied, deviations of N_{δ_a}' from optimum can result in an unacceptable control situation.

Lateral-control sensitivity.- Pilots' comments indicate that roll control sensitivity is an important factor affecting pilot opinion. In figure 10, data of the present study are compared with the roll controllability criteria of reference 6 through the uncoordinated roll control power parameter $[L_{\delta_a}' - N_{\delta_a}'(L_\beta'/N_\beta')]\delta_{a_{max}}$ which is approximately the maximum steady-state rolling velocity divided by the roll subsidence time constant. The reference data presented are for the same value of roll time constant as used in the present study (T_R = 0.33 sec). The coordinated roll control power parameter $L_{\delta_a}\delta_{a_{max}}$ presented in reference 6 was primarily for a single-degree-of-freedom system. The shaded area represents the spread between pilot ratings obtained in the moving simulator and in flight. Data of the present study at the higher Dutch-roll damping compare well with the reference results for values of $[L_{\delta_a}' - N_{\delta_a}'(L_\beta'/N_\beta')]\delta_{a_{max}}$ less than about 7.5. In the range below 7.5, in the present flight tests only N_{δ_a}' was varied while in the simulator tests of reference 6 only L_{δ_a}' was varied. It therefore, appears that in this range an equivalence between L_{δ_a}' and N_{δ_a}' effects is correctly represented by the parameter $[L_{\delta_a}' - N_{\delta_a}'(L_\beta'/N_\beta')]\delta_{a_{max}}$ so long as ζ_d is greater than about 0.10.

Roll rate overshoot parameter.- Reference 3 presents a lateral-directional handling quality criterion in terms of the step-aileron response parameter $(|p|_1/|p_{ss}|)$, which was defined as "the ratio of the amplitude of the oscillatory roll rate at first overshoot to the steady-state roll rate." In the sketch that follows, the parameters appearing in this ratio are depicted as they apply to one of the time histories presented in figure 4. Figure 11 presents the results of reference 3



converted to the pilot rating scale used in the present study. Results of the present study for the Dutch-roll damping ratio of 0.10 are also presented in figure 11 and show good agreement at the reference 3 minimum satisfactory boundary condition of $|p|_1/|p_{ss}| = 4.5$ percent. Beyond this boundary the present study results show that for a given pilot rating, the magnitude of this roll rate ratio can vary markedly, depending on whether N_{δ_a}' is adverse or favorable.

Ratio of uncoordinated to uncoupled roll control effectiveness parameter $(\omega_\varphi/\omega_d)^2$.- It has been suggested in reference 8 that an important factor that might influence pilot opinion of lateral-directional handling qualities is the ratio of the squares of the natural frequencies appearing in the transfer function for bank-angle response to aileron deflection (see appendix A). In reference 8 it is also shown that the parameter $(\omega_\varphi/\omega_d)^2$ can be approximated by the parameter $[L_{\delta_a}' - N_{\delta_a}'(L_\beta'/N_\beta')]/L_{\delta_a}'$ which is simply the uncoordinated roll control power considered in figure 10, divided by the coordinated (zero) sideslip) roll control power $L_{\delta_a}'\delta_{a_{max}}$. A similar parameter $(N_{\delta_a}'L_\beta')/(L_{\delta_a}'N_\beta')$ which is approximately equal to $(1 - \omega_\varphi^2/\omega_d^2)$ was presented in reference 2 and was suggested as an important parameter in defining the degree of lateral-directional coupling. References 4 and 9 present the results of a flight study which also shows the importance of the parameter $(\omega_\varphi/\omega_d)^2$ on pilot opinion of lateral-directional handling qualities. The curves and flight data points with ratings of figure 5 are replotted in figure 12 to show constant pilot opinion contours as a function of $(\omega_\varphi/\omega_d)^2$ and the Dutch-roll damping. In this figure, it is noted that the satisfactory boundary is limited to a narrow region of $(\omega_\varphi/\omega_d)^2$ slightly greater than 1. It is also shown in figure 12 that the optimum values of $(\omega_\varphi/\omega_d)^2$, that is, those values corresponding to minimum satisfactory, acceptable and unacceptable levels of Dutch-roll damping, vary from slightly greater than 1 to about zero. (The latter value is based on an extrapolation of the available data, as indicated by the dashed line in fig. 12.) The unsatisfactory and unacceptable pilot-opinion boundaries show an appreciable effect of damping on $(\omega_\varphi/\omega_d)^2$ for values greater than optimum and show little effect for less than optimum values of $(\omega_\varphi/\omega_d)^2$.

Another control-coupling parameter, which is related to $(\omega_\varphi/\omega_d)^2$, is the ratio $(\omega_d^2 - \omega_\varphi^2)/(L_p'^2 + \omega_\varphi^2)$. With certain simplifying assumptions (see appendix A), this ratio represents the ratio of the Dutch-roll to roll-subsidence contributions to the roll acceleration response for a step aileron input in terms of the constant terms (undamped coefficients) in the roll response equation. Figure 13 presents constant pilot-opinion contours and pilot A flight data points with ratings as a function of this coupling parameter and the Dutch-roll damping. Satisfactory ratings were obtainable for good damping ($\zeta_d = 0.2$) only in a narrow band (approximately 0 to -0.1) of this ratio, while values between ±0.25 at marginally satisfactory damping ($\zeta_d = 0.10$) were considered acceptable.

Results of a flight investigation in which a similar ratio (roll rate response to a step aileron deflection) was studied are presented in reference 10.

Closed-loop Dutch-roll damping.- The effects of $(\omega_\varphi/\omega_d)^2$ on pilot opinion were shown in the previous section. It was suspected that perhaps the primary effect of $(\omega_\varphi/\omega_d)^2$ is on the closed-loop response of the pilot-airframe combination (see appendix A). To assess the significance of the closed-loop response characteristics, the faired curves for the ratings of pilot A from figure 3 are replotted in figure 14 in terms of the closed-loop Dutch-roll damping ratio. Details of the closed-loop response considerations and simplifications used to obtain the results shown in this figure are given in appendix A. In this figure it can be seen that for conditions of $(\omega_\varphi/\omega_d)^2 > 1$ (fig. 14(b)) and the open-loop damping $\zeta_d < 0.1$, the closed-loop damping ratio correlates the data of the present study; pilot opinion appears to be related only to the closed-loop damping level. For conditions of $(\omega_\varphi/\omega_d)^2 < 1$ (fig. 14(a)) there appears to be no systematic correlation of the data through closed-loop response considerations.

Example Control-Coupling Problems

In this section the control-coupling problems of two high-performance aircraft will be examined and correlated with the results of the present study by means of several of the parameters considered in the preceding section. The intent here is to establish which parameter best correlates the pilot-opinion data for these aircraft, thereby establishing a firmer basis for generalizing the results of the present study. In one case, results of a fixed-base simulator study (ref. 2) showed that one of the re-entry configurations investigated became uncontrollable during the high-angle-of-attack portion of atmosphere-entry with the roll damper inoperative. With the roll damper operative, the vehicle had satisfactory control characteristics. In the other case, a flight investigation of factors influencing pilot selection of landing approach speeds (ref. 1) indicated that aileron-induced yaw may have been one of the factors adversely affecting landing approach speeds. In the landing approach study the lateral-directional handling characteristics were considered to be made somewhat worse when external fuel tanks were added.

Re-entry case.- Time histories of roll-rate response to step aileron deflections are presented in figure 15(a) for both the damper-off and the damper-on conditions. The damper-on time history shown is for a 15° aileron step and results in a small and oscillatory roll rate response while the damper-off time history is for only a 1.5° aileron step which produces a large and oscillatory roll-rate response. In the re-entry study of reference 2 this vehicle was designated Configuration B and was rated on the lateral-directional characteristics over the entire re-entry trajectory. It is believed that the time histories presented in figure 15(a) are, considering lateral-directional handling, for the worst condition encountered during the trajectory. Pilot ratings based on the entire flight were 3 for the damper on and 10 for the damper off. Table III presents stability derivatives and other pertinent information for these two conditions. As discussed in reference 2, existing criteria for predicting pilot opinion would not account for the rating of 10.

Landing approach case.- In figure 15(b) are presented time histories of roll rate and sideslip response to approximately an 11° aileron deflection for two test conditions recorded during flight. Both time histories show a very oscillatory and small roll-rate response with a steady-state value of about 0.15 radian per second for the tanks-off configuration and near zero for the tanks on. One pilot rated the tanks-on configuration 8 because of the zero roll rate response, but the tanks-off configuration, which had some positive roll response, even though small, he rated 5 over-all. On the basis of the data of figure 9 in terms of the conventional Dutch-roll handling qualities parameters, the predicted ratings for both configurations would be about 5. Estimated stability derivatives and other pertinent data for this vehicle are presented in table III.

Correlation with results of present study.- The actual pilot ratings of lateral-directional handling characteristics of the two example aircraft and ratings which are predicted by means of several of the parameters discussed in this report are compared in figure 16. The parameter values used to obtain the predicted values shown in this figure are presented in table III.

The comparison indicates that for lateral-directional coupling problems involving negative $N_{\delta_a}'L_\beta'$ products (e.g., in the landing approach), the roll control criteria of reference 6, modified to include coupling terms, provide good prediction of pilot opinion if the Dutch-roll damping is satisfactory. For this case of reduced uncoordinated roll control effectiveness relative to the uncoupled value, the parameter $(\omega_\varphi/\omega_d)^2$ provided fair correlation of the data. For coupling involving positive $N_{\delta_a}'L_\beta'$ products (e.g., in the re-entry), the roll acceleration response ratio (fig. 13) and the closed-loop Dutch-roll damping appear equally useful in predicting pilot opinion.

CONCLUDING REMARKS

Results of a flight and fixed-base simulator study of the effects on pilot opinion of a wide range of adverse and favorable aileron-induced yawing moments at various Dutch-roll damping levels indicate:

(a) The optimum-aileron induced yaw differed only slightly from zero.

(b) Increase of Dutch-roll damping increased the range of aileron-induced yaw considered satisfactory, acceptable, or controllable.

(c) The results of the fixed-base simulator test were essentially identical to the flight results and indicate that the absence of kinesthetic motion cues did not markedly affect pilot opinion, presumably because of the presence of strong visual cues.

Correlation of the results of the present study and other available data show several parameters which may be useful for predicting lateral-directional handling characteristics.

Comparison of the results of brief tests with a three-axis side-arm controller with results of tests with conventional center stick and rudder pedal indicated that for coupling problems associated with a large increase in favorable aileron yaw, the side-arm controller accentuated the control problem. This may be attributable to the cross-control technique required which was more difficult to apply with the side-arm controller.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Aug. 25, 1961

APPENDIX A

DEVELOPMENT AND DISCUSSION OF PERTINENT RELATIONSHIPS

The conventional equations of motion used to describe the perturbed lateral-directional aircraft motions about the stability system of axes are presented in equations (1) to (3) and represent the aircraft maneuvering around the 1g flight path with the aircraft velocity held constant.

$$\dot{r} = N_\beta \beta + N_p p + N_r r + N_{\delta_a} \delta_a + N_{\delta_r} \delta_r + \dot{p} r_z \qquad (1)$$

$$\dot{p} = L_\beta \beta + L_p p + L_r r + L_{\delta_a} \delta_a + L_{\delta_r} \delta_r + \dot{r} r_x \qquad (2)$$

$$\dot{\beta} = -r + \frac{g}{V} \sin \varphi + Y_\beta \beta + Y_{\delta_r} \delta_r \qquad (3)$$

With certain appropriate simplifying relationships, the above set of equations may be transformed into the pertinent transfer function relationships.

$$\frac{\varphi}{\delta_a} \approx \frac{L_{\delta_a}'(s^2 + 2\zeta_\varphi \omega_\varphi s + \omega_\varphi^2)}{s(s - L_p')(s^2 + 2\zeta_d \omega_d s + \omega_d^2)} \qquad (4)$$

$$\frac{\beta}{\delta_r} \approx \frac{-N_{\delta_r}'}{(s^2 + 2\zeta_d \omega_d s + \omega_d^2)} \qquad (5)$$

CLOSED-LOOP RESPONSE CONSIDERATIONS

It has been suggested in reference 8 that the ratio $(\omega_\varphi/\omega_d)^2$ (eq. (4)) is an important factor in lateral-directional handling qualities studies. Favorable yaw, coupled with positive dihedral effect (L_β' less than zero), results in ratios greater than 1 and adverse yaw results in $(\omega_\varphi/\omega_d)^2$ ratios less than 1. For $N_{\delta_a}' = 0$ and $\zeta_\varphi \omega_\varphi \approx \zeta_d \omega_d$, the control of bank angle reduces to the first-order system considered in detail in reference 6 and is referred to as uncoupling the motion. As shown in figure 4, values of $(\omega_\varphi/\omega_d)^2$ which differ appreciably from 1 have a significant effect on the roll rate response. In this figure the time history shown for $N_{\delta_a}' = -0.70$ is for a $(\omega_\varphi/\omega_d)^2$ of 1.10, $N_{\delta_a}' = -2.31$ is for a $(\omega_\varphi/\omega_d)^2$ of 1.66, $N_{\delta_a}' = 1.92$ for an $(\omega_\varphi/\omega_d)^2$ of 0.23, $N_{\delta_a}' = 0$ is the uncoupled case for an $(\omega_\varphi/\omega_d)^2$ of 1. Ratios greater than 1 result in an oscillatory, increased steady-state roll-rate response, while ratios less than 1 result in an oscillatory, decreased response relative to the uncoupled or lightly-coupled configurations.

It can be shown that the primary effect of $(\omega_\varphi/\omega_d)^2$ is on the closed-loop response, that is, the response of the pilot-aircraft combination. This effect assumes increasing importance for relatively low values of Dutch-roll damping since the closed-loop Dutch-roll damping is generally decreased relative to the open-loop damping for ratios greater than 1 and increased for ratios less than 1. To illustrate these effects, closed-loop responses for the range of dynamics covered in the present study, as well as for the control problems experienced with two current high-performance vehicles, were computed. It was assumed that the pilot can be represented by a pure gain K_p, both to simplify the computations and because this is shown in reference 11 to be approximately the preferred mode of pilot operation. Based on unpublished studies made at Ames Research Center in a number of airplanes, a pilot gain of 0.2° of total aileron deflection per degree bank angle error was used. (In these studies the pilots were instructed to bank to 90° and stabilize in the shortest time; it was found the pilots used initially about 15° to 20° aileron deflection.) Although the assumption of a pure gain for the pilot for the entire range of dynamics covered in this study may not be realistic, it seems two equally valid approaches may be used in the problem of isolating closed-loop response parameters related to pilot opinion. One approach is to establish relationships between pilot opinion and pilot-response characteristics required to maintain roughly constant closed-loop performance over a broad range of vehicle dynamics, in a manner similar to that described in references 8 and 11. The other approach - that selected here - is to determine the relationship between pilot opinion and closed-loop response or performance that would result if the pilot adapted a fixed but desired mode of response, that is, a pure gain of reasonable magnitude.

The results of the closed-loop response computations are presented in figures 14, 17, and 18. The results in figure 14, plotted in terms of the variation of pilot opinion with the closed-loop Dutch-roll damping for various open-loop damping ratios, were previously discussed. Representative time histories of closed-loop responses to step bank-angle commands for several problem areas, covered in the present study, are shown in figure 17. The response for the favorable-yaw case $(\omega_\varphi/\omega_d)^2 = 2.6$ is fairly unstable with a time to double amplitude of about 3 seconds. The response for the adverse-yaw case $[(\omega_\varphi/\omega_d)^2 = 0.28]$ is stable, and mildly oscillatory, but extremely sluggish, with only 15 percent of the commanded roll angle attained in 1 second. On the other hand, the closed-loop responses for the uncoupled or mildly coupled configurations appear quite satisfactory with good response and only mild overshoot tendencies.

The results for the control problem experienced with the re-entry configuration (fig. 18(a)) are of interest because they reveal a serious control problem with the pilot in the loop, which would not necessarily be inferred from the open-loop response (see fig. 15(a)). For the configuration lightly damped in roll, the closed-loop response is highly unstable with a time to double amplitude of about 1 second. With sufficient roll damping, the closed-loop response is only mildly oscillatory and somewhat sluggish. The comparison shown (fig. 18(a)) indicates the powerful effect of roll damping in reducing pilot-aircraft instabilities associated with $(\omega_\varphi/\omega_d)^2$ ratios greater than 1.

The closed-loop responses for the control problem experienced during the landing approach of a current high-speed fighter (ref. 1) are shown in figure 18(b). For both the tanks-on and tanks-off configurations, $(\omega_\varphi/\omega_d)^2$ was considerably less than 1 with attendant open-loop roll-rate reversal tendencies (see fig. 15(b)). The closed-loop responses for this airplane are not so instructive and indicative of the control problem involved as for the re-entry configuration. However, it is clear the closed-loop response for the tanks-off configuration is considerably better than that for the tanks-on case. The response in the former case is quite similar to that obtained in the present study for high adverse yaw (see fig. 17). In the latter case, the ailerons are practically useless for controlling bank angle (which concurs with pilot's observations for this configuration).

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Although these closed-loop responses provide additional insight into the nature of the control coupling problem, it is apparent they are not in themselves sufficient to relate and integrate the results of the two example control problems considered with those of the present study. In the case of the landing-approach example considered, other factors not amenable to the closed-loop type of analysis considered here apparently had an overriding effect on pilot opinion.

OPEN-LOOP RESPONSE CONSIDERATIONS

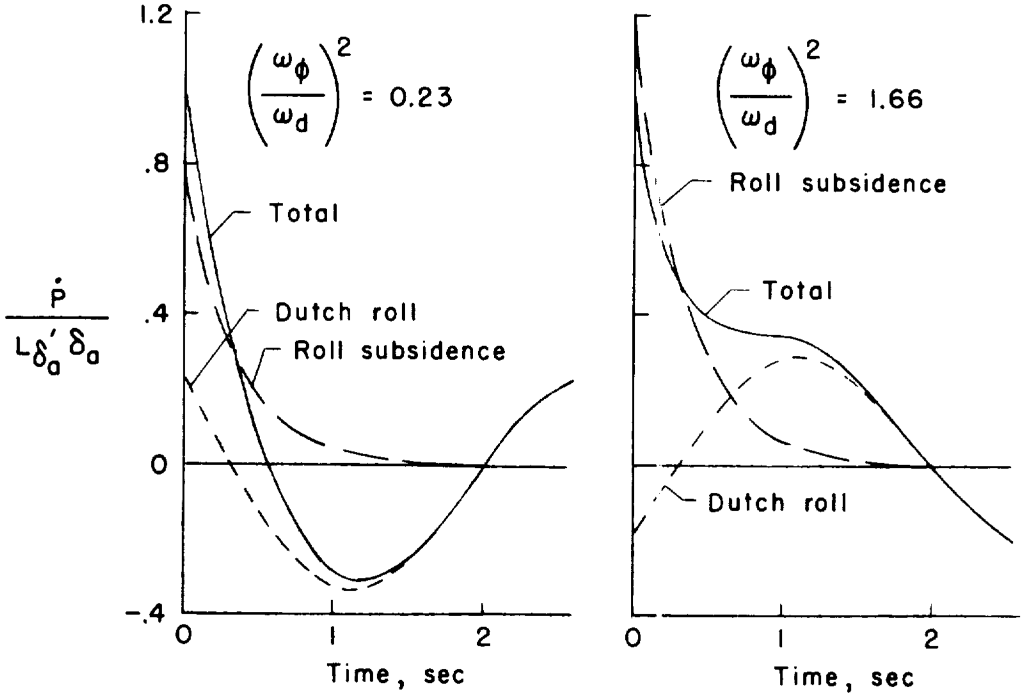
Most of the current data bearing on lateral-directional handling qualities criteria (e.g., refs. 3, 6, and 7) present boundaries of acceptable and unacceptable regions in terms of various open-loop response parameters. Since attempts to relate the results of the present study with the re-entry vehicle example control problem by means of the several suggested response parameters met with little success, an attempt was made to derive a response parameter which provided better agreement among the available data. In particular, in view of the marked deterioration of pilot opinion with a decrease in roll damping for the re-entry configuration, a response parameter which took this into account was sought. One possible parameter found was based on the roll-rate response to an aileron impulse (or roll-acceleration response to an aileron step input). The pertinent transfer-function relationship (eq. (4)) is

$$\frac{p(s)}{L_{\delta_a}'\delta_a} = \frac{s^2 + 2\zeta_\varphi\omega_\varphi s + \omega_\varphi^2}{(s - L_p')(s^2 + 2\zeta_d\omega_d s + \omega_d^2)} \qquad (6)$$

If $2\zeta_\varphi\omega_\varphi$ and $2\zeta_d\omega_d$ are assumed to be small and negligible, the time response can be written

$$\frac{p(t)}{L_{\delta_a}'\delta_a} \approx \left(\frac{L_p'^2 + \omega_\varphi^2}{L_p'^2 + \omega_d^2}\right) e^{L_p' t} + \left(\frac{\omega_\varphi^2 - \omega_d^2}{L_p'^2 + \omega_d^2}\right) \frac{\sqrt{L_p'^2 + \omega_d^2}}{\omega_d} e^{-\zeta_d\omega_d t}\sin(\omega_d t + \epsilon) \qquad (7)$$

where $\epsilon = \tan^{-1}(-\omega_d/-L_p')$. The first term in equation (7) is the desired roll-subsidence contribution to the over-all response, and the second term is the undesired Dutch-roll contribution. Time histories of these contributions in terms of acceleration response for two coupling conditions of the present tests (fig. 4) are given in the sketches that follow:



Since both the Dutch-roll and the roll-subsidence characteristics are recognized to be important factors affecting the lateral-directional handling, one measure of the degree of coupling of the two modes is the initial (t = 0) step aileron Dutch roll to roll subsidence acceleration response ratio; that is,

$$\dot p_d/\dot p_R \approx (\omega_d^2 - \omega_\varphi^2)/(L_p'^2 + \omega_\varphi^2)$$

This ratio for the results of the present study were computed and presented in figure 13. As indicated in figure 16(c), good success in relating pilot opinion through this open-loop acceleration-response ratio was obtained for only the re-entry case for which $(\omega_\varphi/\omega_d)^2$ was greater than 1.

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TABLE I.- PILOT OPINION RATING SYSTEM

	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[1]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[1]	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

[1] Failure of a stability augmenter

TABLE II.- VALUES OF STABILITY DERIVATIVES AND FLIGHT CHARACTERISTICS FOR THE TEST CONDITIONS

Flight measured characteristics			Computed characteristics for estimated stability derivatives			Estimated stability derivatives	
ζ_d	ω_d	$\frac{\lvert\varphi\rvert}{\lvert v_e\rvert}$	ζ_d	ω_d	$\frac{\lvert\varphi\rvert}{\lvert v_e\rvert}$	N_β	N_r
0.22	1.90	0.58	0.22	1.95	0.40	2.48	-0.94
.10	1.86	.58	.10	2.00	.42	2.60	-.42
.01	1.78	.59	.01	1.81	.47	1.83	-.02
-.06	1.67	.59	-.06	1.61	.53	1.18	.24
-.13	1.57	.59	-.13	1.52	.56	.95	.51

$L_p = -2.91/\text{sec}$
$L_r = 1.12/\text{sec}$
$L_\beta = -14.4/\text{sec}^2$
$L_{\delta_a} = -11.2/\text{sec}^2$
$L_{\delta_r} = 0.79/\text{sec}^2$
$N_p = -0.22/\text{sec}$
$N_{\delta_r} = -2.85/\text{sec}^2$
$Y_\beta = 0.14/\text{sec}$

$Y_{\delta_r} = -0.03/\text{sec}$
$b = 37.1$ ft
$I_X = 7,430$ slug-ft^2
$I_{XZ} = -1,230$ slug-ft^2
$I_Z = 23,260$ slug-ft^2
$S = 287.9$ sq ft
$W = 12,800$ lb
$\delta_{a_{max}} = \pm 30^\circ$

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TABLE III.- STABILITY AND CONTROL INFORMATION FOR THE EXAMPLE COUPLING PROBLEM CASES

(a) Re-entry vehicle (ref. 2, configuration B):

	Roll damper off	Roll damper on
L_p	-0.062	-4.945
L_r	-.076	1.702
N_p	.035	.352
N_r	-.030	-.146
ζ_d	.041	.002
$\lvert\varphi\rvert / \lvert v_e\rvert$	.19	.04
ω_d	2.04	2.30
$(\omega_\varphi/\omega_d)^2$	1.69	1.33
$N_{\delta_a}'L_\beta'$	103	103
$(\omega_d^2 - \omega_\varphi^2)/(L_p'^2 + \omega_\varphi^2)$	-.39	0
ζ_{CL}	-.245	-.018

$L_\beta = 15.735/\text{sec}^2$
$L_{\delta_a} = -9.130/\text{sec}^2$
$N_\beta = 6.828/\text{sec}^2$
$N_{\delta_a} = 0.890/\text{sec}^2$
$Y_\beta = -0.037/\text{sec}$
$\alpha = 20^\circ$
$\delta_{a_{max}} = \pm 15^\circ$

$b = 22.36$ ft
$h = 112{,}000$ ft
$I_x = 12{,}250$ slug-ft^2
$I_{xz} = -24{,}260$ slug-ft^2
$I_z = 68{,}420$ slug-ft^2
$S = 200$ ft^2
$V = 6{,}000$ ft/sec
$W = 13{,}390$ lb

TABLE III.- STABILITY AND CONTROL INFORMATION FOR THE EXAMPLE COUPLING PROBLEM CASES - Concluded

(b) Landing approach vehicle (ref. 1, yaw damper off, 125 knots, I.A.S.):

	Tanks on	Tanks off
L_p'	-1.0	-1.5
L_{δ_a}'	-3.5	-5.0
ζ_d	.13	.09
$\lvert\varphi\rvert / \lvert v_e\rvert$	1.35	1.28
ω_d	1.74	1.74
$(\omega_\varphi/\omega_d)^2$	0	.25
$(L_{\delta_a}' - N_{\delta_a}'L_\beta'/N_\beta')\delta_{a_{max}}$	0	.85
$N_{\delta_a}'L_\beta'$	-10.5	-11.2
$(\omega_d^2 - \omega_\varphi^2)/(L_p'^2 + \omega_\varphi^2)$	3.02	.75
ζ_{CL}	.13	.13

$b = 33.5$ ft

$h = 8{,}000$ ft

$S = 557$ ft^2

$V = 242$ ft/sec

$\delta_{a_{max}} = \pm 39^\circ$

Note: All derivatives and parameters based on derivatives in this table were estimated from the complete time histories of the motion, portions of which are presented in figure 15(b).

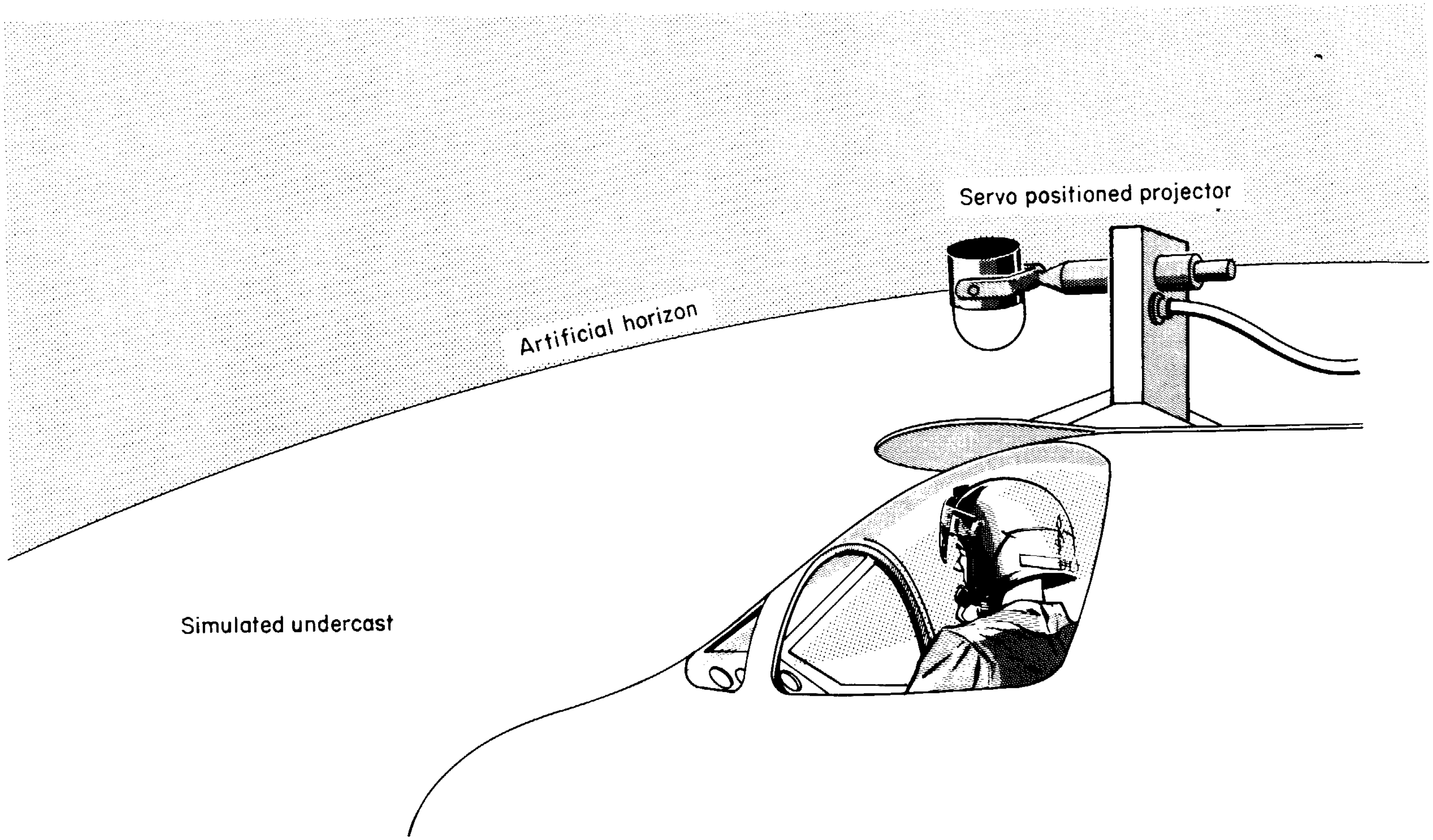

Figure 1.- Fixed cockpit flight simulator.

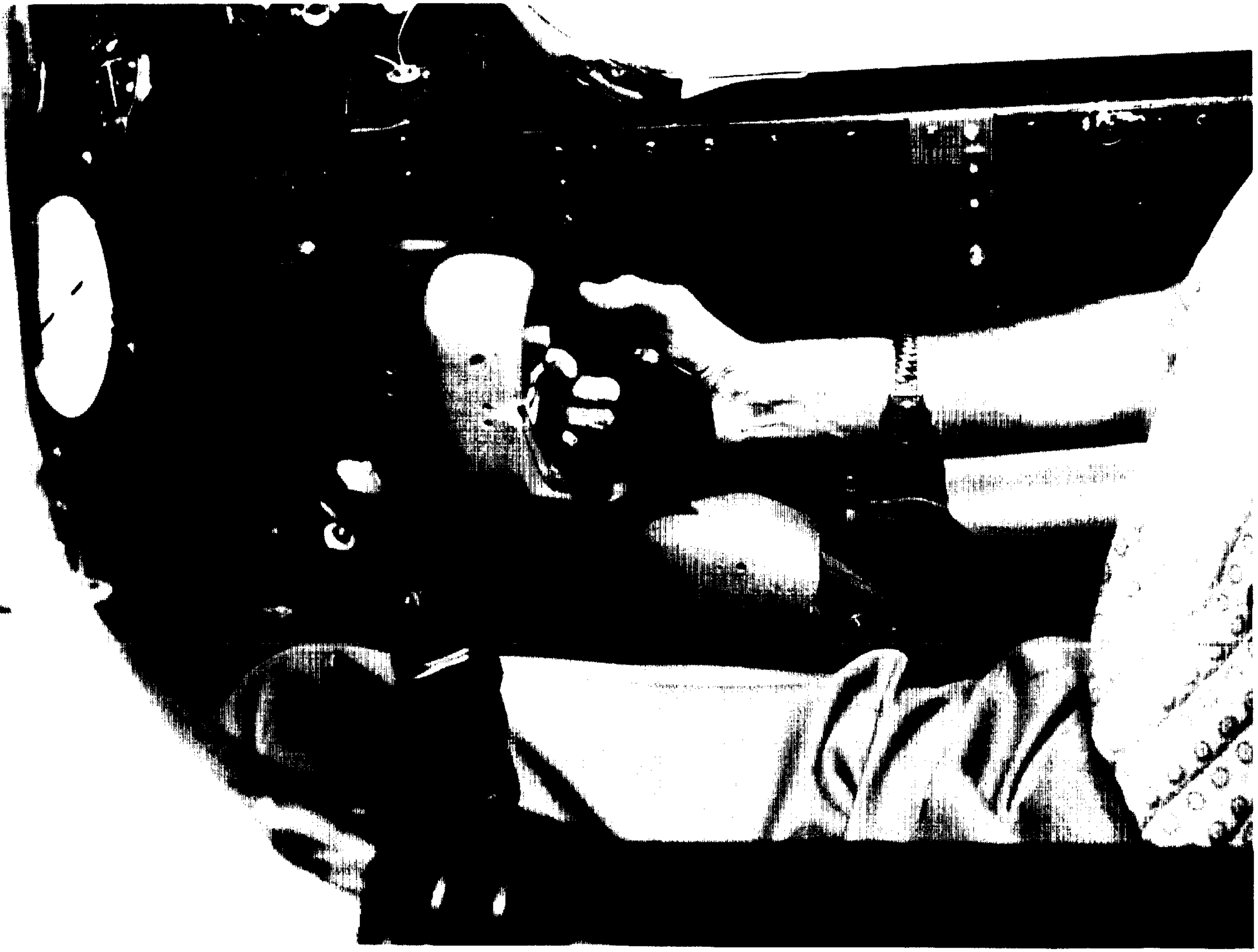

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Figure 2.- Photograph of side-arm controller installed in the simulator cockpit.

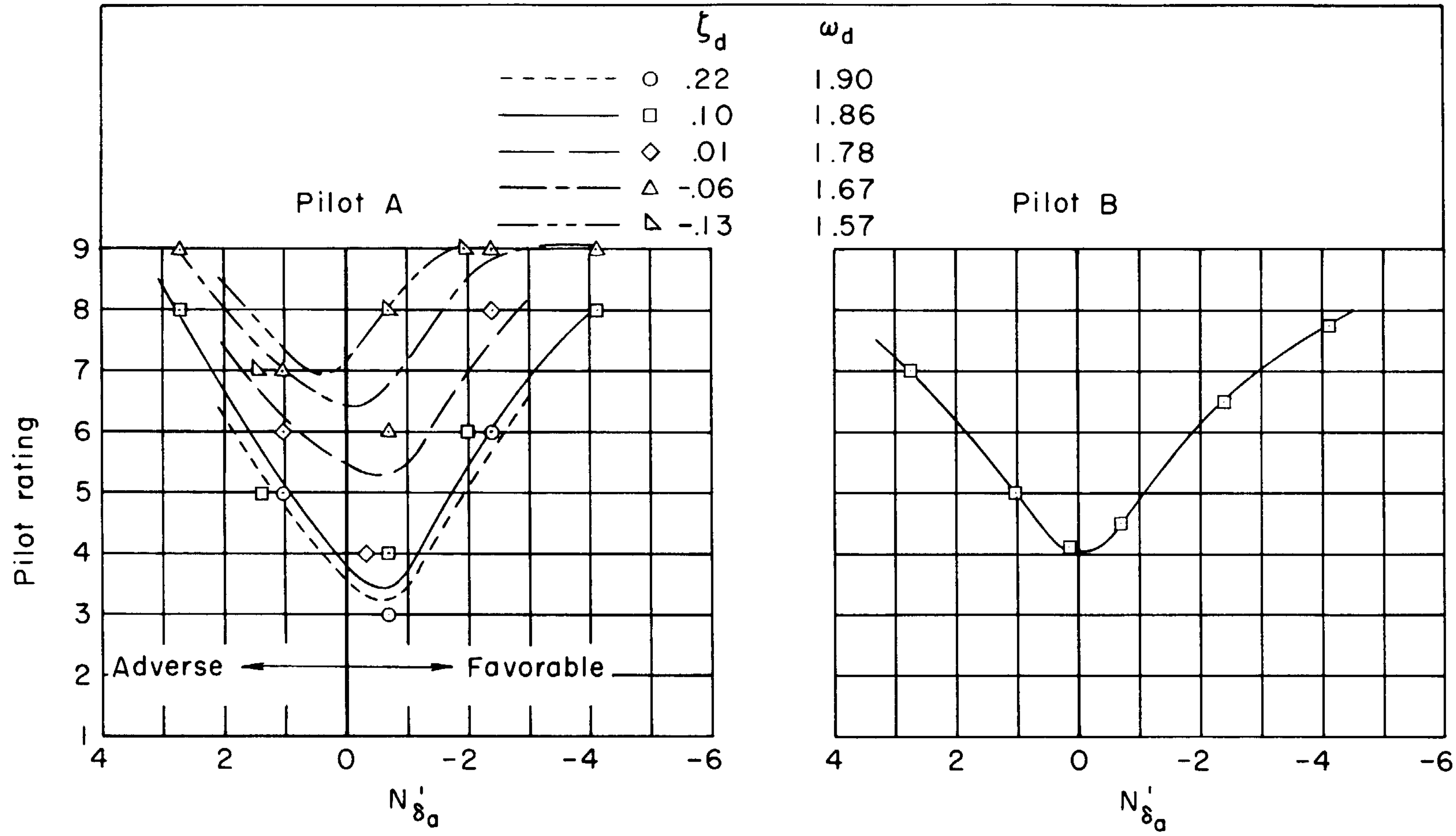

Figure 3.- Pilot-opinion data obtained in the flight tests (center stick control); $|\varphi|/|V_e| \approx 0.59$.

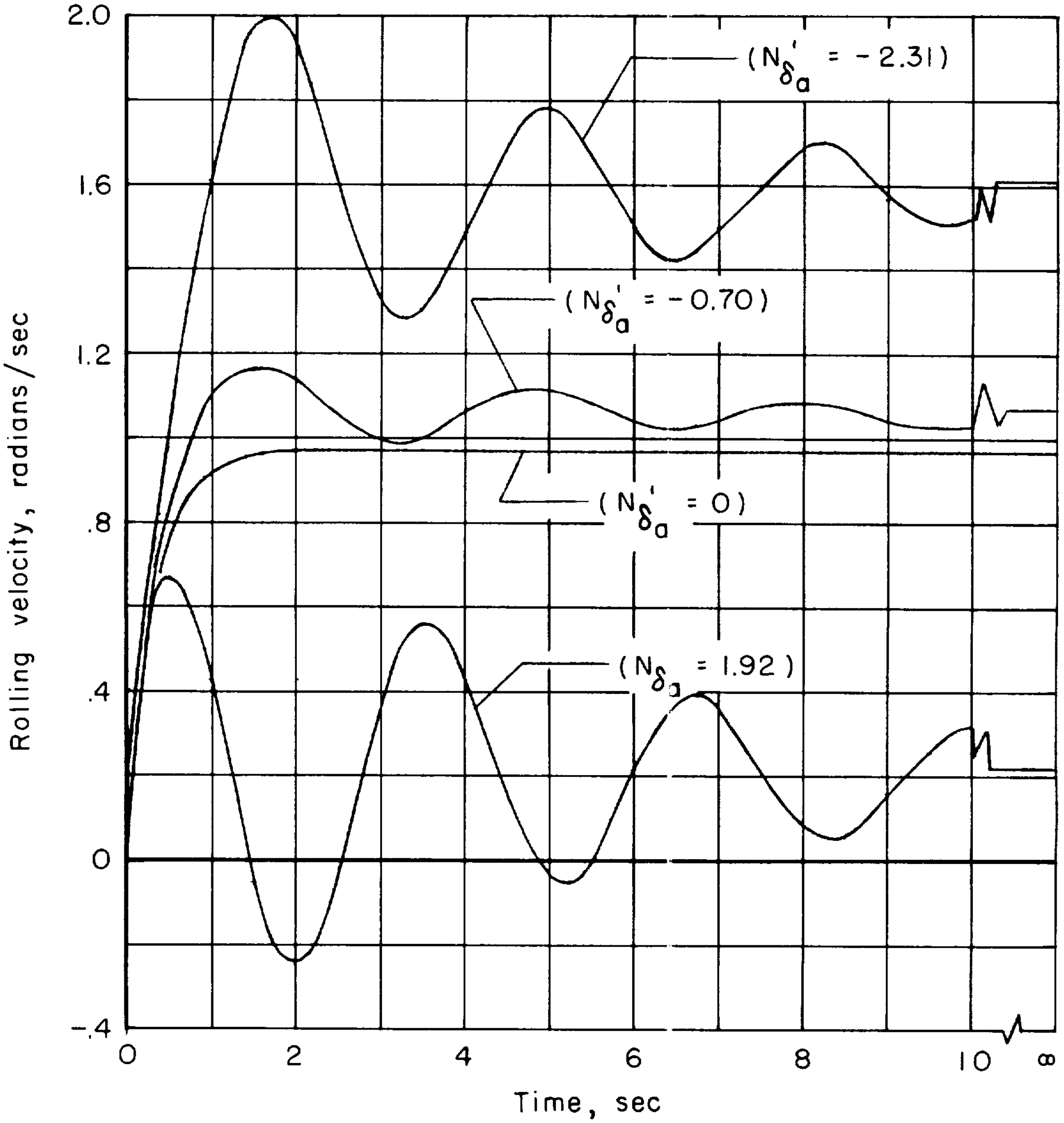

Figure 4.- Time histories of response to a 15° aileron step for $\zeta_d = 0.10$.

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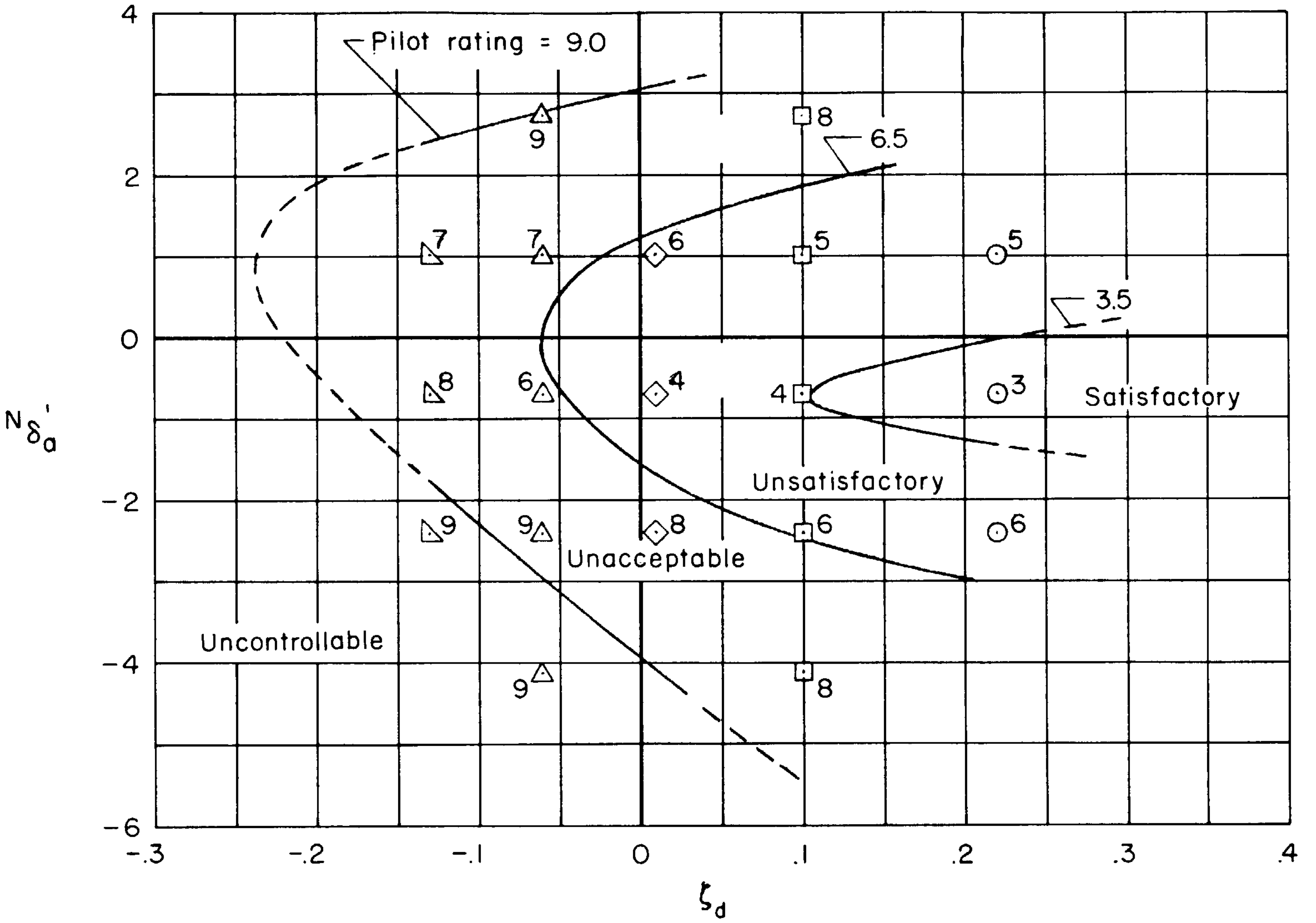

Figure 5.- Pilot-opinion boundaries derived from data of figure 3 (center stick control).

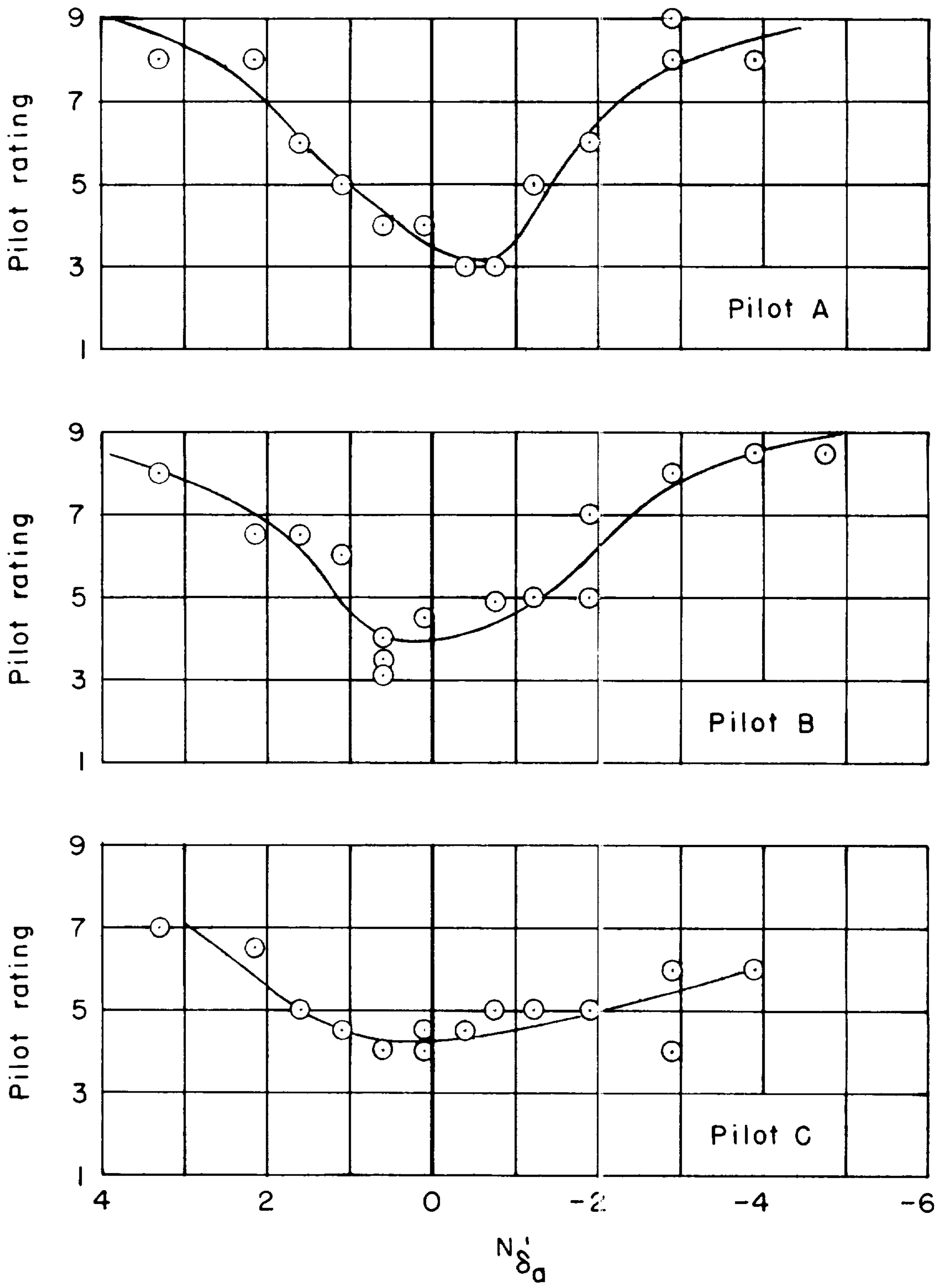

Figure 6.- Fixed-base simulator results (ζ_d = 0.10, center stick control).

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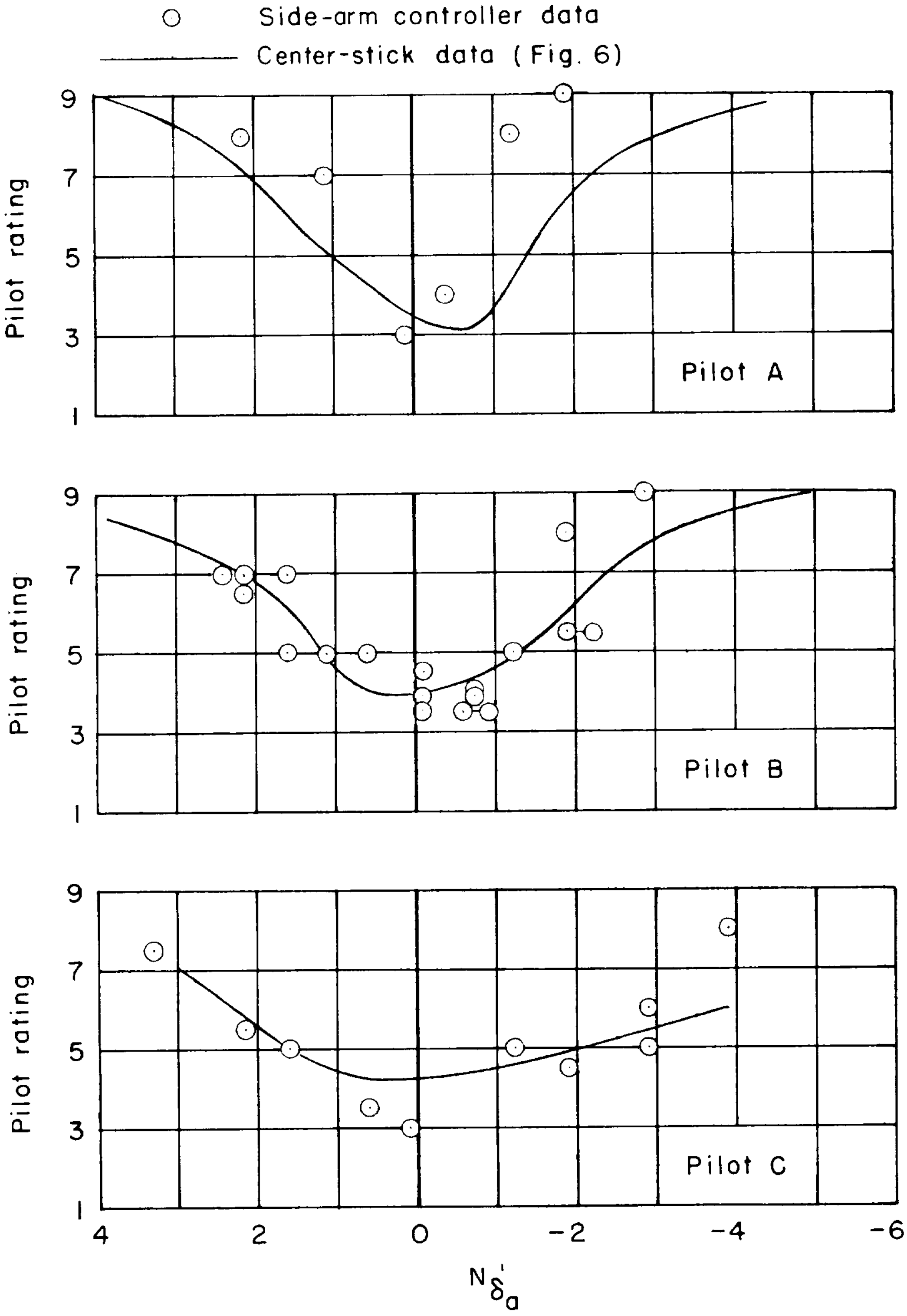
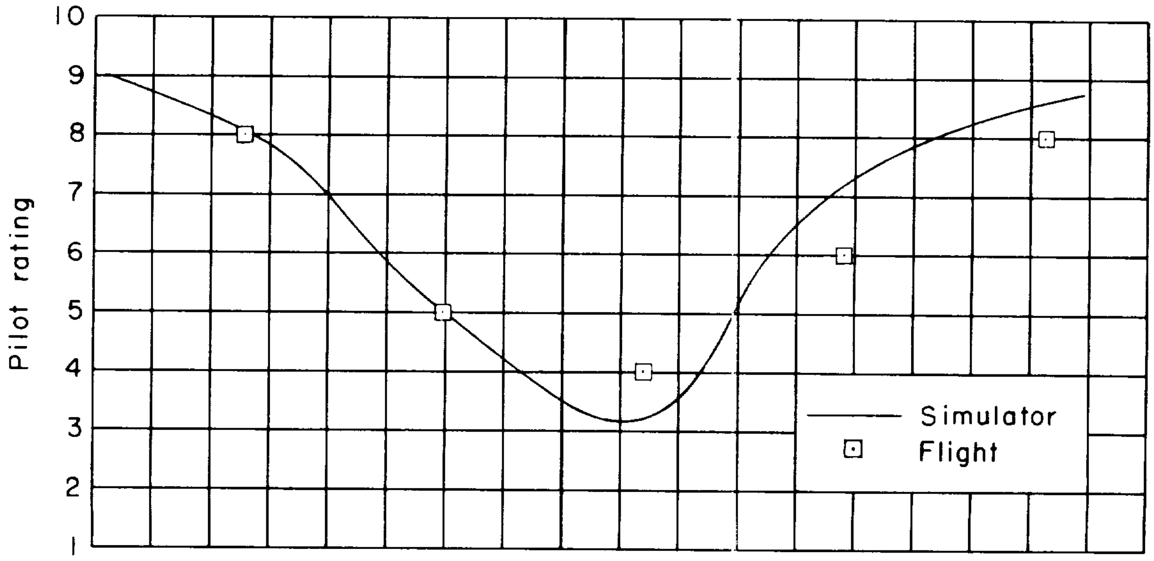
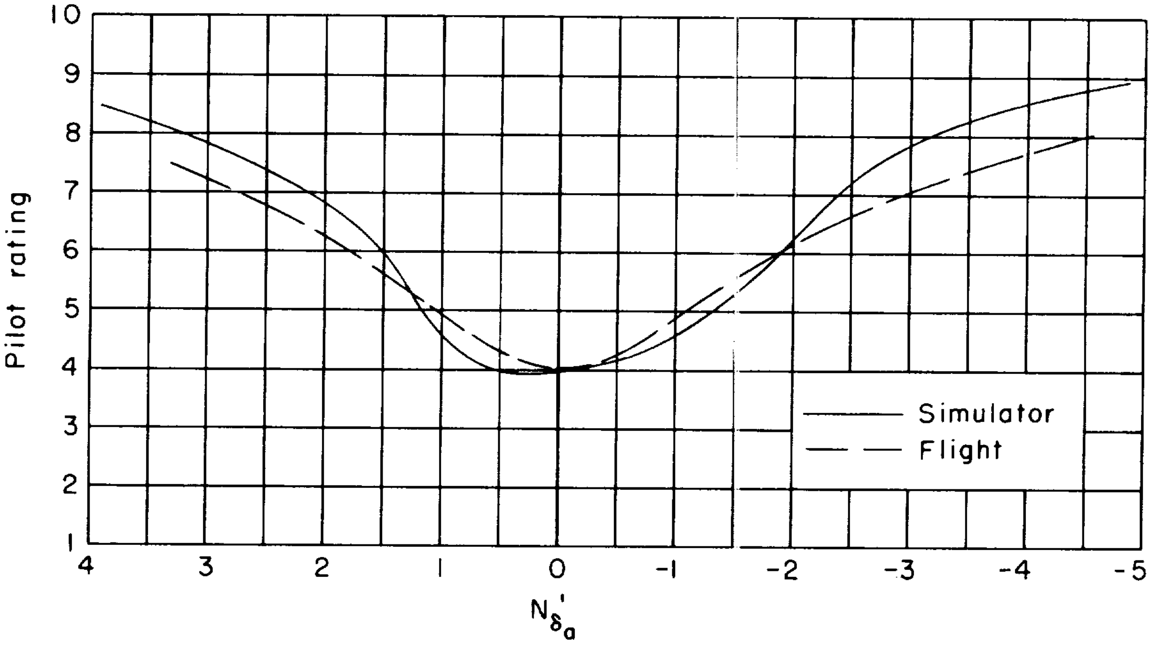


Figure 7.- Comparison of side-arm controller data with simulator center stick and rudder pedal results (ζ_d = 0.10).



(a) Pilot A.



(b) Pilot B.

Figure 8.- Comparison of flight and fixed-base simulator results (ζ_d = 0.10, center stick control).

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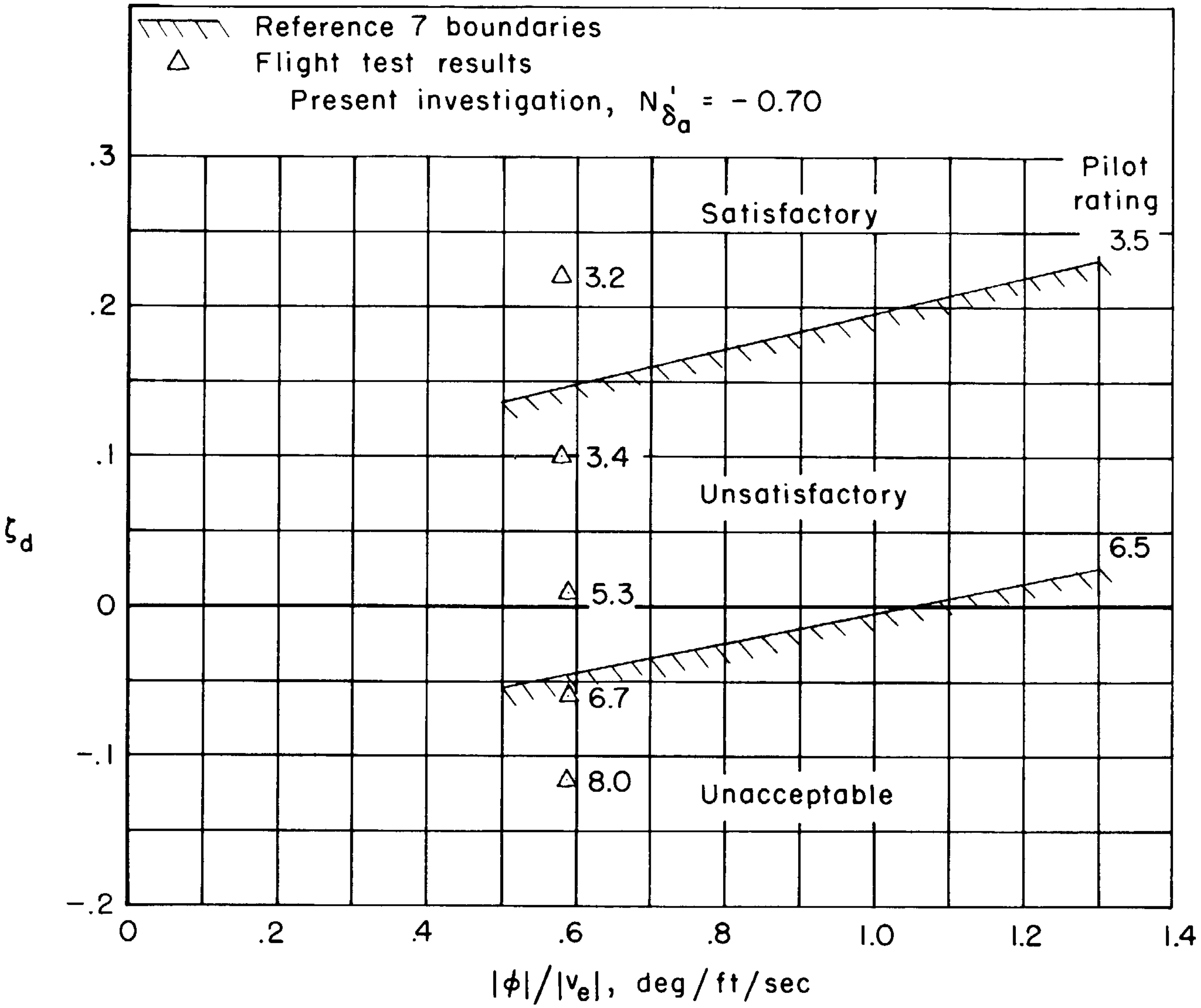


Figure 9.- Comparison of results of present study with reference 7 results (center stick control).

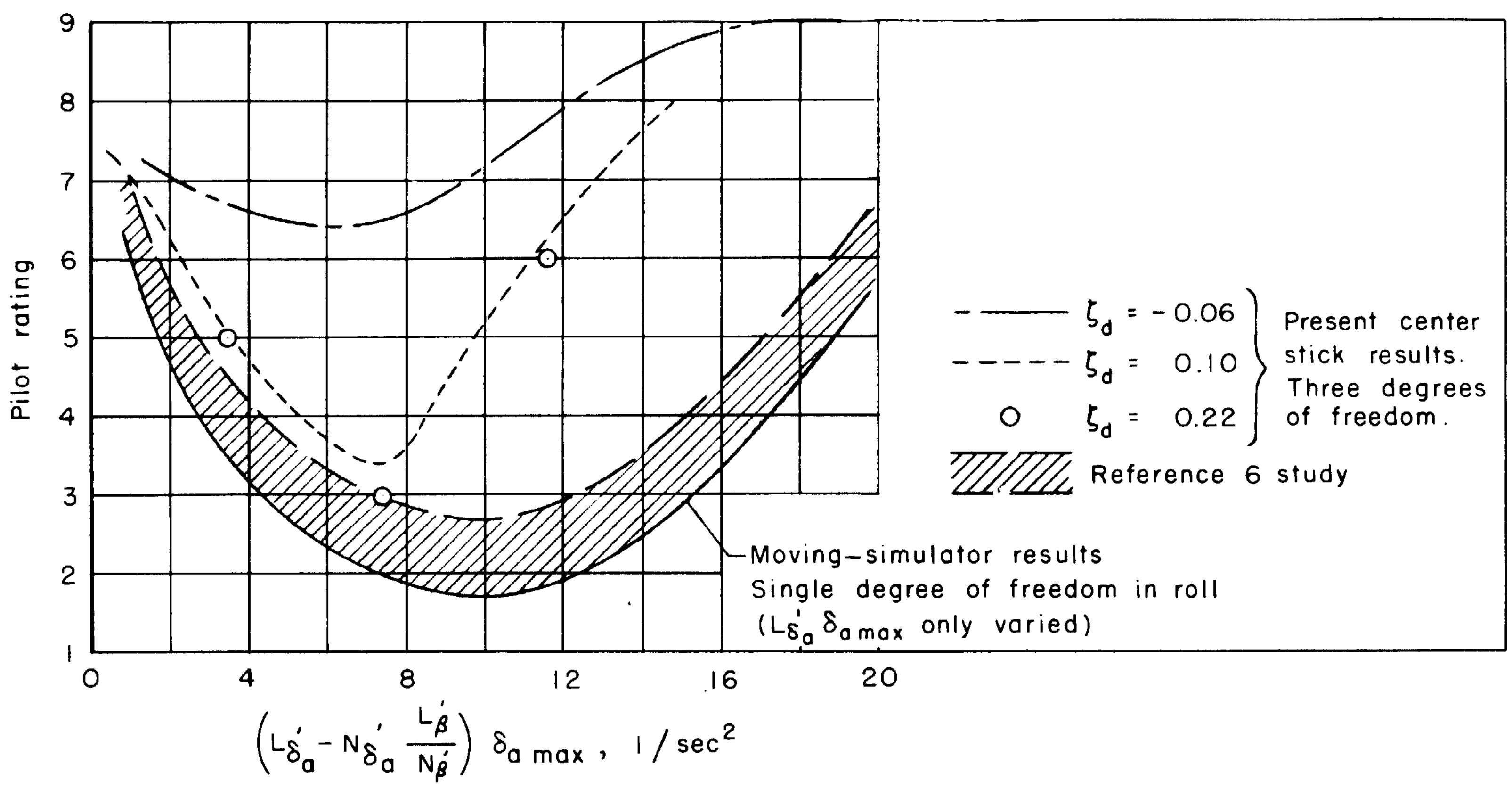


Figure 10.- Comparison of results of present study with criterion of reference 6 for condition of T_R = 0.33 second.

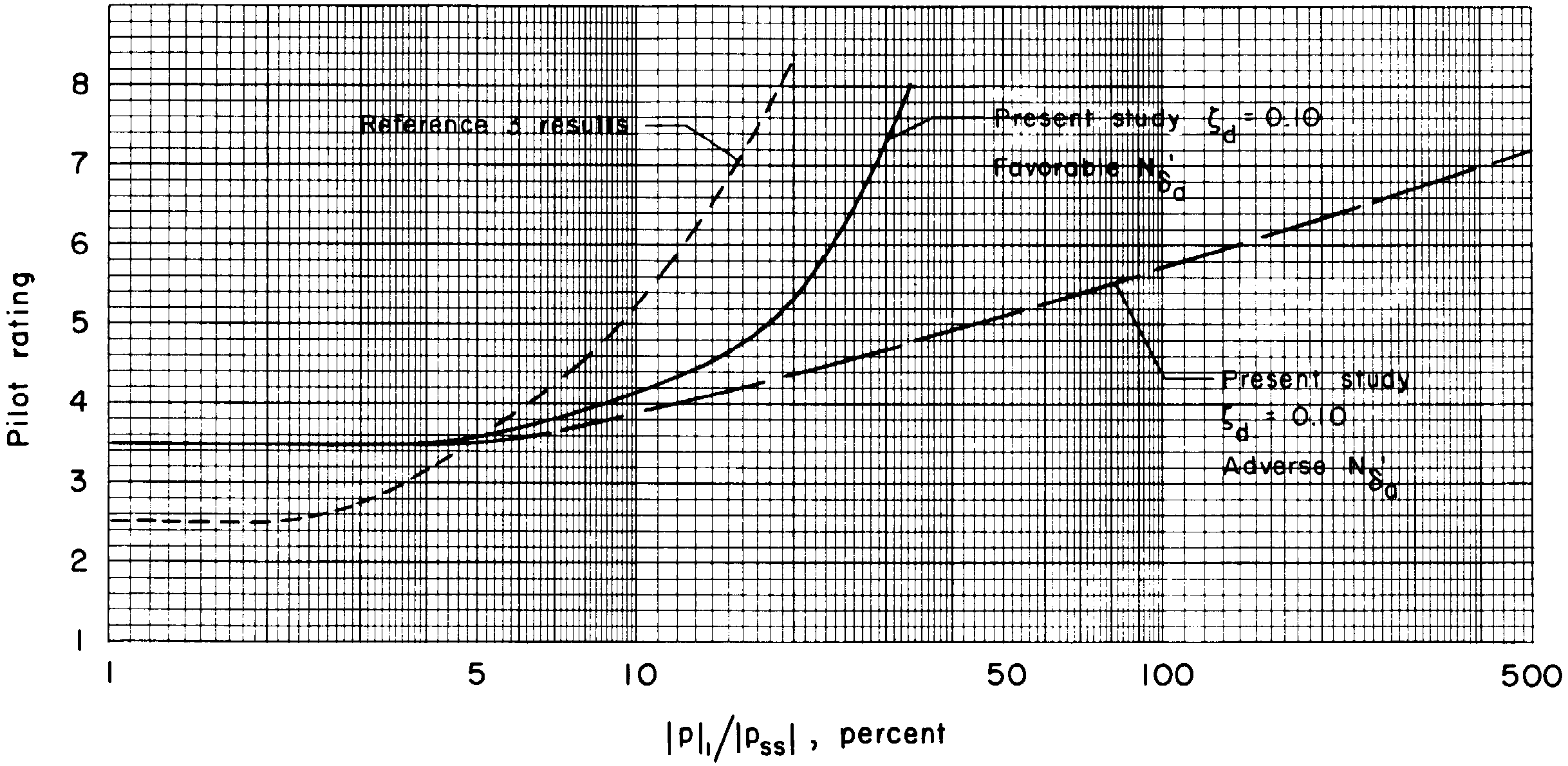


Figure 11.- Comparison of data of the present study with results of reference 3 (center stick control).

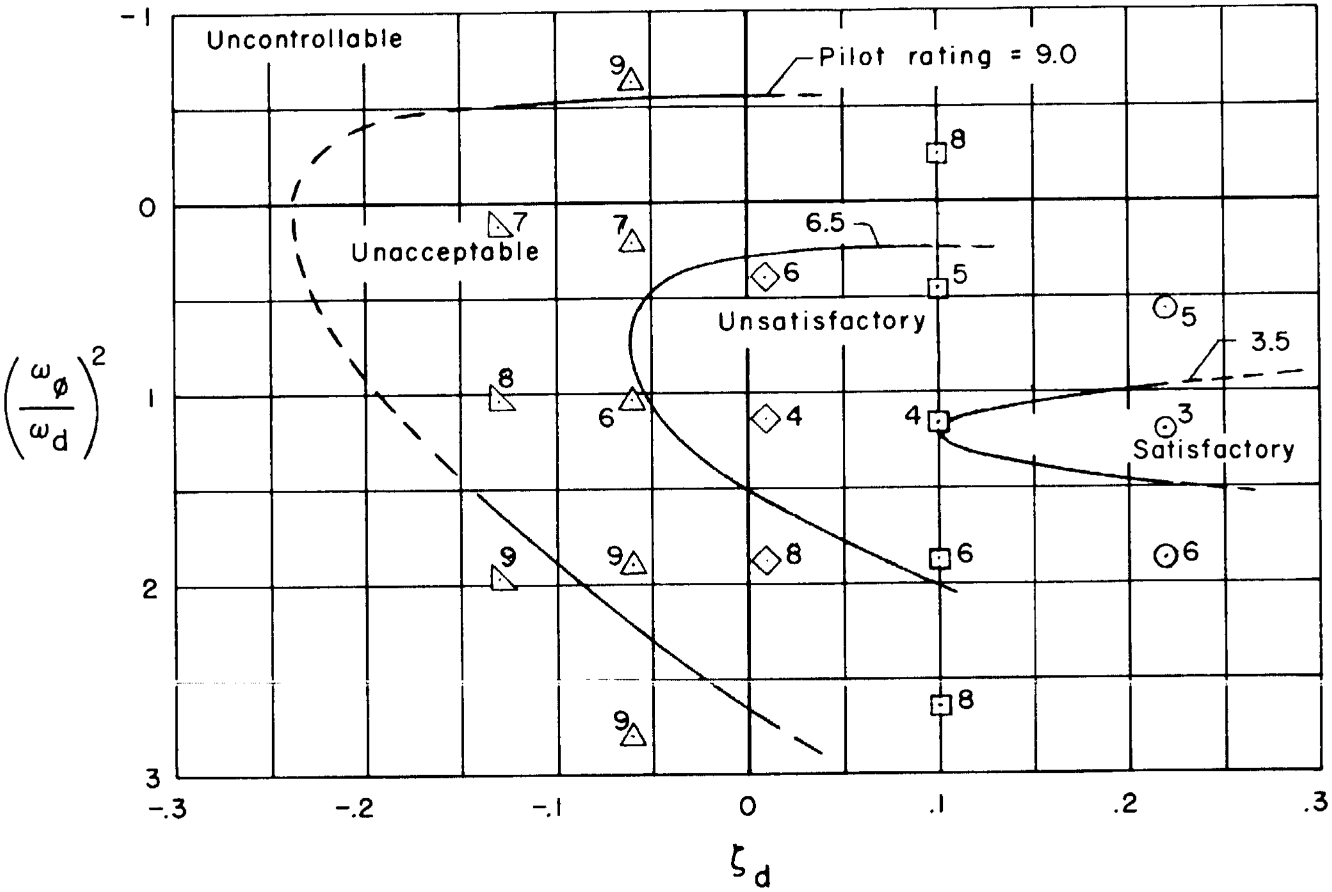


Figure 12.- Pilot opinion as a function of ζ_d and the uncoordinated to uncoupled roll-control effectiveness parameter (center stick control).

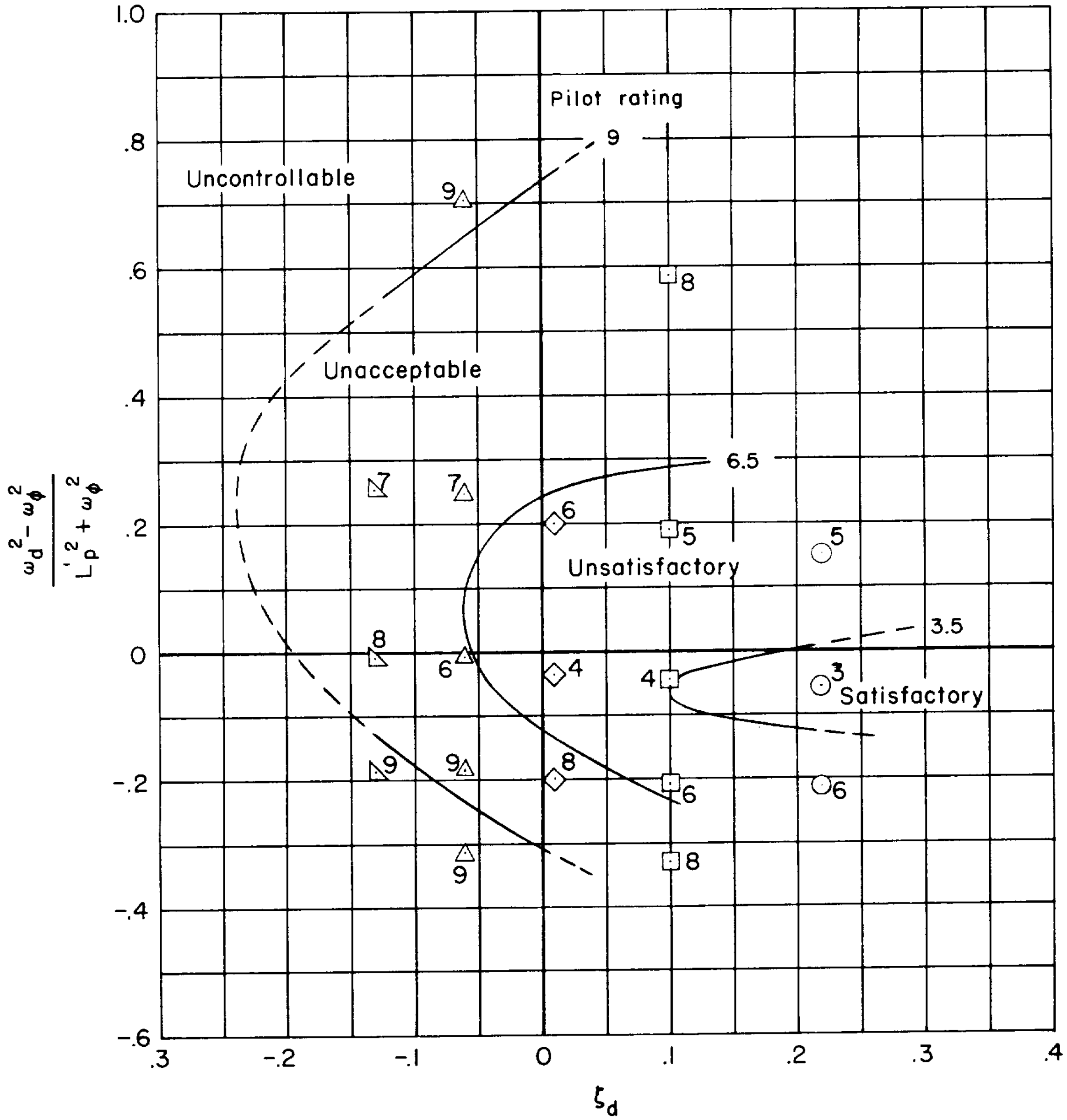
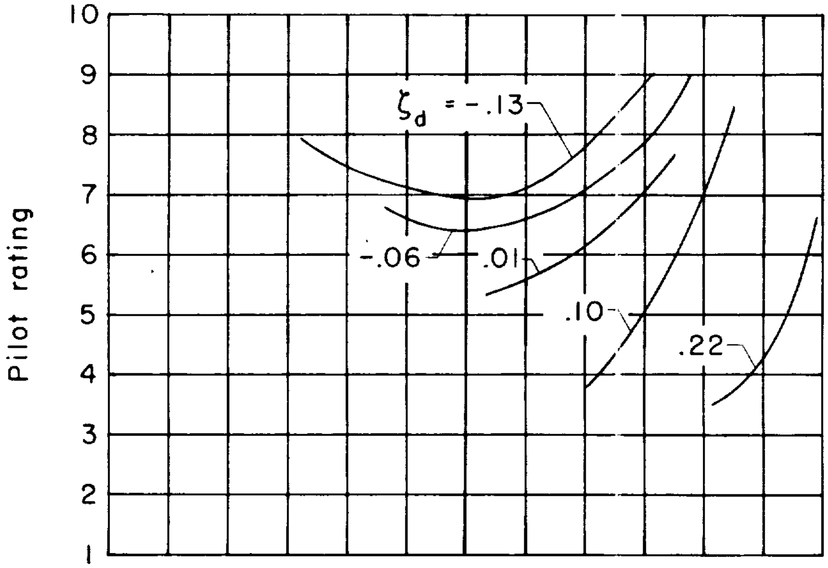
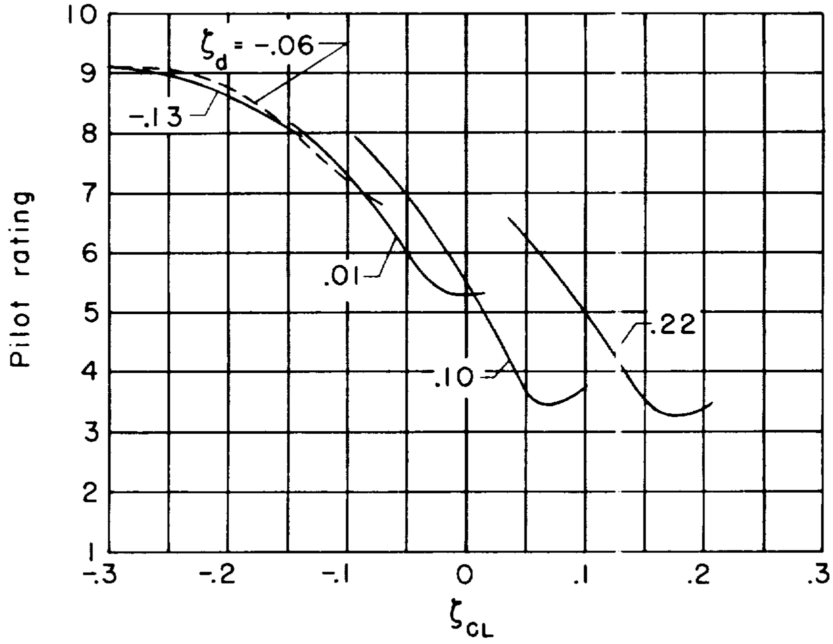


Figure 13.- Pilot opinion as a function of ζ_d and the ratio of the Dutch roll to roll subsidence acceleration-response parameter (center stick control).



(a) $(\omega_\varphi/\omega_d)^2 < 1.0$



(b) $(\omega_\varphi/\omega_d)^2 > 1.0$.

Figure 14.- Variation of pilot opinion rating with closed-loop Dutch-roll damping for various levels of open loop Dutch-roll damping (center stick control), pilot gain = 0.2°/deg.

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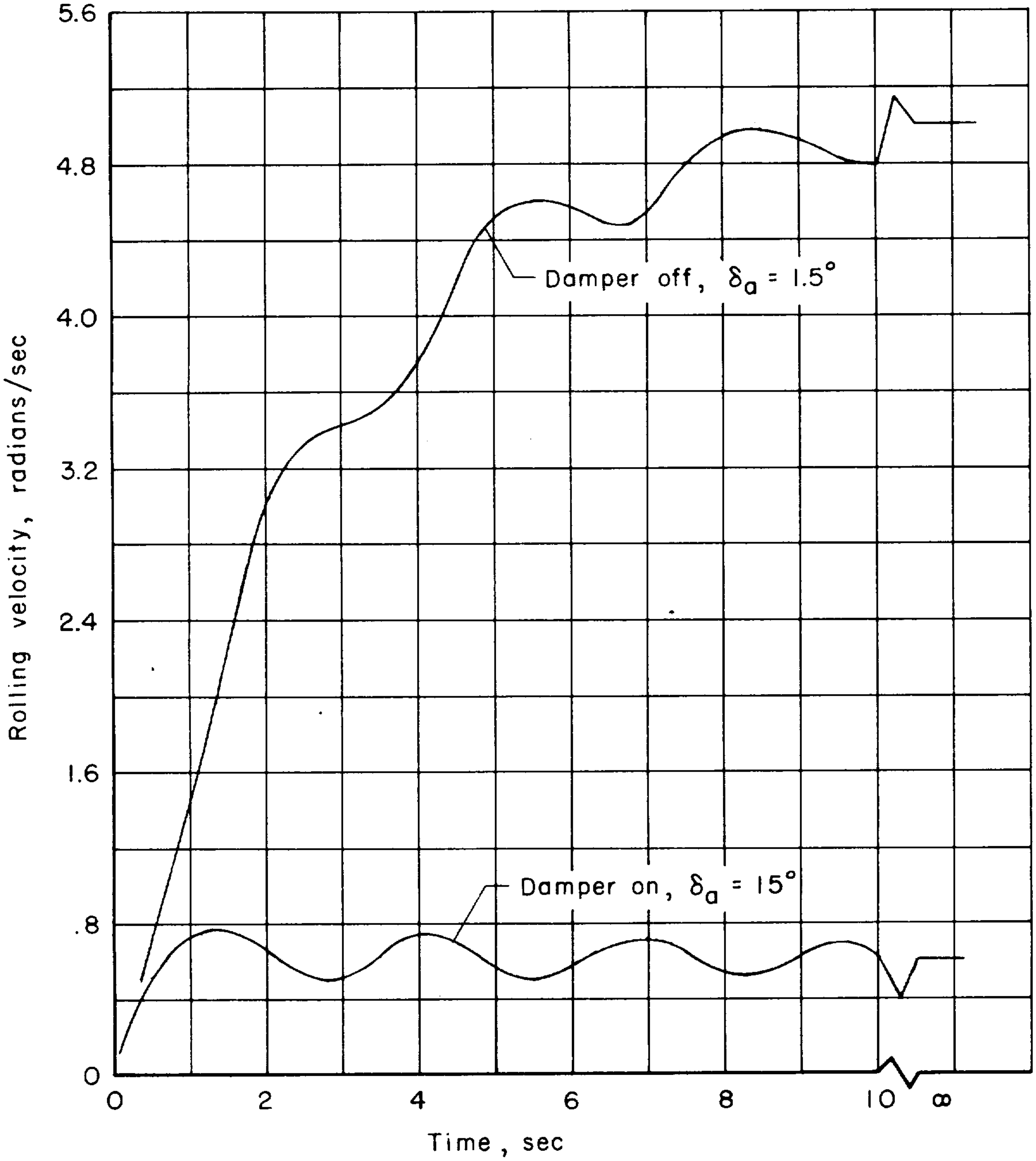
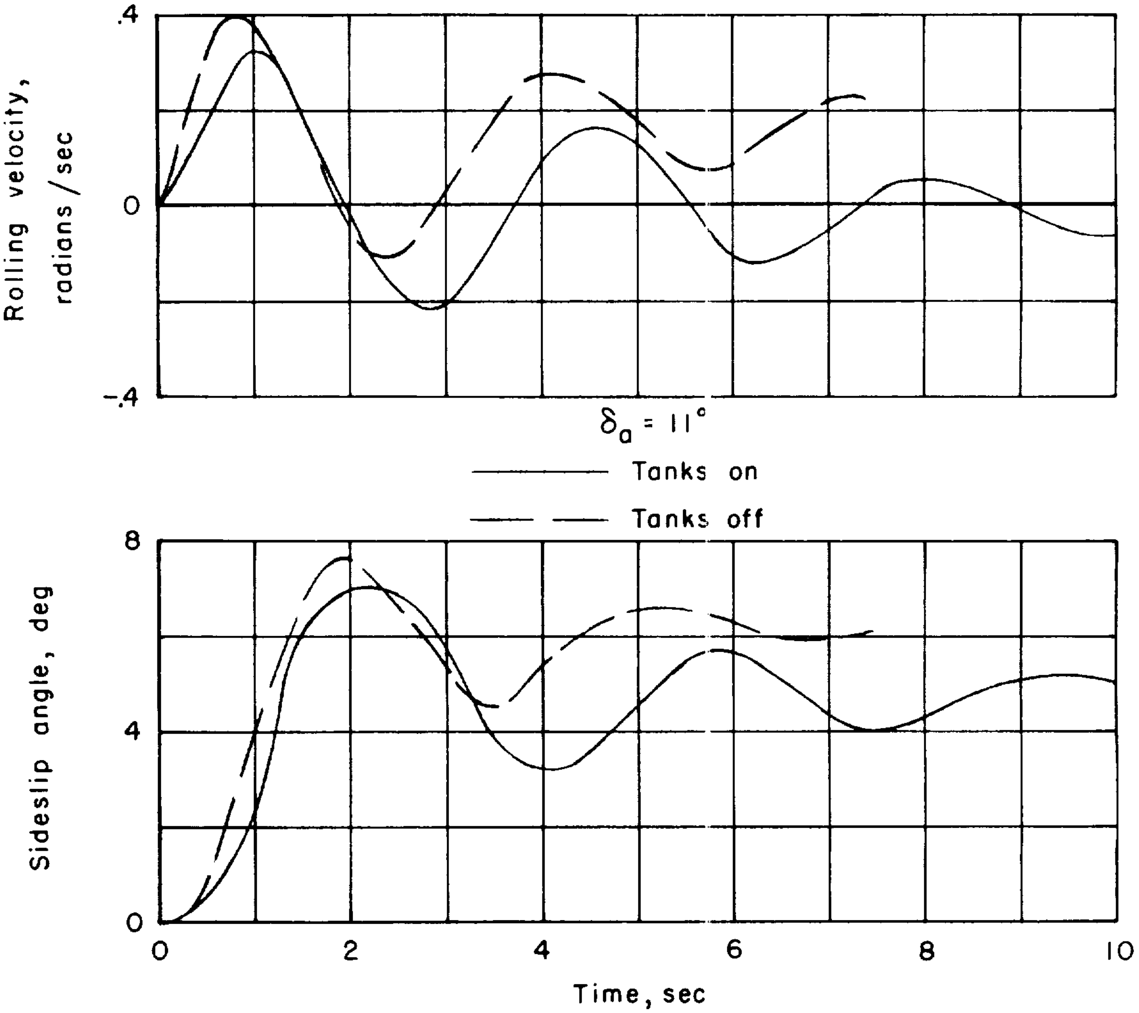


(a) Re-entry vehicle.

Figure 15.- Time histories of response to step aileron deflections for the example vehicles.



(b) Landing-approach vehicle.

Figure 15.- Concluded.

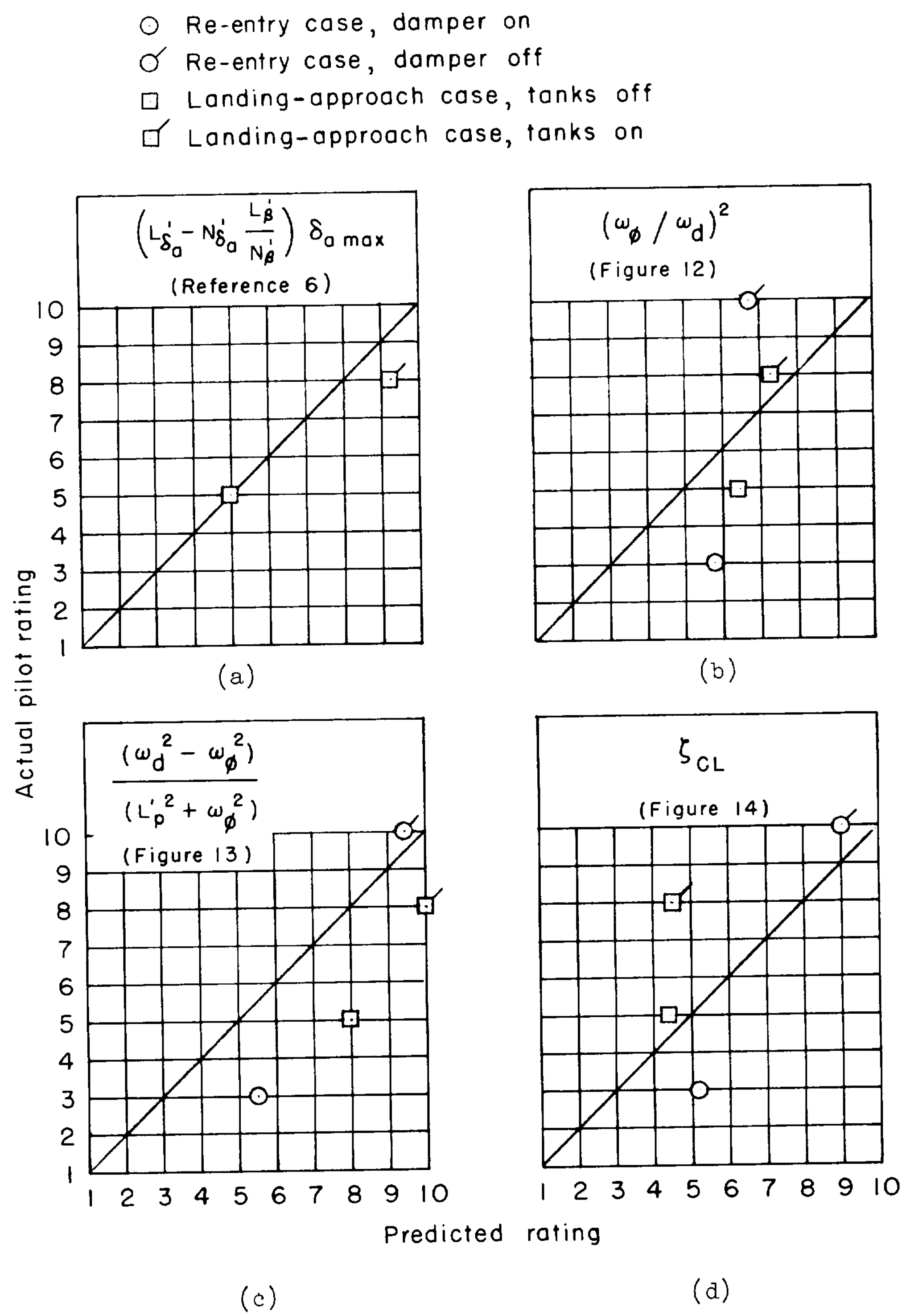


Figure 16.- Correlation of predicted and actual ratings by means of various parameters.

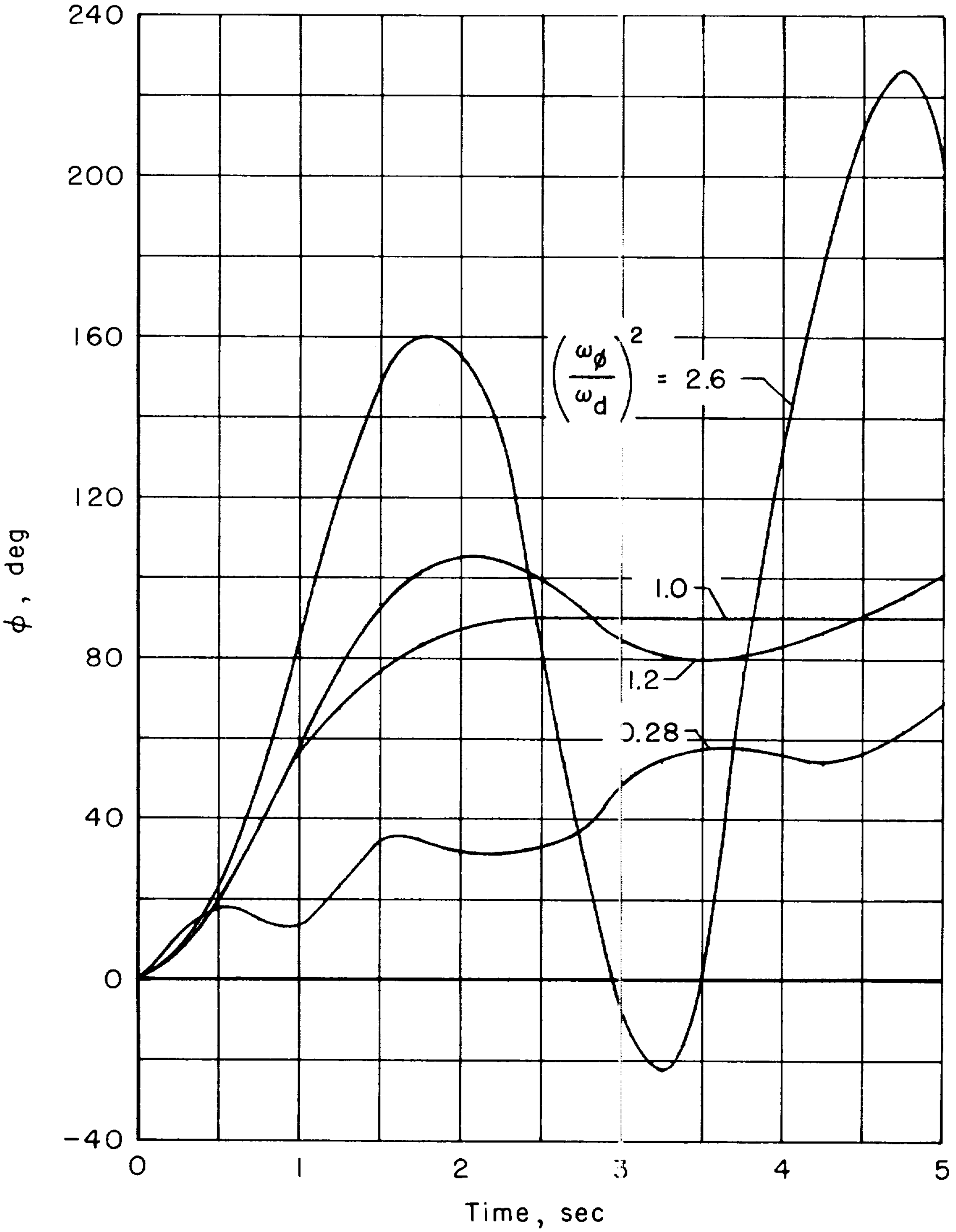


Figure 17.- Closed-loop bank-angle response for the test conditions (pilot gain = 0.2°/deg), $\varphi_c = 90^\circ$ and $\zeta_d = 0.10$, $\omega_d = 2.0$.

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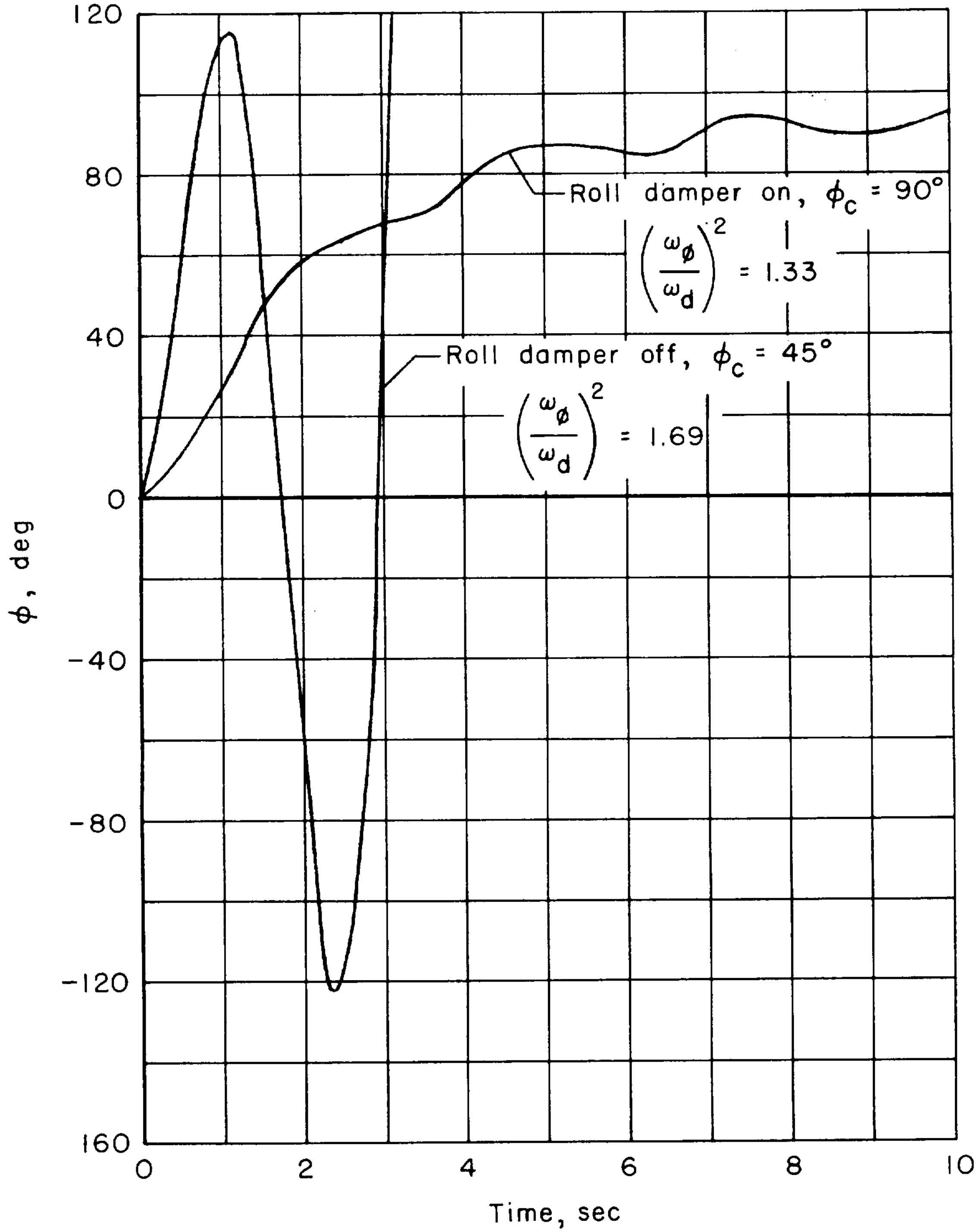
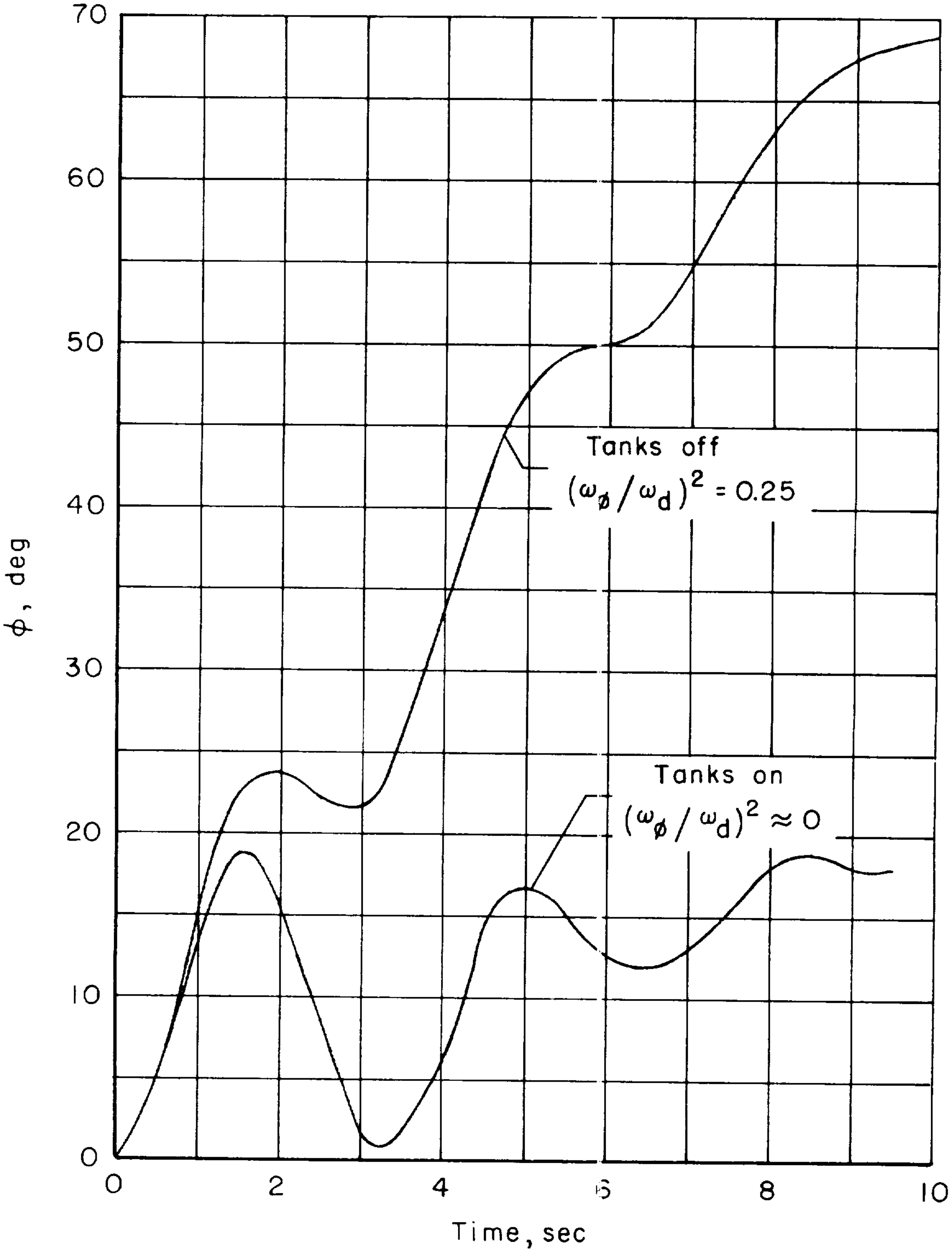


(a) Re-entry example case, $\delta_{a_{max}} = \pm 15^\circ$.

Figure 18.- Closed-loop responses for re-entry and landing-approach configurations (pilot gain = 0.2°/deg).



(b) Landing-approach example case, $\varphi_c = 90^\circ$.

Figure 18.- Concluded.

NASA-Langley, 1961