NASA TECHNICAL NOTE

NASA TN D-2966

c/

NASA TN D-2966

A FLIGHT AND SIMULATOR STUDY OF THE HANDLING QUALITIES OF A DEFLECTED SLIPSTREAM STOL SEAPLANE HAVING FOUR PROPELLERS AND BOUNDARY-LAYER CONTROL

by Curt A. Holzhauser, Robert C. Innis,
and Richard F. Vomaske

Ames Research Center
Moffett Field, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • SEPTEMBER 1965

NASA TN D-2966

A FLIGHT AND SIMULATOR STUDY OF THE HANDLING QUALITIES OF A DEFLECTED SLIPSTREAM STOL SEAPLANE HAVING FOUR PROPELLERS AND BOUNDARY-LAYER CONTROL

By Curt A. Holzhauser, Robert C. Innis,
and Richard F. Vomaske

Ames Research Center
Moffett Field, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – Price $2.00

A FLIGHT AND SIMULATOR STUDY OF THE HANDLING QUALITIES OF A DEFLECTED SLIPSTREAM STOL SEAPLANE HAVING FOUR PROPELLERS AND BOUNDARY-LAYER CONTROL

By Curt A. Holzhauser, Robert C. Innis,
and Richard F. Vomaske
Ames Research Center

SUMMARY

Flight and simulator tests were made to study low-speed handling qualities, potential STOL problem areas, and causes of deficiencies and their solutions. Tests of the STOL seaplane were made in the 50- to 60-knot speed range with Automatic Stabilization Equipment (ASE) engaged and disengaged. During the simulation, several stability and damping derivatives were varied and evaluated.

During the flight tests, take-offs and landings were made from water at 50 knots, corresponding to a lift coefficient of about 4. With the ASE engaged, the handling characteristics of the aircraft were satisfactory. The ASE provided roll and pitch attitude stabilization and increased rate damping about these axes. With the ASE off, the handling characteristics were unsatisfactory because of low static longitudinal stability, a very unstable spiral mode, and large sideslip excursions during turn entries. Response to control inputs was satisfactory about the roll and pitch axes, but the like rotation propellers reduced the directional control to an unsatisfactory level.

The simulator tests were useful in providing a preliminary evaluation and in studying the causes of deficiencies and their solutions. Good correlation was obtained between the simulator and flight results with the exception that the sideslip excursions during manuevering were larger in flight than on the simulator.

INTRODUCTION

An STOL seaplane has been developed by the Shin Meiwa Industry Company, Ltd. (SMIC) to provide the Japanese Maritime Self Defense Force (JMSDF) with a test bed for exploring the potential of a seaplane with low landing and take-off speeds. This aircraft, designated the UF-XS, utilizes Boundary-Layer Control (BLC) and the propeller slipstream to fly at low speeds; Automatic Stability Equipment (ASE) for improved handling at low speeds; and a hull with good hydrodynamic characteristics. Preliminary Japanese flight tests indicated that these features allowed the aircraft to operate in seas with 6-foot high waves.

To further document and evaluate the STOL seaplane, a brief flight test program was performed by a U. S. Navy and NASA team. Prior to this flight program, a simulator study of the handling qualities in the STOL regime was made at Ames Research Center (using preliminary flight results and estimates of the UF-XS characteristics). This simulation was used for obtaining a preliminary evaluation, for studying potential problem areas and their solutions, and for investigating areas beyond the normal flight envelope of the UF-XS.

Previous flight experience with STOL aircraft reported by NASA in references 1 and 2 demonstrated that when good high-lift systems are used the propeller slipstream can be utilized to augment wing lift and reduce flight speeds. However, various deficiencies in the handling qualities resulted at these reduced speeds. Consequently, the primary emphasis in this report will be on handling qualities at low speed rather than on performance. The results of the flight tests will be compared with the simulator tests. Further, since the aerodynamic characteristics of the UF-XS are similar to those of other STOL vehicles (refs. 1 and 2), comparisons with these aircraft will be included. Also, previously unpublished results of simulator studies using the characteristics of the Breguet 941 will be presented since the basic characteristics were generally similar to those of the UF-XS and a larger range of test conditions was covered in some areas.

Additional aerodynamic results and complete hydrodynamic characteristics have been reported by the U. S. Navy members of this evaluation team (ref. 3). The flight tests reported herein were performed in cooperation with the Japanese Maritime Self Defense Force and Shin Meiwa Industry Co., Ltd., of Japan.

NOTATION

C_D	drag coefficient, including thrust
C_L	lift coefficient, $\frac{W}{\bar{q}S}$
C_n	yawing-moment coefficient
g	acceleration of gravity
I_{xx}, I_{yy}, I_{zz}	moments of inertia, slug-ft^2
I_{xz}	product of inertia, slug-ft^2
L_p	roll damping, $\frac{\partial L/I_{xx}}{\partial p}$, 1/sec
L_r	roll due to yaw rate, $\frac{\partial L/I_{xx}}{\partial r}$, 1/sec

L_β — dihedral effect, $\frac{\partial L/I_{XX}}{\partial\beta}$, 1/sec^2

$L_{\delta_a}\delta_{a_{max}}$ — maximum roll control power, $\frac{\partial L/I_{XX}}{\partial\delta_a}\delta_{a_{max}}$, rad/sec^2

$\frac{L_{\delta_r}}{N_{\delta_r}}$ — roll produced by directional control, $\frac{\frac{\partial L/I_{XX}}{\partial\delta_r}}{\frac{\partial N/I_{ZZ}}{\partial\delta_r}}$

m — aircraft mass, $\frac{W}{g}$, slugs

M_q — damping in pitch, $\frac{\partial M/I_{YY}}{\partial q}$, 1/sec^2

$M_{T'}$ — pitching moment due to thrust change, $\frac{\partial M/I_{YY}}{\partial T/W}$, 1/sec^2

M_V — speed stability, $\frac{\partial M/I_{YY}}{\partial V}$, 1/sec^2/ft/sec

M_α — angle-of-attack stability, $\frac{\partial M/I_{YY}}{\partial\alpha}$, 1/sec^2

$M_{\dot\alpha}$ — pitching moment due to angle-of-attack change, $\frac{\partial M/I_{YY}}{\partial\dot\alpha}$, 1/sec^2

$M_{\delta_e}\delta_{e_{max}}$ — maximum longitudinal control power, $\frac{\partial M/I_{YY}}{\partial\delta_e}\delta_{e_{max}}$, rad/sec^2

N_p — yaw due to roll rate, $\frac{\partial N/I_{ZZ}}{\partial p}$, 1/sec

N_r — directional damping, $\frac{\partial N/I_{ZZ}}{\partial r}$, 1/sec

N_β — directional stability, $\frac{\partial N/I_{ZZ}}{\partial\beta}$, 1/sec^2

$N_{\dot\beta}$ — damping due to rate of sideslip, $\frac{\partial N/I_{ZZ}}{\partial(\dot\alpha\beta/dt)}$, 1/sec

N_{δ_a} — adverse yaw due to aileron, $\frac{\partial N/I_{ZZ}}{\partial\delta_a}$, rad/sec^2

$N_{\delta_r}\delta_{r_{max}}$ — maximum directional control power, $\frac{\partial N/I_{ZZ}}{\partial\delta_r}\delta_{r_{max}}$, rad/sec^2

p — roll angular velocity (right roll, positive), rad/sec

PR	pilot rating
q	pitch angular velocity (nose up, positive), rad/sec
$\bar{q}$	free-stream dynamic pressure, lb/ft^2
r	yaw angular velocity (nose right, positive), rad/sec
R/C	rate of climb, ft/min
S	wing area, ft^2
SHP	shaft horsepower
T	propeller thrust, lb
T_c'	thrust coefficient, $\frac{T}{\bar{q}S}$
V	true airspeed, knots
W	gross weight, lb
Y_{prop}	propeller side force, $\frac{C_{Y_{prop}}\bar{q}S}{mV}$, 1/sec
Y_β	side-force stability, $\frac{\partial Y/mV}{\partial \beta}$, 1/sec
Y_{δ_r}	side force due to directional control, $\frac{\partial Y/mV}{\partial \delta_r}$, 1/sec
α	angle of attack, deg
β	angle of sideslip, deg
δ_a	reference lateral control surface deflection (right aileron down, positive) deg
δ_{a_p}	lateral control wheel position, deg
δ_e	elevator angle (trailing edge down, positive), deg
δ_{e_p}	longitudinal control position (forward, positive), in.
δ_f	trailing-edge flap deflection, deg
δ_r	rudder deflection (trailing edge left, positive), deg
δ_{r_p}	rudder pedal position, in.

θ	pitch attitude (nose up, positive), deg
σ	density ratio
φ	bank angle (right wing down, positive), deg
ω_n	undamped natural frequency, rad/sec

Subscripts

i	indicated or uncorrected
x	longitudinal axis
y	lateral axis
z	vertical axis
max	maximum

DESCRIPTION OF AIRPLANE AND SIMULATOR

Airplane

The UF-XS seaplane (figs. 1 and 2) has a high wing, four engines, and boundary-layer control (BLC) on the flaps and on all control surfaces. This aircraft, originally a twin-engined Grumman UF-1 amphibian, was extensively modified by SMIC to lower the landing and take-off speeds and improve hydrodynamic characteristics. Table I contains additional geometric data for this aircraft.

High-lift devices.- The wing was rebuilt for larger span flaps with flap-type blowing and for ailerons with shroud-type blowing over the upper surfaces. A fixed leading-edge slat extended from the inboard nacelle to the wing tip.

Controls.- For the landing and take-off configuration, lateral control was provided by ailerons, spoilers, and differential deflection of the midspan portion of the flap. A rudder with BLC provided directional control and the elevator, which had BLC on the lower surface, provided longitudinal control. A slat, in an inverted position, was attached to the fixed-incidence horizontal tail. The relation between maximum surface deflection and pilot's control movement in the STOL configuration is given in table II. A gear changer was used to reduce the maximum surface deflections in the cruise configuration. All of the surfaces were actuated by an irreversible, fully powered hydraulic system.

The ASE from an S-58 helicopter was incorporated to provide attitude stabilization and rate damping about the roll and pitch axes, and to displace the rudder when the ASE commanded an aileron deflection. The reference attitude for the ASE was wings level and the hull inclined 6° nose up so that the aft portion of the hull was parallel to the water. The maximum surface deflections and equations approximating the ASE output are given in table III.

Propulsion and BLC systems.- The four propellers had the same rotation, counterclockwise when viewed from the front. The inboard propellers were 11 feet in diameter and were driven by Wright R-1820 reciprocating engines with a take-off rating of 1425 horsepower; the outboard propellers were 9.3 feet in diameter and were driven by Pratt-Whitney R-1340 reciprocating engines with a take-off rating of 600 horsepower. The BLC air to the flaps, ailerons, elevator, and rudder was supplied by two compressors (constructed by Ishikawajima Harima Heavy Industry) and driven by two General Electric T-58 engines (rated at about 1000 hp). Each compressor delivered 24 pounds of air per second at a pressure ratio of 1.5.

Hull design.- The original hull was lengthened fore and aft and provided with a "T" tail. Incorporated in the hull were spray suppressors, shown in cross section in figure 2, that extended from the fuselage nose past the propeller plane.

Instrumentation.- An oscillograph and photopanel were used to measure flight and engine conditions and surface and control deflections. The airspeed, angle of attack, and angle of sideslip were measured on a vertical strut between the cockpit and fuselage nose. The angle of attack and angle of sideslip were not displayed in the cockpit. Based on altimeter and attitude values, it appears that the corrected angle of attack (with respect to the waterline) should be indicated angle of attack minus 6°. At angles of attack near the stall, the indicated values appear to be unreliable, probably because of the flow being affected by the hull. Comparison of the directional stability computed from static and dynamic data infers that the indicated sideslip is greater than the true value (indicated sideslip may be of the order of 3/2 times the true value). Based on wing-tip boom measurements, it appears that the indicated airspeed measured at the strut is close to the correct airspeed.

SIMULATOR

The simulator used in this test was the Ames Moving Base Transport Simulator which has limited movement in pitch and roll. It was equipped with instrument displays and flight controls similar to those in the UF-XS aircraft. A Dalto visual simulator, a closed-circuit television system with the camera servo-driven over a model runway, projected the approach lighting and runway as would be seen in hazy, 1/2-mile visibility. All simulated landings were on this runway since the equipment could not simulate water and sea conditions. Figure 3 is a pictorial block diagram of the simulation. The cockpit had a maximum roll angle capability of 9° and was programed so that this corresponded to a commanded bank angle of 13°. The pitch movement was 14° up and 6° down and was programed to correspond directly to the commanded attitude. Six-degrees-of-freedom equations of motion were programed on the analog computer.

TEST PROCEDURES AND CONDITIONS

Flight Tests

The flight tests were conducted from Omura Naval Air Base at Omura, Japan, under VRF flight conditions. The airplane was flown at an average gross weight of 32,000 pounds (W/S = 38 psf), and the center of gravity was about 22-percent mean aerodynamic chord aft of the wing leading edge. In the landing and take-off configuration the inboard flap was at 55°, the midflap at 30°, and the ailerons undrooped. This configuration had been chosen by the JMSDF pilots to have adequate acceleration in the water during take-off and adequate wave-off capability during landing. Higher flap deflections were not tested by the U. S. team, and lesser flap deflections were tested only to ascertain the trim change. Some data were available at other flap deflections from previous tests performed by JMSDF.

The aircraft's stability, control and damping characteristics were measured at an altitude of 4,000 to 6,000 feet with the ASE on and off at speeds higher than 50 knots. Tests could not be made with ASE off below 50 knots or with an engine out because these conditions were beyond the normal operational envelope prescribed by SMIC. All landings and take-offs were made at sea level with the ASE on. The majority of tests at altitude were performed with power set for level or slightly descending flight.

Simulator Tests

Piloted simulator studies of handling qualities were made for the landing approach configuration at speeds of 45 to 60 knots. The simulated characteristics of the UF-XS were for a weight of 29,500 pounds, compared to the normal flight value of 32,000 pounds. The pilot's task was to make landing approaches initiated under IFR conditions at 500 feet altitude on a 3° glide slope 2 miles from the end of the runway. The pilot flew on conventional instruments down to 200-feet altitude where a closed-circuit television runway display came into view. Also included in the task for some runs were lateral side-step maneuvers to acquire the ILS localizer path which was offset 170 feet at the initiation of the run, and later, to correct back to the runway center line when it came into view. Control of lateral displacement was also studied by maneuvering from side to side of the runway (200 feet wide) at an altitude of between 20 and 50 feet. During some runs the effects of crosswinds of 10 knots and turbulence of 1.6 root mean square feet per second velocity were studied. Runs were terminated at contact with the simulated runway or ground. The longitudinal handling qualities during the flare and touchdown portion of the landing were not evaluated because of the poor quality of altitude information presented to the pilot. However, handling characteristics during the flare did give some insight into the existing control and stability. Main propulsion and BLC engine failures were simulated for selected configurations in both the instrument and visual portions of approach.

RESULTS AND DISCUSSION

The parameters presented in the following sections were varied in the simulation and the pilot's evaluation is discussed and compared with those obtained during the flight program. In some cases results from the UF-XS simulation are combined with those from a similar unpublished study of the Breguet 941 on the same simulator using the same pilots. These results are combined because a greater range of parameters was studied during some of the Breguet tests, and the stability derivatives of these two vehicles are similar. The derivatives for the "basic" UF-XS were based on limited flight test data available before the U. S. Navy-NASA flight evaluation and on theoretical and semiempirical calculations. The derivatives for the "basic" Breguet 941 were based on extensive flight test data. Table IV lists these derivatives and also gives the ranges of parameters tested, and the values measured during the flight tests reported herein.

Low-Speed Envelope

Figure 4 shows the low-speed envelope for the UF-XS at 5,000 feet altitude in the STOL configuration of 55° inboard flap, 30° midspan flap, ailerons undrooped, and BLC on. The corresponding lift, drag, and thrust coefficient characteristics are given in figure 5. It should be noted that these data are based on indicated angle of attack and speeds, and that the 100-percent power curve is an extrapolated curve. The majority of the tests at altitude were at 55 knots with power for level flight or for slightly descending flight. The stall speeds were 54 knots at low power (this low power, 34 percent of take-off power, was greater than idle power) and 45 knots at high power, corresponding to maximum lift coefficients of 4 to 6, respectively. At sea level, approaches and take-offs with adequate stall margins were made at and below 50 knots, speeds that corresponded to stalled flight at altitude. Such an expansion of envelope between operation at altitude and sea level was also noted and documented in more detail in reference 1, which contained flight tests of a very similar BLC equipped STOL aircraft.

Insufficient time was available to the U. S. Navy-NASA team to examine optimum take-off and approach speeds, descent rates, and limiting conditions. The power-on stall of the aircraft was very mild and was preceded by a mild buffeting. A slow uncontrollable roll-off occurred at the stall; however, satisfactory recovery was made by applying nose-down control.

The lift and drag characteristics of the UF-XS were very similar to those of the NC-130 with BLC and the Breguet 941 (refs. 1 and 2).

Flight Control Characteristics

Forces.- The force characteristics of each control are given in figure 6. The lateral forces were rated satisfactory - a pilot rating of 3.5 (table V describes the pilot ratings (PR)). The wheel throw of 100° was too great for STOL operation, and a wheel throw of 60° to 70° would have been preferred. The longitudinal forces were satisfactory (PR = 3). The rudder force gradient was considered to be too light (PR = 4); a 50-percent increase in the gradient would have been preferred.

Response.- The following table presents the aircraft response characteristics measured at 55 knots with ASE off and it also gives the corresponding pilot rating. The control power is in terms of initial acceleration with full deflection of the control from the trim position. (When tests were performed with partial deflections only, data were linearly extrapolated to full surface deflection.) The damping is in terms of damping moment divided by moment of inertia. The response after 1 second was computed for a control input that takes 0.2 second to complete.

Axes	Control power, rad/sec^2	Damping, 1/sec	Response after 1 sec, deg	Pilot rating
Lateral	±0.5	-0.8	10	3
Directional	.07 nose right	-.3	1	5
	.27 nose left	-.3	5	3
Longitudinal	.55 nose up	-1.1	10	3
	.21 nose down	-1.1	3	3-1/2

The different responses in the directional mode resulted from a large trim required to compensate for like-rotation propellers and maintain 0° bank angle; this will be discussed later. The effect of losing an engine was not considered in this rating. The different longitudinal responses are due primarily to a different range of elevator deflections (see table I) although some trim is included. The trim requirement at speeds below 55 knots further reduced the nose-down pitch capability; however, even though the trailing-edge down limit was approached at the stall, the pilot felt that the combination of pitchdown at the stall and the available pitching capability was sufficient to effect a satisfactory recovery.

With the ASE on, the initial aircraft response to a control input was not affected by the ASE because the lag of the ASE was about 1 second. After 1 second, the response was reduced because of increased damping and a control input to restore attitude.

Longitudinal Stability

Simulator.- Figure 7 shows how the pilot rating is affected by angle-of-attack stability (M_{α}) and speed stability (M_V) with ASE off and at a speed of about 50 knots. As would be expected, reducing angle-of-attack stability caused the handling to deteriorate. It can be noted that the pilot tolerated low stability (even static angle-of-attack instability, $+M_\alpha$). His tolerance of such low stability can probably be attributed partially to high damping ($M_{\dot\alpha} + M_q$ about -1), and to the fact that the airplane is not easily disturbed by gusts. In contrast to what might have been expected, increasing the speed stability ($+M_V$) made the handling worse because the pilot was less aware of the improved stability than in the corresponding increased trim change with thrust or power; that is, the speed stability and trim change with thrust are interrelated.

$$M_V = \frac{\partial M/I}{\partial V} = \frac{\partial M/I}{\partial T/W}\left(\frac{dT}{dV}\frac{1}{W} - \frac{2qS}{VW}T_c{'}\right)$$

where the

$$\frac{\partial M/I}{\partial T/W} = M_{T'}$$

These adverse handling effects of trim due to power may have been aggravated by the static instability in pitch used in the tests. One way to reduce this detrimental effect of thrust on pitching moment is to couple the elevator to the throttle. Flight tests of such an interconnect are reported in reference 1, where the large moment change obtained during a wave-off was eliminated. In such a case it would be expected that the handling would improve with increased values of M_V in contrast to the results shown in figure 7(b).

The tests with ASE on were made using an M_α of 0.25 and an $M_{T'}$ of -0.5 for which conditions the aircraft was statically unstable with ASE off. Engaging the ASE improved the longitudinal characteristics from a PR of 6 to 2-1/2. The ASE satisfactorily modified the aircraft characteristics so that a given attitude was maintained during glide path changes and the airplane responded as though it were stable (an effective M_α of -0.4 compared to an M_α of +0.25, ASE off), with 50-percent increase in pitch damping.

Flight.- The longitudinal characteristics of the aircraft with ASE off are indicated by the variation of the elevator angle with speed at constant power (fig. 8). These curves indicated that at 55 knots the static stability of the airplane was neutral. From throttle step data $M_{T'}$ was found to be -0.1, and then M_α was estimated as +0.15. The corresponding undamped natural frequency was calculated to be about 0.2 rad/sec. This low stability is further verified in figure 9 by the close correspondence of the calculated response (using $M_\alpha = 0$) to an elevator step with the measured response for the case with ASE off. It is also seen that the pitching velocity increased until corrective action was taken. Generally, the phugoid motion could not be excited; on the occasion that it was obtained, the period was about 30 seconds, and it was lightly damped. The pilot reported that the aircraft was characterized by a heavily damped, mildly divergent motion; this motion appeared to be divergent because the short period was so long corrective action had to be taken before a tendency to return could be noted (see fig. 9). Low longitudinal stability and large pitching-moment changes with power changes have been observed with other STOL aircraft (refs. 1 and 2) and these characteristics require moderate pilot effort to correct and maintain flight path. The pilot considered these characteristics unsatisfactory on the UF-XS with the ASE off and rated them 5-1/2, although no actual approaches and landings were made with this configuration. The corresponding values of stability and trim change with power and the rating are included in figure 7. It is seen that good correlation was obtained with the simulator results and the pilot remarked that it felt like the corresponding configuration "flown" on the simulator.

With the ASE on, the aircraft responded as if it were statically stable; it returned to its original trim attitude in less than 10 seconds after being disturbed. Although the pilot considered the aircraft overdamped, the longitudinal characteristics of the UF-XS with the ASE on were satisfactory (PR = 3-1/2). This improvement with ASE on was not quite as large as obtained on the simulator. A comparison of response to an elevator pulse in flight with ASE on and off is shown in figure 10. Identical response was obtained initially because the ASE introduced a lag of about 0.5 to 1.0 second and included a term to avoid reducing the control effectiveness (see table III). This lag was not included in the simulation program.

Static Lateral-Directional Characteristics

Flight.- The steady-state sideslip data measured in flight are given in figure 11. Similar characteristics were used during the simulator tests. The sideslip vane on the aircraft had limited motion (±15°), and the values presented at higher angles in figure 11 were based on the assumption that sideslip developed was linearly related to the rudder deflection. Figure 12 shows the side-force coefficient caused by the like-rotation propellers. The data from the current tests (55-30-0) showed higher side-force values than the previous data used for the simulator tests. A reference line showing the relation of side-force coefficient equivalent to a 3° right bank angle and zero sideslip is included. This line shows that 3° right bank would be required to trim the side-force at zero sideslip. In figure 11, it is seen that little control deflection is required to produce a 3° bank angle; however, maintaining 3° during the approach was found to be uncomfortable and sideslipping was preferred. The indicated steady-state sideslip angle was 11° for zero bank angle. It was noted earlier that the indicated sideslip angle may be 3/2 true sideslip angle. This flight condition required considerable rudder deflection and greatly reduced the directional control power available (see earlier section) so that concern was expressed that an engine failure might be catastrophic. No engine-out data were obtained in flight. An engine failure (at wave-off power) was approximated on the simulator, and the handling qualities were found to be acceptable for VFR, but unacceptable under IFR conditions.

Wind-tunnel tests by SMIC indicated that the side force resulted largely from asymmetric pressures on the nacelles. Smaller nacelles, such as used on turboprop configurations would significantly reduce the side force. This is somewhat substantiated by the smaller side-force values for the BLC-130 shown in figure 12. Side force was not a concern with that aircraft. A better solution, of course, would be to have opposite rotation propellers like those on the aircraft of reference 1.

Dynamic Lateral-Directional Stability

Previous tests with STOL aircraft have shown that when the aircraft is banked into a turn, a turn rate in the desired direction does not develop for several seconds, and large excursions in sideslip angle result. For these STOL aircraft, the directional period was moderately long, damping was low, and there frequently was cross-coupling; therefore, it was difficult to coordinate the turn with the rudder. These characteristics have been highlighted in a step-bank maneuver with rudder fixed. (See refs. 1, 2, and 4.) A typical response to a 15° step bank with rudder fixed is shown in figure 13. Large sideslip excursions can be noted. The following discussion and tests will pertain to the factors affecting these characteristics.

Simulator.- The effect of different levels of static directional stability and directional damping on pilot opinion is shown in figures 14(a) and (b), respectively. At low values of directional stability, the periods become longer and larger sideslip excursions are produced by a given control input or by a disturbance; therefore, more of the pilot's attention is required to control sideslip. With high stability, the aircraft is too sensitive to gusts and has insufficient damping, when N_r is maintained constant. At low values of damping the aircraft is too sensitive to gusts and at high values it becomes too sluggish. This latter condition could be somewhat improved with additional directional control power. These data are combined in figure 15 to show the desired levels of satisfactory (PR = 3.5) and unsatisfactory (PR = 6.5) directional stability and damping for STOL aircraft with approach speeds of 50 to 60 knots, directional control power of 0.2 rad/sec^2, and little cross coupling. Flight values for the NC-130B, the BR 941, and the UF-XS without stability augmentation are included and these data indicate good correlation with the simulator results. The UF-XS flight values are discussed in more detail in a later section. Reference 5 reports similar boundaries obtained with a variable stability helicopter at 45 knots and IFR conditions.

Figure 16(a) shows the effect of roll due to yaw rate, L_r without stability augmentation. At high values of L_r large spiral instability resulted, and the lateral motion was similar to that of an aircraft with a large negative dihedral effect; the bank angle was doubled in about 3 seconds. Figure 16(b) shows how the handling is affected by different values of the dihedral effect, L_β. Separate curves derived from the UF-XS and Breguet 941 simulation are shown. The marked difference was due to a larger value of L_r for the "basic" UF-XS than for the "basic" Breguet 941 (as noted on the curves). For both cases, near zero dihedral effect was desired. With zero L_β the simulated "basic" UF-XS was laterally unstable, with the bank angle doubling in 10 seconds; the rating was 4. With a positive dihedral effect poor Dutch roll characteristics were obtained and the directional damping was reduced. Negative dihedral effect increased the lateral instability.

Varying yaw due to lateral control ($N_{\delta_a}/L_{\delta_a}$) over a large range had a surprisingly little effect on the pilot rating; that is, when this ratio was increased from 0 to -0.4, the rating changed only by 1/2 a unit. Similar results were reported in the simulation tests of reference 4.

Since much of the difficulty in the lateral-directional mode was related to a lack of turn coordination which caused sideslip excursions, tests were performed using $N_{\dot{\beta}}$ or N_p to improve the handling qualities. The effect of these are shown in figure 17. Reference 4 discussed, in considerable detail, the ability of $N_{\dot{\beta}}$ to reduce sideslip excursions during maneuvering. Reference 6 also discusses recent flight results with different methods of $N_{\dot{\beta}}$ augmentation. This reference also shows how N_p can be used for turn coordination. Further, it shows that the optimum value of N_p corresponds to the ratio of g/V. Figure 17 shows that $N_{\dot{\beta}}$ or N_p can greatly improve the handling of these STOL aircraft. It should be further noted that aircraft generally have zero $N_{\dot{\beta}}$ and small values of N_p; therefore, augmentation equipment will be required for producing the desired levels of these terms.

Tests were also performed simulating the ASE of the UF-XS. The ASE provided attitude stabilization and increased damping in the roll axis, and deflected the rudder when the ASE deflected the aileron (table III). The pilot considered the handling greatly improved, and rated it 2-1/2.

Flight.- The directional stability and damping characteristics of the UF-XS with ASE off are given in figure 15. The directional period was 6-1/2 seconds and fairly well damped (damping ratio of 0.3), and the pilot rated these characteristics 3-1/2. The rating of 3-1/2 compares well with the generalized simulator derived boundary. The corresponding dimensional characteristics are an N_β of 0.8 and an N_r of -0.3. In contrast, the steady-state sideslip data indicated an N_β of 0.5 which should have produced a period of 9 seconds (values that corresponded to the "basic" UF-XS simulated). The reason for this discrepancy is not understood, but it seems reasonable that a portion of it could be caused by erroneous sideslip measurements due to the flow field at the mast on the fuselage.* From figure 14, it is seen that either of these values of N_β would have resulted in similar pilot ratings of the stability and damping.

The spiral instability with the ASE off is seen in the time history in figure 18; the bank angle is doubled in about 4 seconds. This high instability was caused by the large value of roll due to yaw rate (L_r of about 0.5) and near zero dihedral effect. Because of this instability the pilot's constant attention was required to maintain the desired bank angle and heading, and this characteristic was considered unsatisfactory (PR of 4-1/2). The measured L_r was greater than used for the "basic" UF-XS simulated; when the correct L_r was used, good correlation was obtained between the simulator and flight results (fig. 16).

---

*All other derivatives are based on the assumption that sideslip was accurately measured.

The pilot rated the over-all lateral-directional characteristics of the UF-XS in flight with ASE off as 5-1/2 to 6; whereas the rating was 4 for the basic UF-XS simulated. The characteristics include the lateral instability, ease of making a coordinated turn, and the response to control inputs. Closer agreement is obtained when the derivatives used for the "basic" UF-XS in the simulator are corrected to those measured in flight. Even then a difference of about 1 rating value remains. The reason for this discrepancy is not clear; however, there are several contributing factors. The primary objection reported by the pilot was "high adverse yaw," which to him appeared to be higher for the aircraft than for the simulated vehicle. This reported "adverse yaw" includes not only adverse yaw due to ailerons ($N\delta_a/L\delta_a$), but also the terms that cause sideslip (because of low stability or cross coupling of aerodynamic or inertia terms), making it difficult to reduce the sideslip excursions in a turn entry. In flight, the adverse yaw due to ailerons was smaller and the directional stability was greater than the values used for the "basic" simulated vehicle, so these factors did not contribute to the discrepancy. However, the simulator lacked yaw motion, and the product of inertia was not included in the equations of motion. In flight, the pilot did not have a sideslip indicator, and the trim sideslip was greater than that on the simulator because of the larger propeller side force. Further, this large trim sideslip angle of 11° made it difficult to have a good reference during maneuvering so that the turn coordination could be evaluated.

With the ASE on, the ailerons are deflected to maintain wings level and to increase the roll damping; the rudder is also deflected proportional to the aileron commanded by the ASE (see table III). Figure 19 compares the response to an aileron step with ASE on and off. With ASE on, the initial response is similar to that with ASE off because of a 1-second lag in the augmentation system and a term included to avoid reducing the control effectiveness (see table III). After this 1 second, the response is reduced because of the stabilizing and damping input. A constant aileron defection is seen to occur from time 1 second to about 4 seconds because of the authority limit in the system. (The absolute value of yaw rate plotted in figure 19 for ASE on may be incorrect.) The ASE eliminated the bad spiral instability (Fig. 18), and the aircraft was easier to fly and maintain on a given patn. However, the directional period was increased to 8 seconds, the damping ratio decreased to 0.2, and the sideslip excursions during maneuvering was not eliminated. The lateral-directional characteristics with the ASE on were considered to be satisfactory (PR = 3-1/2). However, the high attitude stability and sideslip excursions would be more objectionable on an STOL land plane where more extensive maneuvering would be required.

Operational Characteristics and Pilots' Comments

All take-offs and landings were made in VFR conditions with ASE on; one flight was made from moderately rough water with 18 to 20 knots of wind. Acceleration during the take-off is low but steady, with little or no spray striking the propellers. Control of pitch attitude is easy and lift-off is accomplished in a slight nose-up attitude between 45 and 50 knots (depending upon gross weight). Immediately after lift-off, the nose swings noticeably to the right as the aircraft assumes its trim sideslip angle for a level wing attitude. On the simulator, this asymmetry was counteracted by banking the aircraft slightly to the right. In flight, however, this proved impractical since the side force due to like-rotation propellers was about twice the value simulated and the resultant side force felt uncomfortable to the pilots. With ASE off, the combination of neutral longitudinal stability, spiral instability, and large sideslip excursions in turn entries rendered the aircraft handling qualities unacceptable for all but emergency operation. Although no actual approaches were attempted with ASE off, it was felt that under visual conditions, it would be possible to land the aircraft with ASE off. Operation under instrument conditions with ASE off, however, would be quite hazardous.

The landing approaches were made in a flat attitude at a rate of descent of about 500 ft/min. Sink rate was adjusted with power while pitch attitude was held relatively constant to maintain the desired 55-knot approach speed. At about 200 to 300 feet, power was adjusted to reduce the rate of descent to about 300 ft/min and the airspeed to about 50 knots. Just before the airplane contacted the water, its nose was raised slightly to the landing attitude. As it entered the "ground effect" its nose swung abruptly to the left as the aircraft alined itself in the direction of flight, without any action being taken by the pilot. This was not considered objectionable for the seaplane but would probably create a problem for an aircraft landing on a runway. The slight flare and favorable ground effect reduce the sink rate somewhat before touchdown. This, in combination with the deep hull design, provided a soft landing with little tendency to bounce.

The ASE does a reasonable job of stabilizing the airplane and makes the approach and landing task relatively easy. The objectionable features of the ASE were that a lateral control force had to be maintained during steady-state turns (ASE attempting to return the airplane to wings level) and that a slight longitudinal oscillation occurred during pitch maneuvers (due to lag in the ASE). This did not compromise the seaplane approach and landing since very little maneuvering is required. This type of stability system would be much more objectionable in a land plane, however, where many more constraints are placed on the landing area.

CONCLUDING REMARKS

The following remarks pertain to the seaplane characteristics in the 50- to 60-knot speed regime.

The aircraft could easily be operated from the water at take-off and landing speeds of 50 knots, which corresponded to a lift coefficient of about 4. With the Automatic Stabilization Equipment (ASE) engaged the handling characteristics were satisfactory for the seaplane mission. The ASE stabilized the roll and pitch attitudes and increased the rate damping about these axes. Without the ASE, the following deficiencies resulted in an unsatisfactory aircraft; low static longitudinal stability, a very unstable spiral mode, and large sideslip excursions during turn entries. Satisfactory response to control inputs was obtained about the roll and pitch axes, but the like-rotation propellers reduced the directional control to an unsatisfactory level.

The simulator tests performed prior to flight tests were useful in providing a preliminary evaluation, showing potential problem areas and some causes and solutions to these problem areas. Good correlation was obtained between the simulator and flight results with the exception that in maneuvers the sideslip excursions were larger in flight than on the simulator.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., June 7, 1965

REFERENCES

1. Quigley, Hervey C.; Innis, Robert C.; and Holzhauser, Curt A.: A Flight Investigation of the Performance, Handling Qualities, and Operational Characteristics of a Deflected Slipstream STOL Transport Airplane Having Four Interconnected Propellers. NASA TN D-2231, 1964.

2. Quigley, Hervey C.; and Innis, Robert C.: Handling Qualities and Operational Problems of a Large Four-Propeller STOL Transport Airplane. NASA TN D-1647, 1963.

3. Vagianos, LCDR Nicholas J., USN; and Rooney, Eugene C.: Final Report Flight Test Evaluation of the UF-XS Japanese STOL Seaplane. Tech. Rep. FT 212-031R-64, Naval Air Test Center.

4. Quigley, Hervey C.: and Lawson, Herbert F., Jr.: Simulator Study of the Lateral-Directional Handling Qualities of a Large Four-Propellered STOL Transport Airplane. NASA TN D-1773, 1963.

5. Garren, John F., Jr.; Kelly, James R.; and Reeder, John P.: Effects of Gross Changes in Static Directional Stability on V/STOL Handling Characteristics Based on a Flight Investigation. NASA TN D-2477, 1964.

6. Anderson, Seth B.; Quigley, Hervey C.; and Innis, Robert C.: Stability and Control Considerations for STOL Aircraft. Presented at the Advisory Group for Aeronautical Research and Development Panel Meeting on Flight Mechanics, Paris, France, June 9-11, 1965.

TABLE I.- GEOMETRIC DATA OF AIRPLANE

Wing	
Total area, sq ft	835
Span, ft	80
Mean aerodynamic chord	10 ft, 9 in.
Taper ratio	0.5
Aspect ratio	7.69
Incidence	5.0°
Airfoil section	
Root	NACA 23017
Tip	NACA 23012
Dihedral (lower surface)	$2^\circ 10'$
Flap	
Span (percent wing span)	
Inboard	30
Outboard	30
Chord (percent wing chord)	25
Deflection (maximum)	
Inboard	80°
Outboard	60°
Aileron	
Span (percent wing span)	28
Chord (percent wing chord)	25
Horizontal tail	
Area, sq ft	200
Span, ft	31.5
Airfoil section	Inverted NACA 2414
Elevator area, sq ft	60
Vertical tail	
Area, sq ft	137.5
Span, ft	12.9
Airfoil section	NACA 0014
Rudder area, sq ft	41.2

TABLE II.- GEOMETRIC CHARACTERISTICS OF CONTROLS IN TAKE-OFF AND LANDING CONFIGURATION

	Maximum control deflection	Maximum surface deflection
Longitudinal	8.2 in. aft	Elevator -40° (up)
	4.0 in. forward	Elevator $+22^\circ$ (down)
Lateral*	105° right	Right aileron 25° up Right outboard flap 5° down Right spoiler 57° up Left aileron 18° down Left outboard flap 45° down Left spoiler 0°
	100° left	Vice versa
Directional	2.4 in. right 2.5 in. left	Right rudder 36° Left rudder 44°

*The right aileron deflection is used throughout the report as a reference for the lateral control input; the spoiler does not start deflecting until about 50-percent control input.

TABLE III.- EQUATIONS FOR AUTOMATIC STABILIZATION EQUIPMENT (ASE)

$$\delta_{e_{total}} = \delta_{e_{ASE}} + \delta_{e_{pilot}} \qquad \delta_{e_{ASE}} = 0.9\ (\theta - \theta_o) + 0.8q + K_e\delta_{e_{pilot}}$$

$$\delta_{a_{total}} = \delta_{a_{ASE}} + \delta_{a_{pilot}} \qquad \delta_{a_{ASE}} = 1.2\varphi + 0.9p + K_e\delta_{a_{pilot}}$$

$$\delta_{r_{total}} = \delta_{r_{ASE}} + \delta_{r_{pilot}} \qquad \delta_{r_{ASE}} = \delta_{a_{ASE}}$$

where θ_o is 6^o and $K_e\delta_{e_{pilot}}$ and $K_a\delta_{a_{pilot}}$ are provided so that the ASE does not reduce the apparent control effectiveness. These equations and constants were provided by SMIC. The constants, applied to the attitude and rate portions of the equation, approximate the flight system with its 1-second time lag. The values for K_e and K_a were not given but their magnitude was between 0.5 and 1.5. The authority of the ASE was 20 percent of the maximum surface deflection.

TABLE IV.- VALUES OF DERIVATIVES USED IN SIMULATION AND MEASURED IN FLIGHT

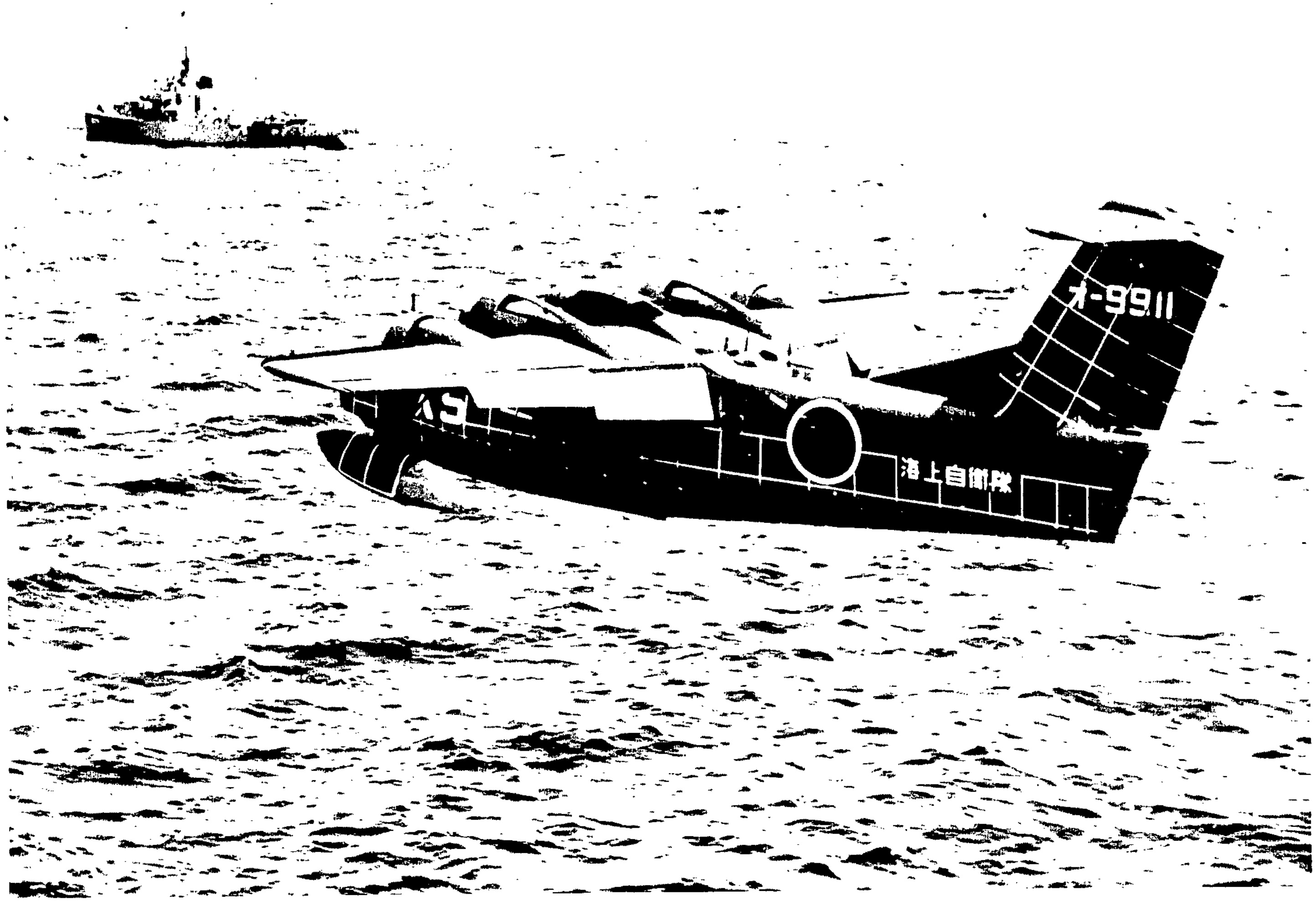
Derivative	Simulation				Flight
	UF-XS		Breguet 941		
	"Basic"	Variation	"Basic"	Variation	UF-XS ASE off
M_α	0.25	0.25 to -0.25	-0.09	---	0.15
$M_{T'}$	-0.47	-0.22 to -0.94	-0.41	---	-0.1
$M_{\dot{\alpha}}$	-0.40	---	-0.43	---	-0.4
M_q	-0.67	---	-1.02	---	-0.7
$M_{\delta_e}\delta_{e_{max}}$	0.61 -0.28	---	1.05 -0.75	---	0.55 -0.21
N_β	0.46	---	0.54	0 to 2.0	0.8
N_r	-0.30	-0.2 to -0.4	-0.33	0 to -2.0	-0.3
N_p	-0.16	0.5 to -0.5	-0.05	0.5 to -0.5	-0.1
$N_{\dot{\beta}}$	0	---	0	0 to 3.2	---
$N_{\delta_r}\delta_{r_{max}}$	±0.20	---	±0.19	---	0.07 nose right 0.27 nose left
L_β	0	0.2 to -0.2	-0.32	0.6 to -1.6	-0.03[1]
L_r	0.25	0.25 to 0.60	0.14	---	0.5
L_p	-0.67	---	-0.82	---	-0.8
$L_{\delta_a}\delta_{a_{max}}$	±0.50	---	±0.42	---	±0.5
$N_{\delta_a}/L_{\delta_a}$	-0.20	0 to -0.4	-0.01	0.8 to -1.1	-0.06
$L_{\delta_r}/N_{\delta_r}$	-0.10	---	0.23	---	-0.2
Y_β	-0.13	-0.08 to -0.13	-0.10	---	-0.14[1]
Y_{δ_r}	0.03	---	0.05	---	---
Y_{prop}	-0.008	---	0	---	-0.018
V	51 knots		60 knots		55 knots
C_L	4.0		3.7		3.7
m = W/g	916		1196		994
I_{xx}	164,000		228,000		184,000[2]
I_{yy}	155,200		136,000		173,500[2]
I_{zz}	294,000		417,000		329,000[2]
I_{xz}	12,300				13,800[2]
c	10.75		12.15		10.75
b	80.0		76.1		80.0

[1]Based on indicated sideslip reading, see text.
[2]Estimated from values provided at lower gross weights.

TABLE V.- PILOT OPINION RATING SYSTEM FOR UNIVERSAL USE

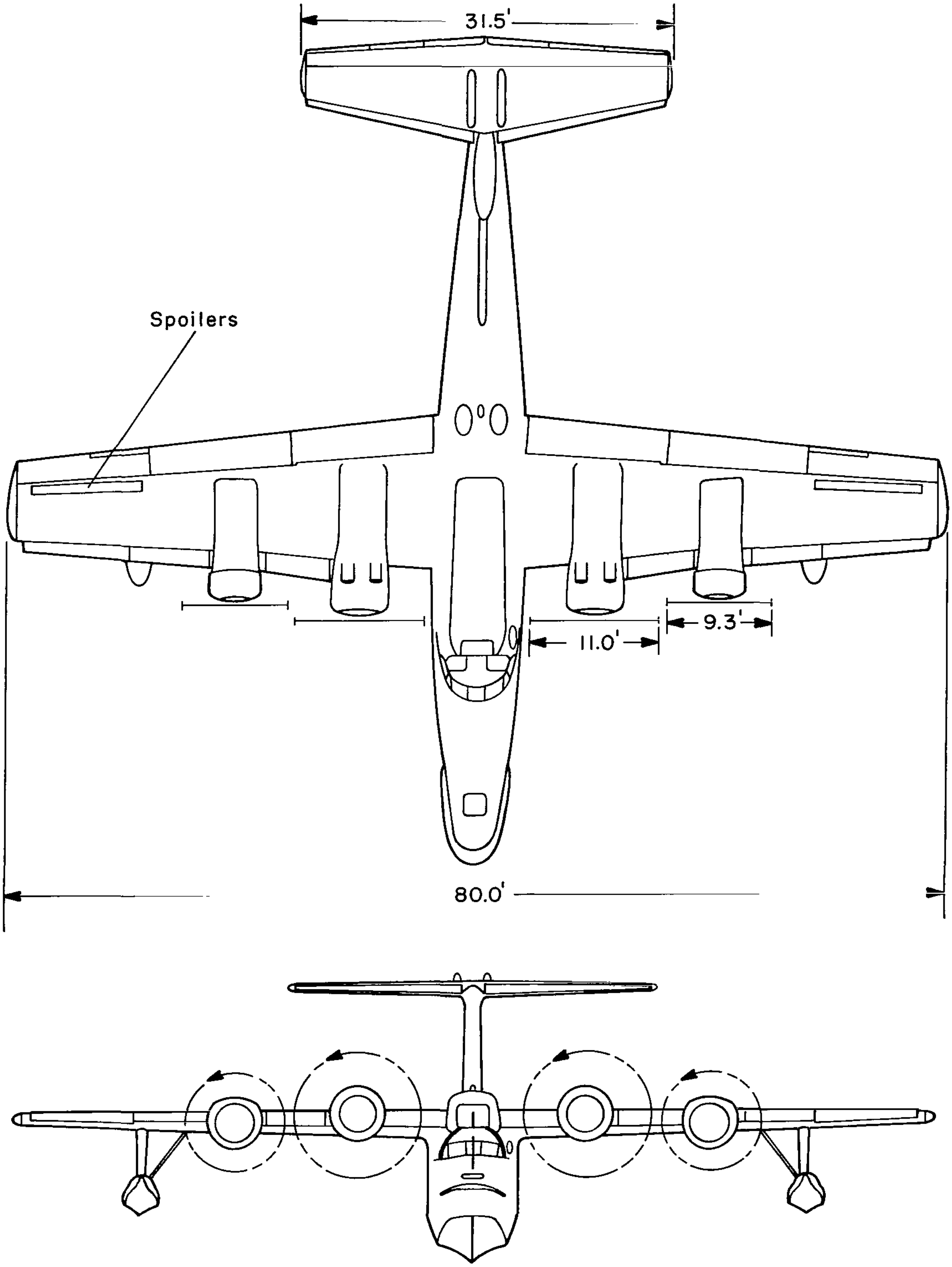
	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	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

[1]Failure of a stability augmenter.



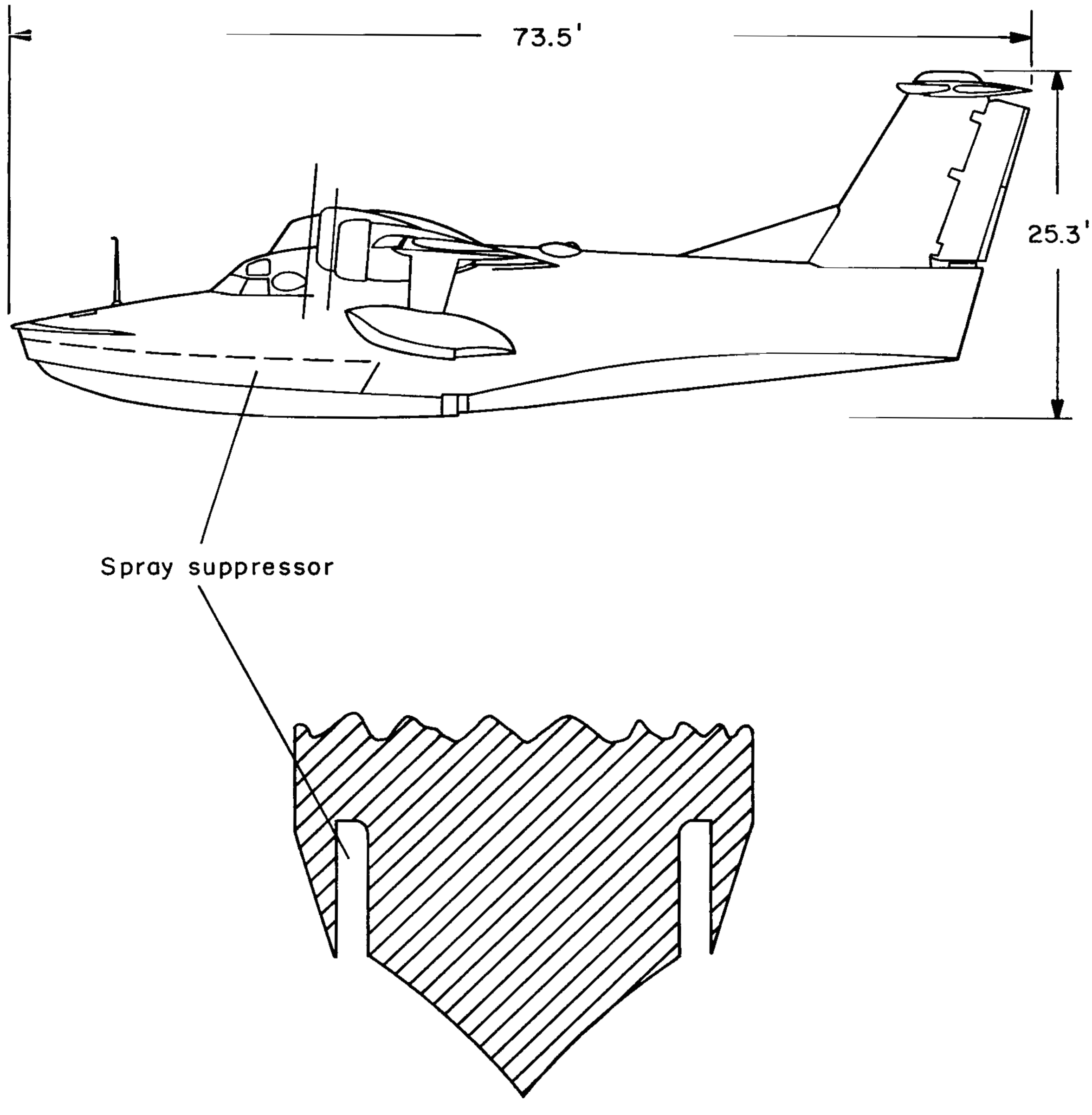
A-33534

Figure 1.- The UF-XS in STOL configuration.



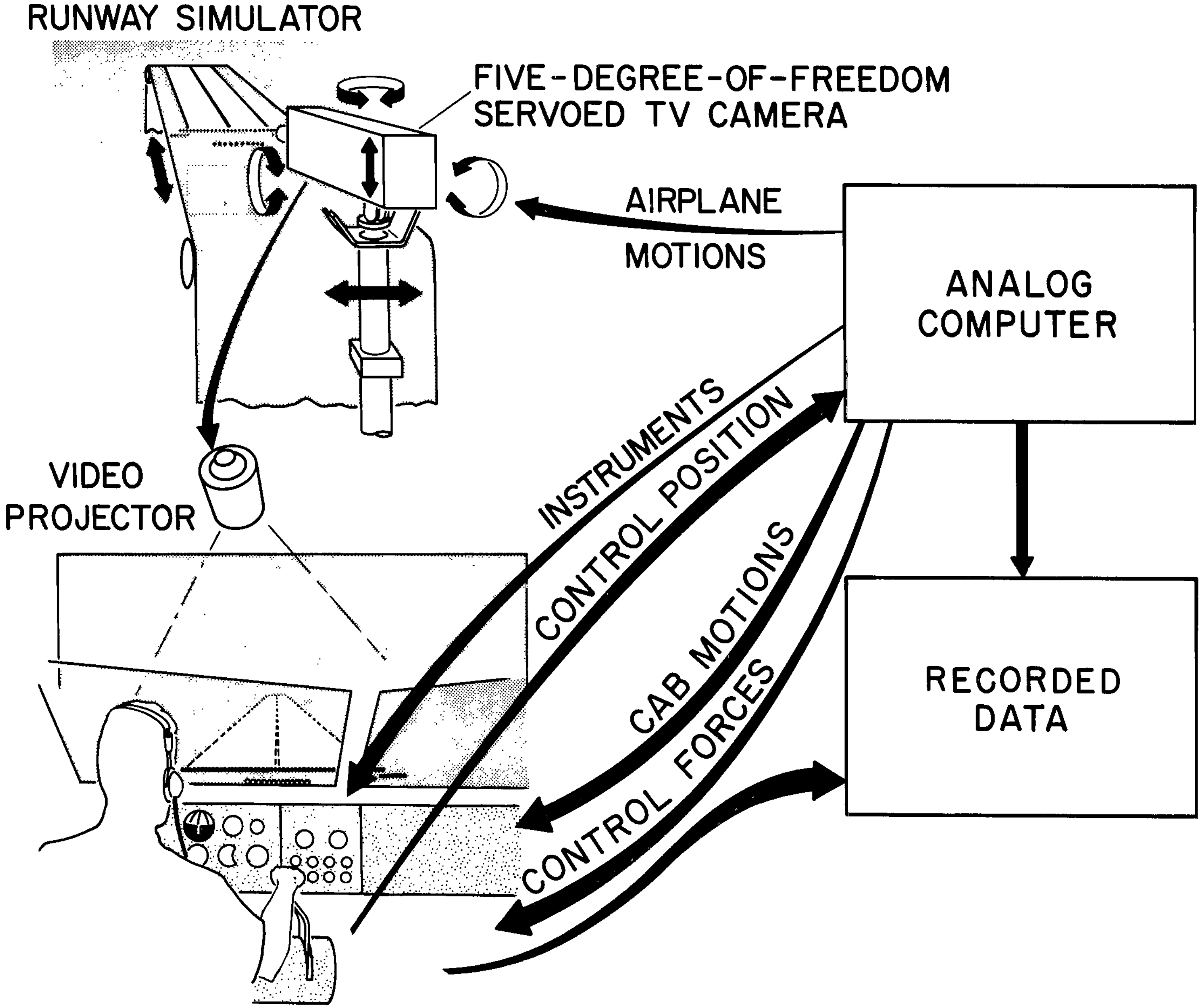
(a) Top and front view

Figure 2.- Sketch of airplane.



(b) Side view and hull cross section

Figure 2.- Concluded.



A-34701

Figure 3.- Diagram of Ames Moving Base Transport Simulator.

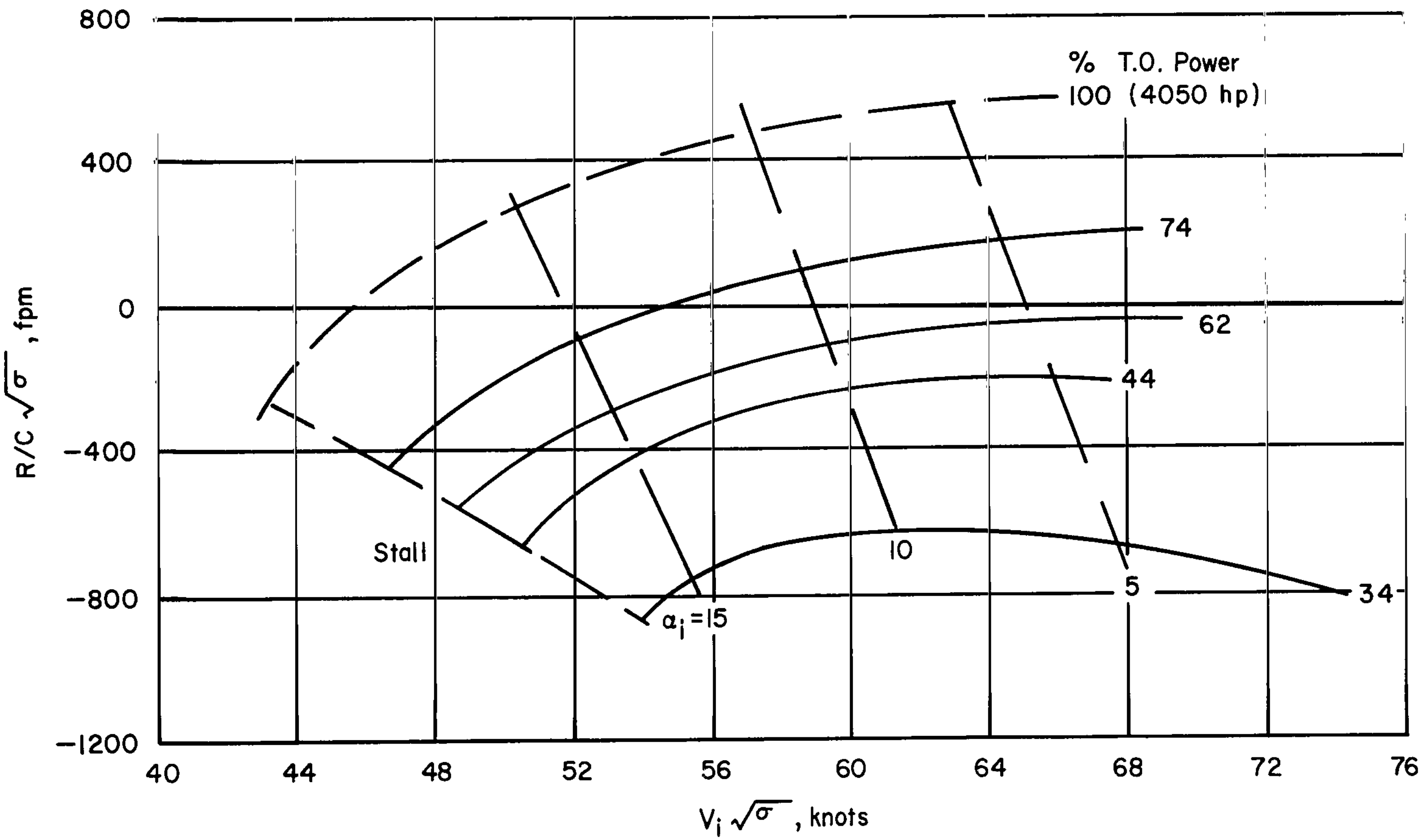


Figure 4.- Operating envelope in STOL configuration at 5,000 feet; δ_f = 55/30/0, BLC on.

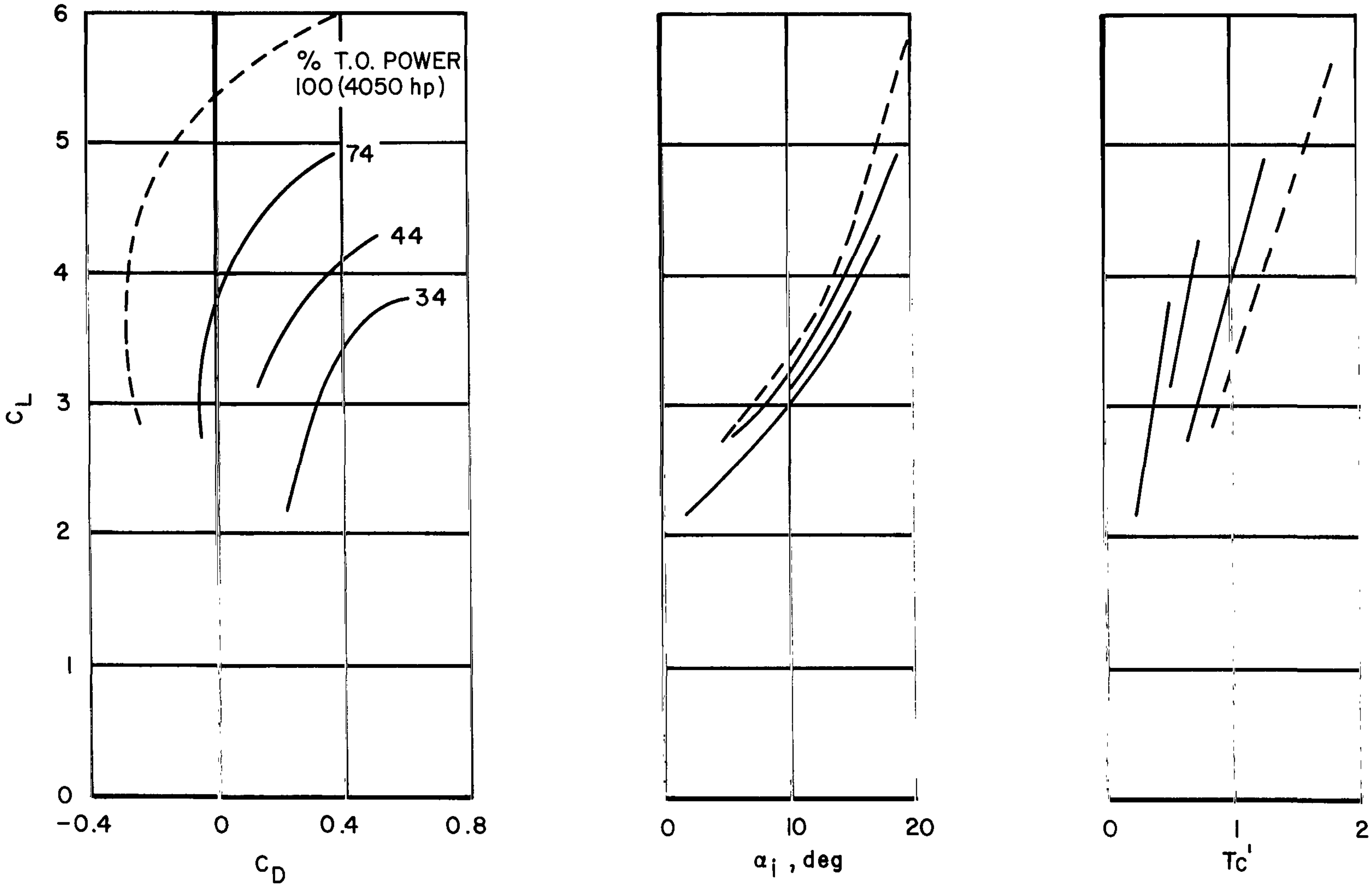


Figure 5.- Approximate lift and drag characteristics in STOL configuration at 5,000 feet; $\delta_f = 55/30/0$, BLC on.

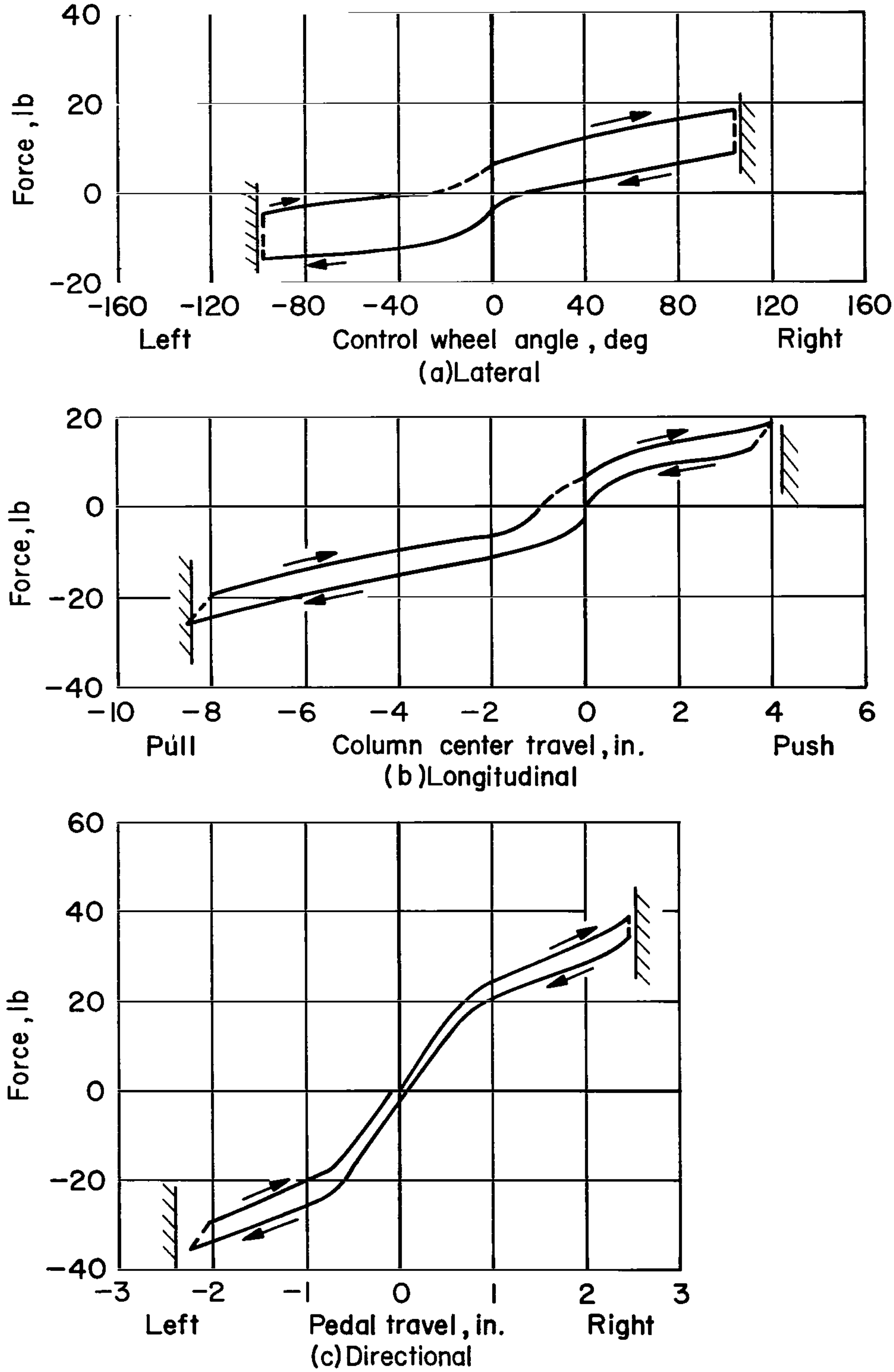


Figure 6.- Force characteristics of control system.

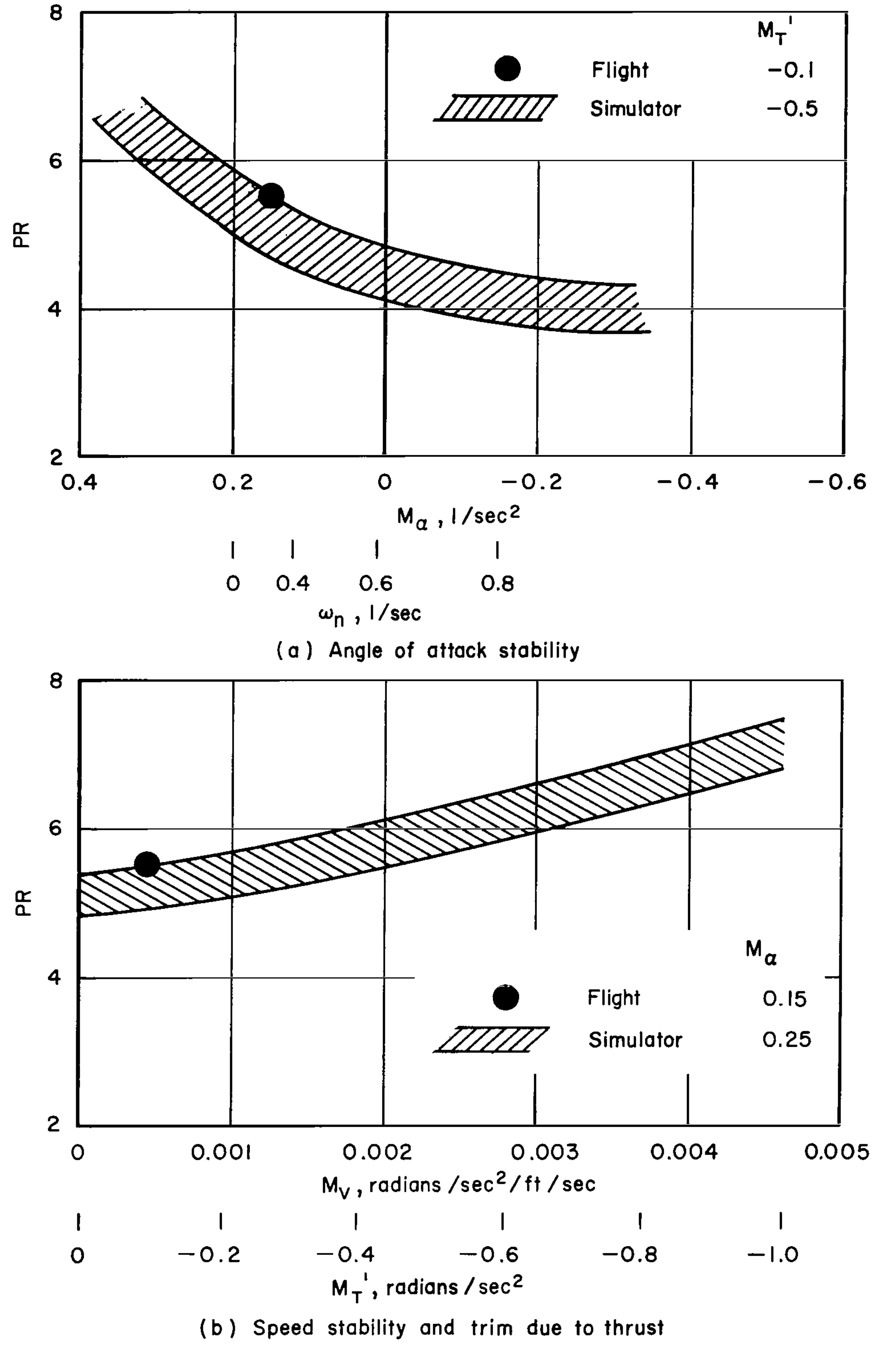


Figure 7.- Effect of longitudinal stability on pilot rating; ASE off.

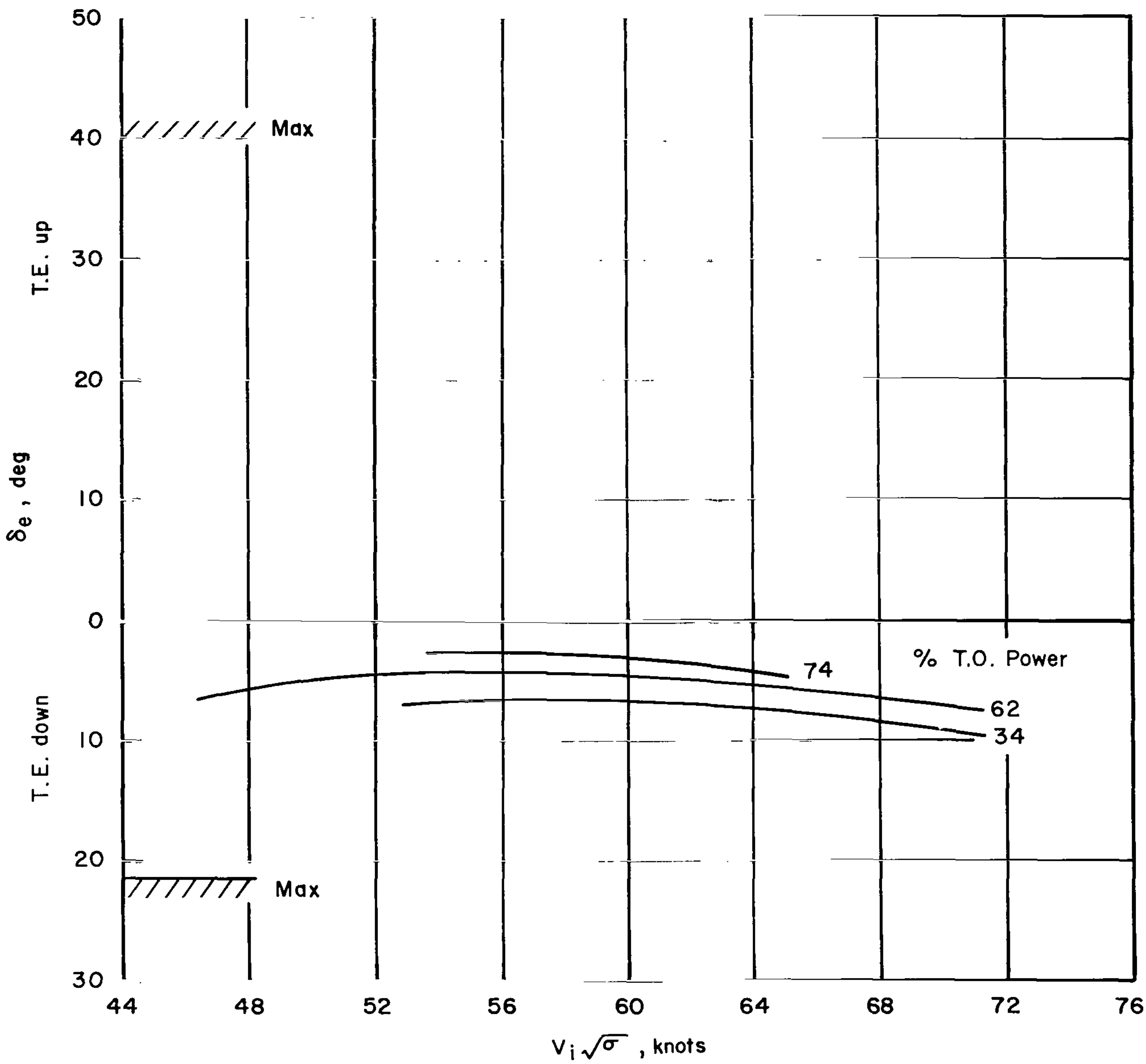


Figure 8.- Variation of elevator angle with speed of constant power.

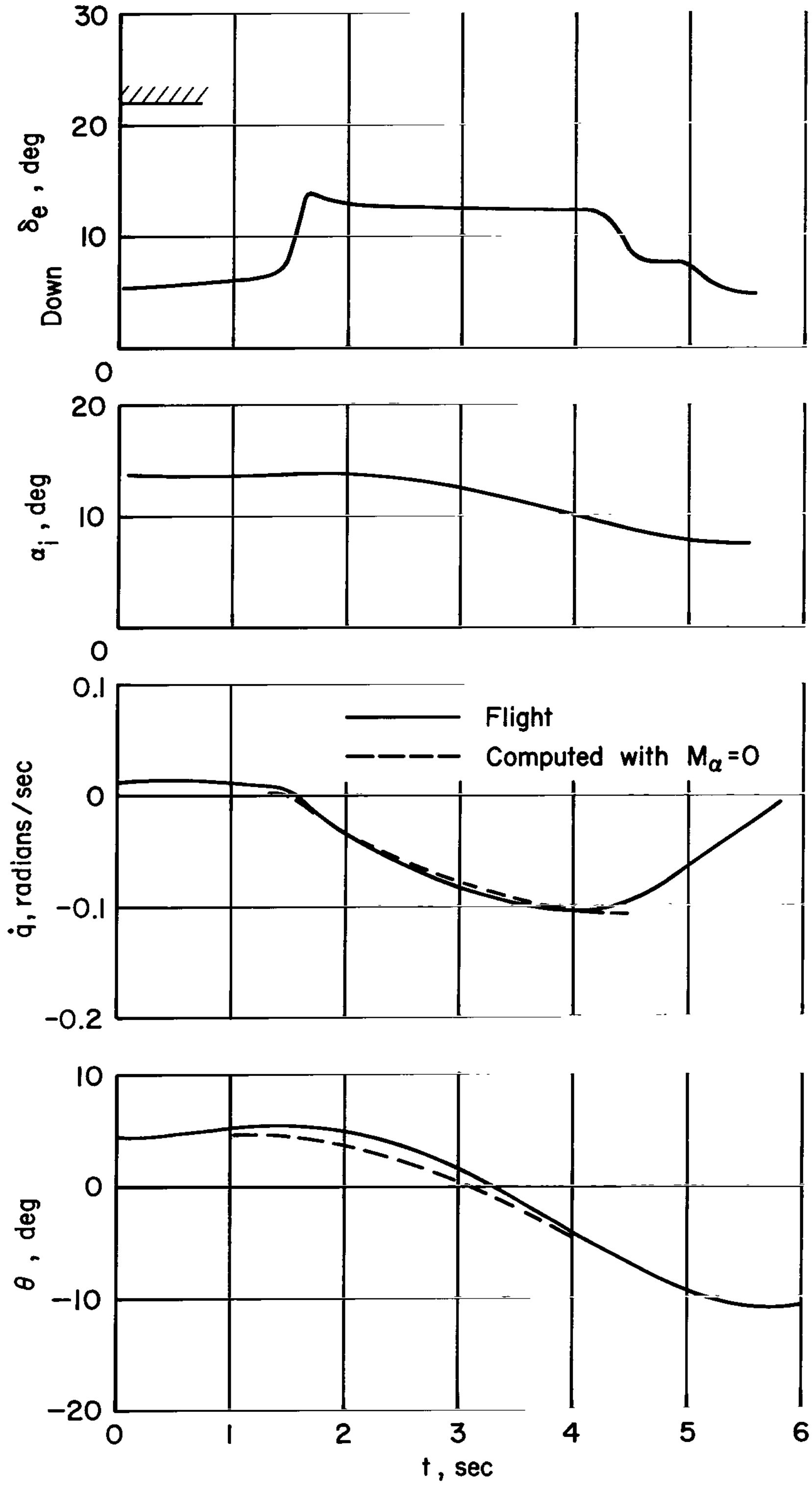


Figure 9.- Response to elevator step; ASE off.

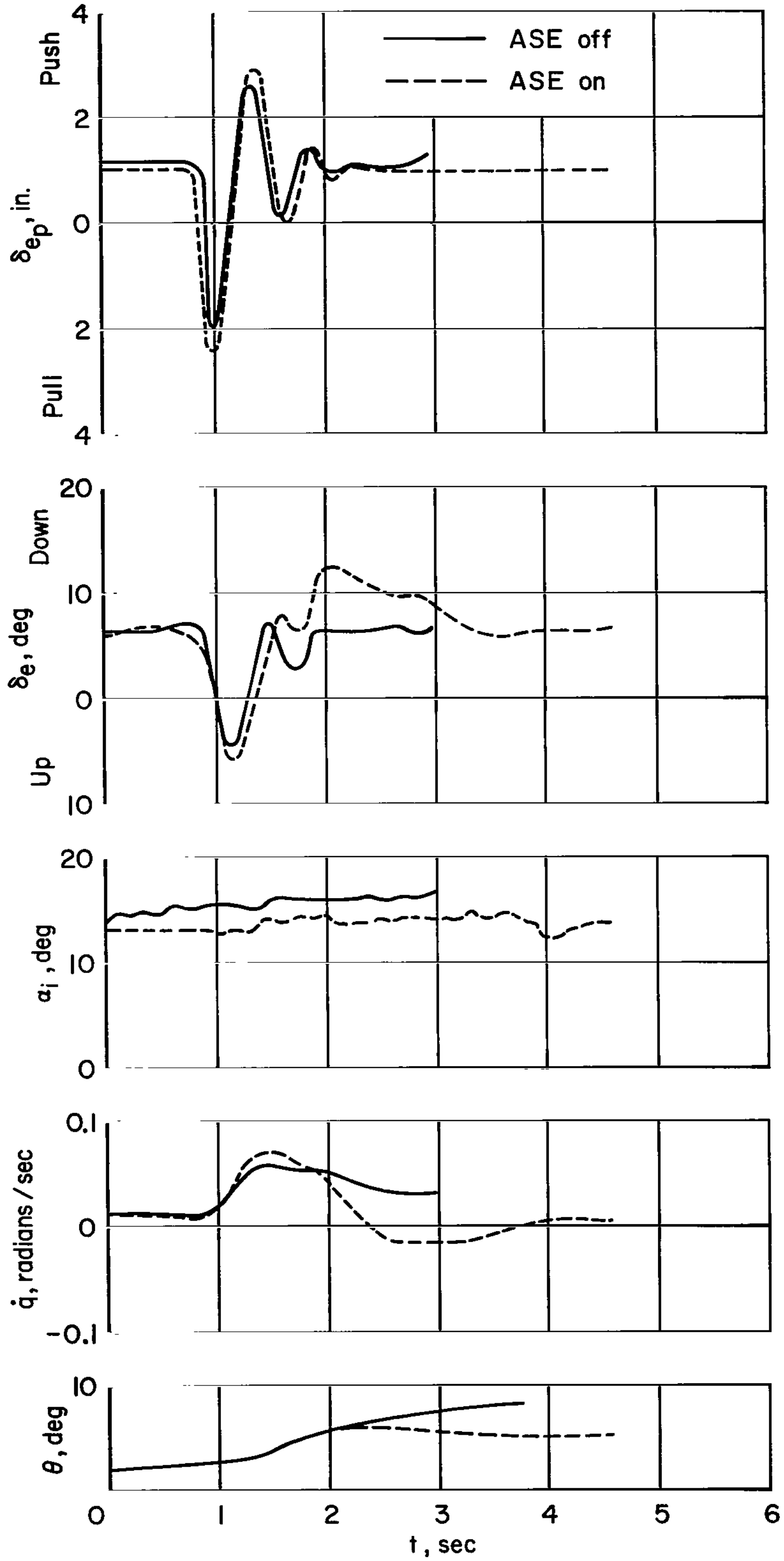


Figure 10.- Comparison of response to stick rap with ASE on and ASE off.

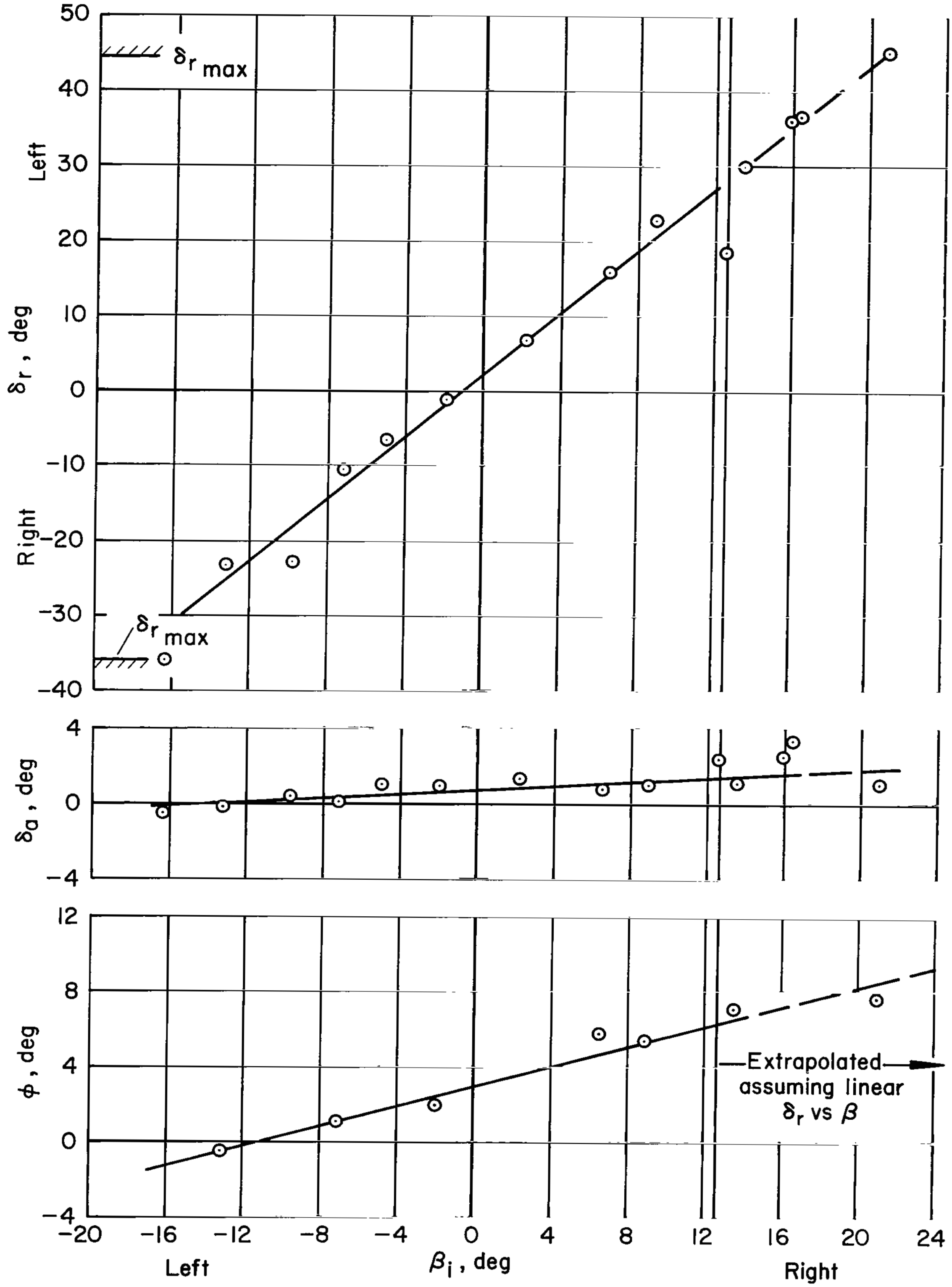


Figure 11.- Steady-state sideslip characteristics.

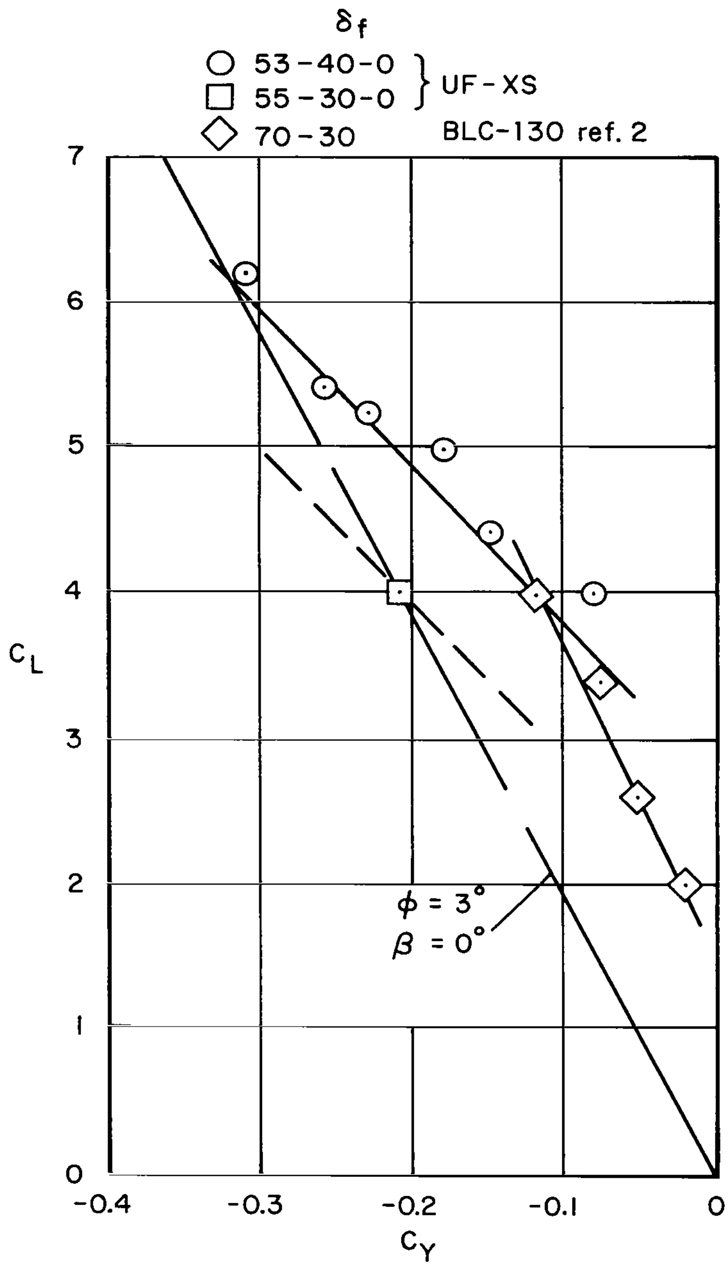


Figure 12.- Side-force characteristics with like-rotation propellers.

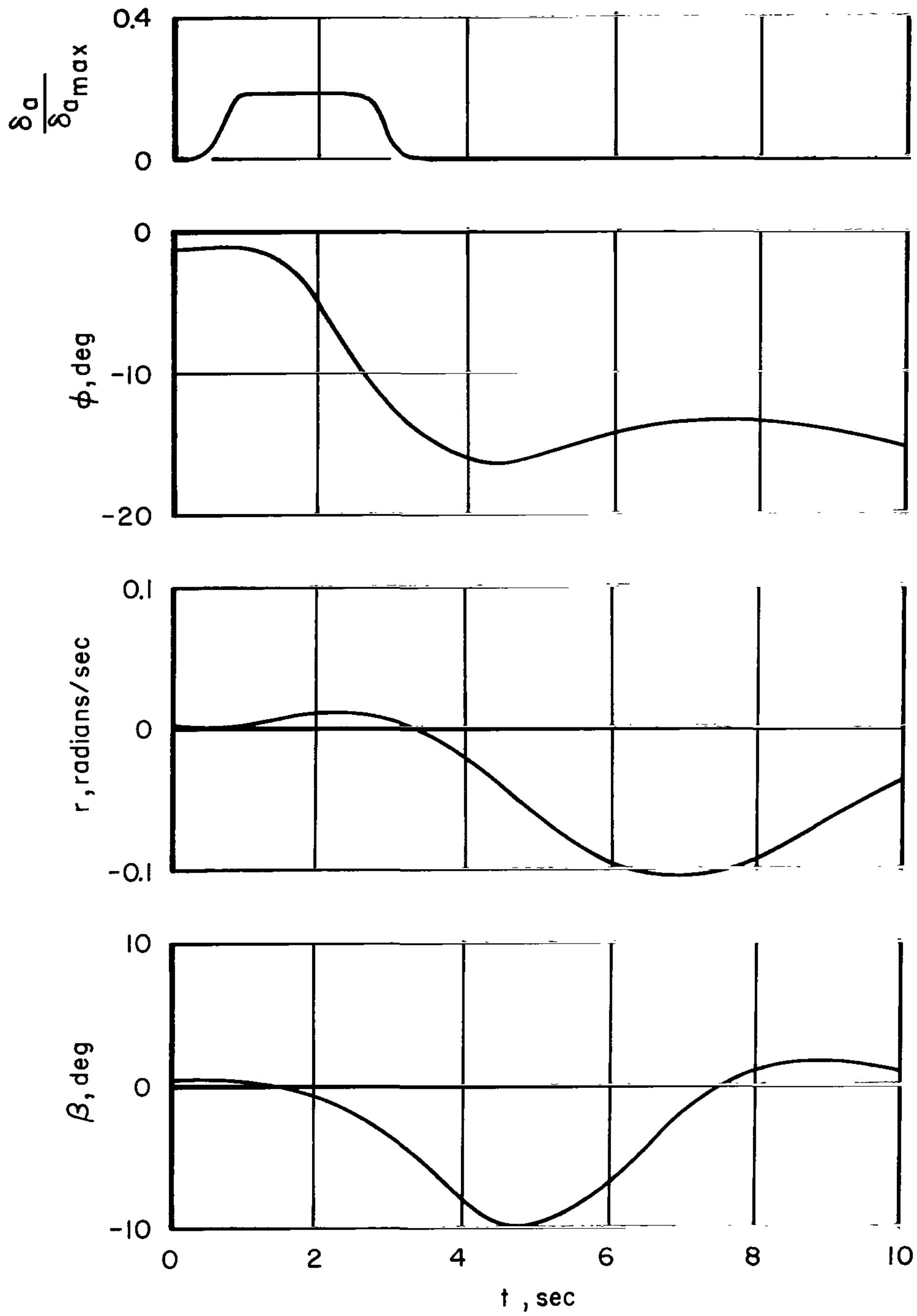
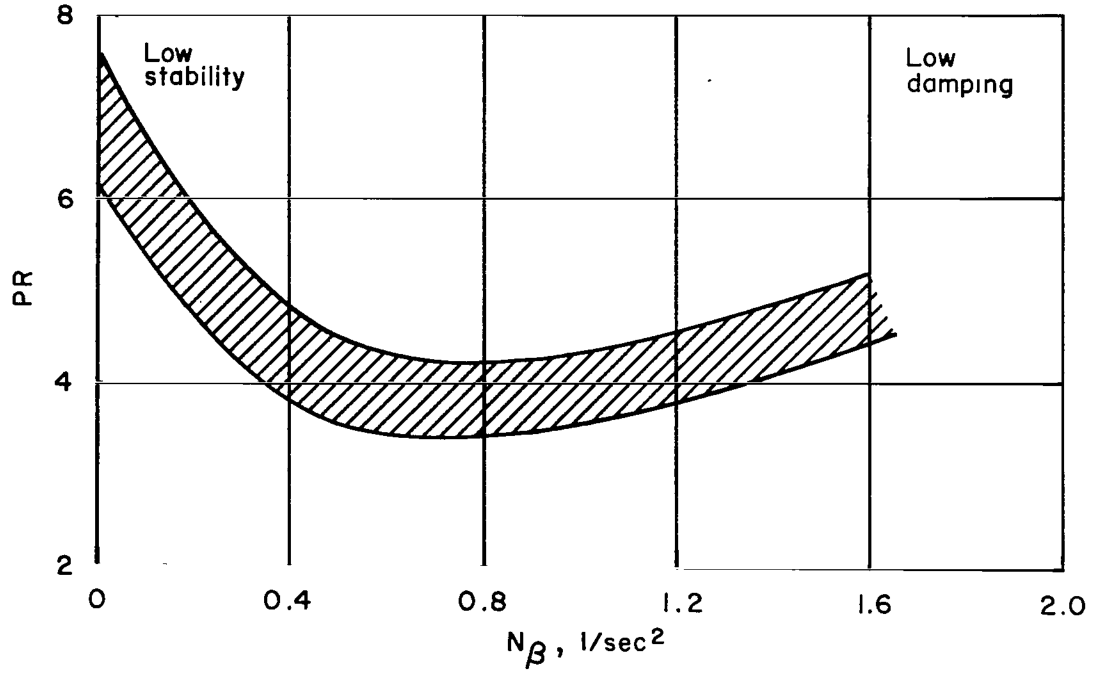
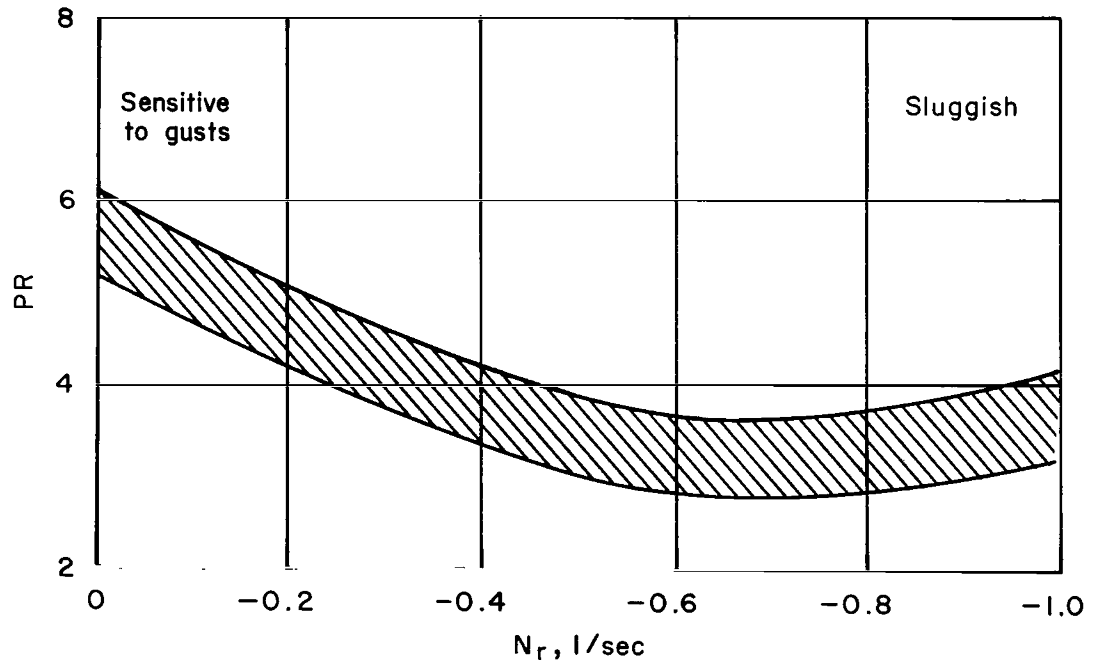


Figure 13.- Time history of typical lateral-directional oscillation following lateral control input for STOL aircraft; V ~ 60 knots.



(a) Directional stability, $N_r = -0.3$/sec



(b) Directional damping, $N_\beta = 0.5$/sec^2

Figure 14.- Effect of directional stability and damping; V = 50 to 60 knots, $N_{\delta_r}\delta_{r_{max}} = 0.2$ rad/sec^2, $L_\beta = 0$ to -0.3/sec^2, $Y_\beta = -0.1$/sec, $N_p = -0.1$/sec.

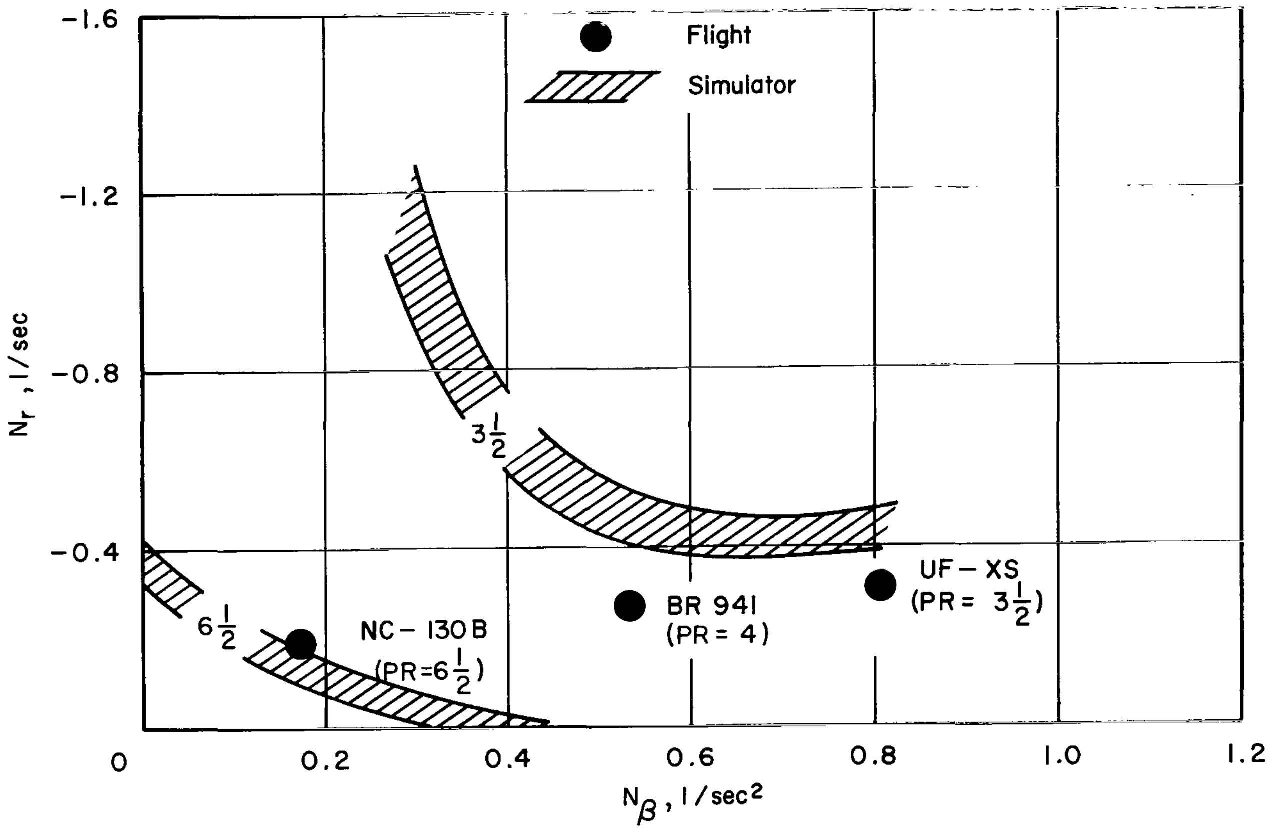
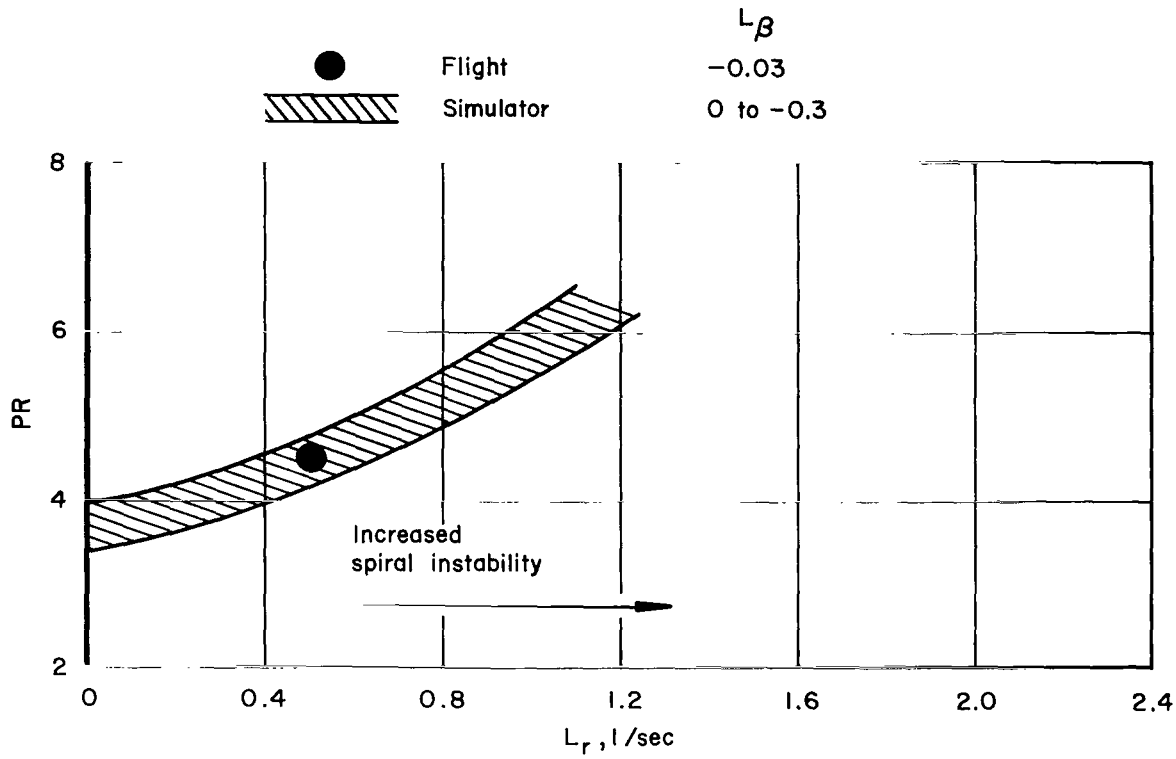
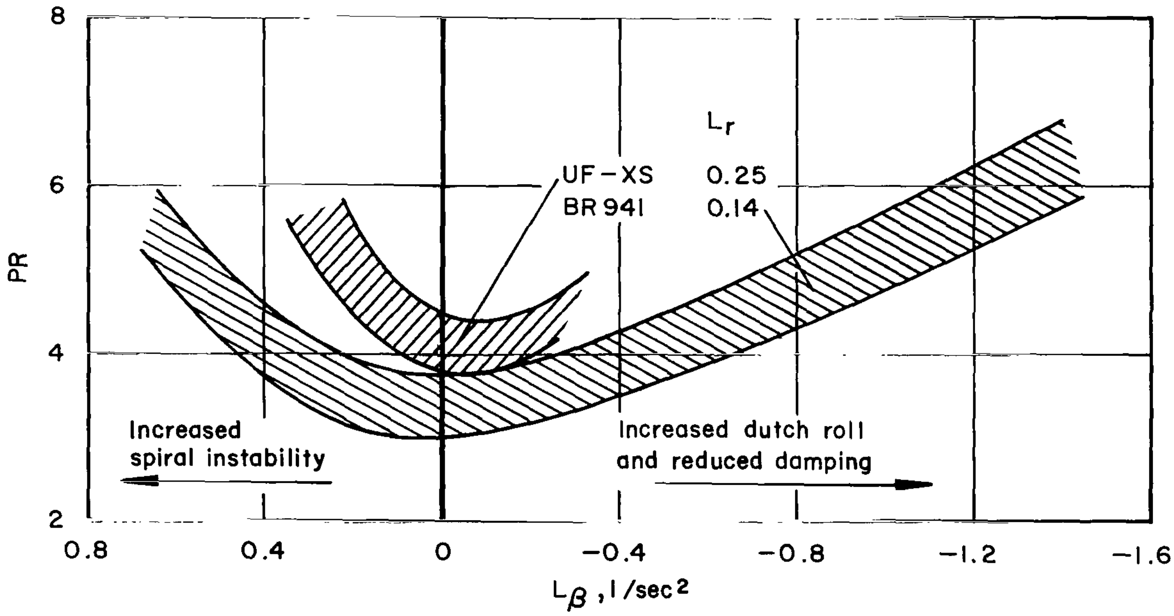


Figure 15.- Directional stability and damping boundaries for unaugmented aircraft with low cross coupling; V = 50 to 60 knots, $N_{\delta_r}\delta_{r_{max}}$ = 0.2 rad/sec^2, L_β = 0 to -0.3/sec^2, Y_β = -0.1/sec, N_p = -0.1/sec.

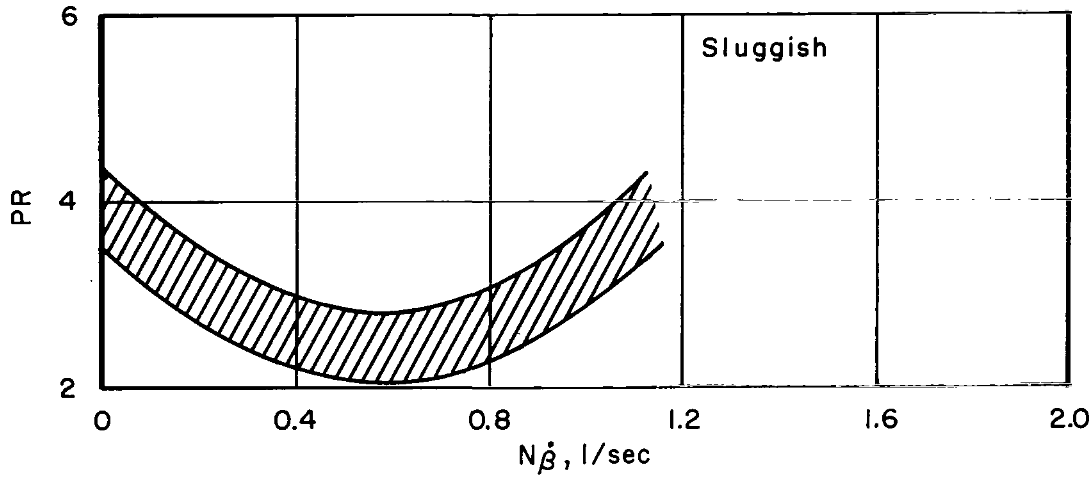


(a) Roll due to yaw rate

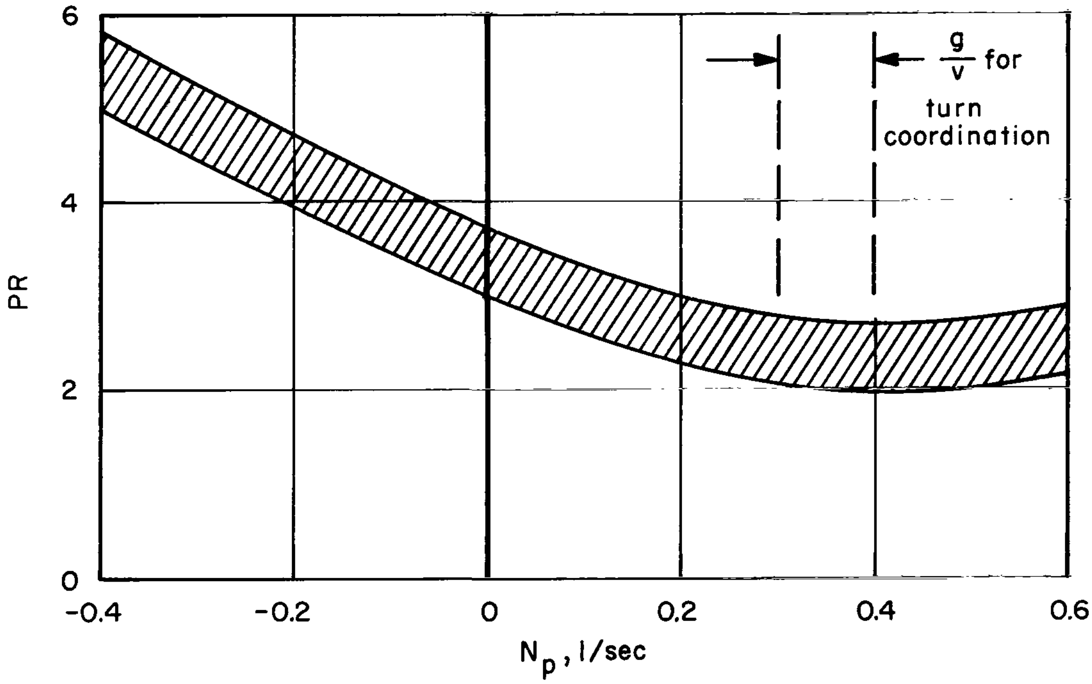


(b) Dihedral effect

Figure 16.- Effect of lateral parameters on pilot opinion; ASE off, V = 50 to 60 knots, $N_\beta = 0.5/\text{sec}^2$, $N_r = 0.3/\text{sec}$.



(a) Damping due to sideslip rate



(b) Yaw due to roll rate

Figure 17.- Augmentation to improve turn coordination; V = 50 to 60 knots, $N_\beta = 0.5/\text{sec}^2$, $N_r = -0.3/\text{sec}^2$, $N_{\delta_r}\delta_{r_{max}} = 0.2\ \text{rad/sec}^2$, $L_\beta = 0$ to $-0.3/\text{sec}^2$, $Y_\beta = -0.1/\text{sec}$, $N_p = -0.1/\text{sec}$.

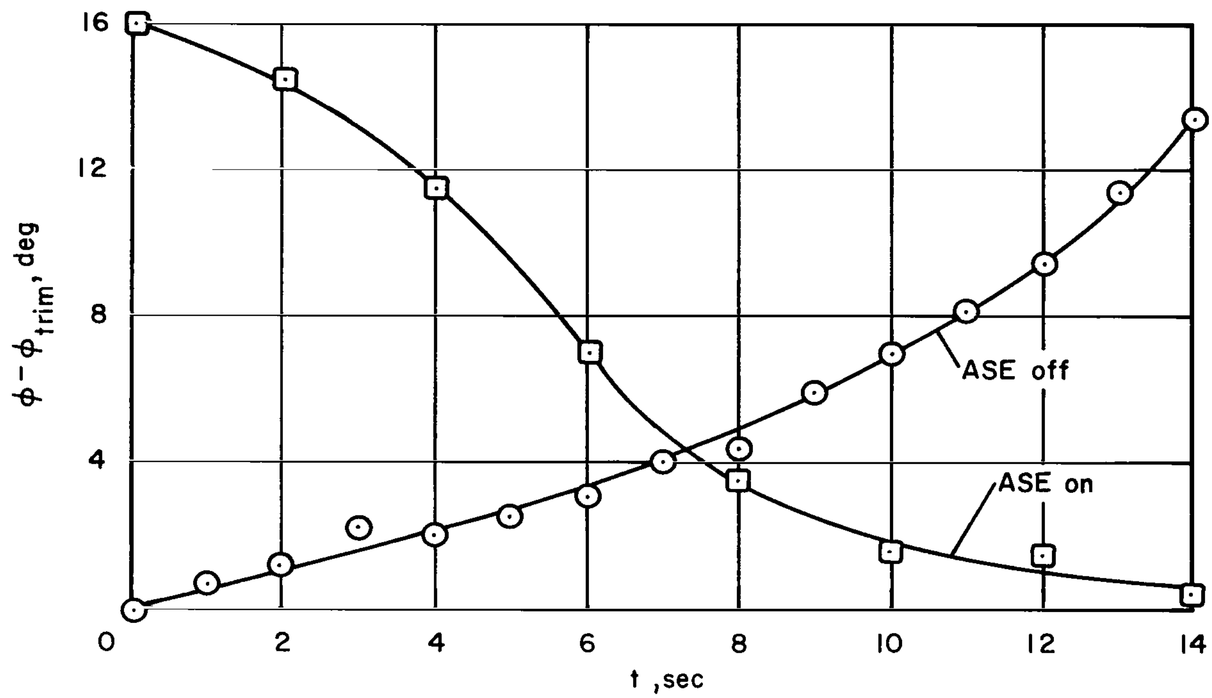


Figure 18.- Flight time history of bank angle change with controls trimmed for 3° bank.

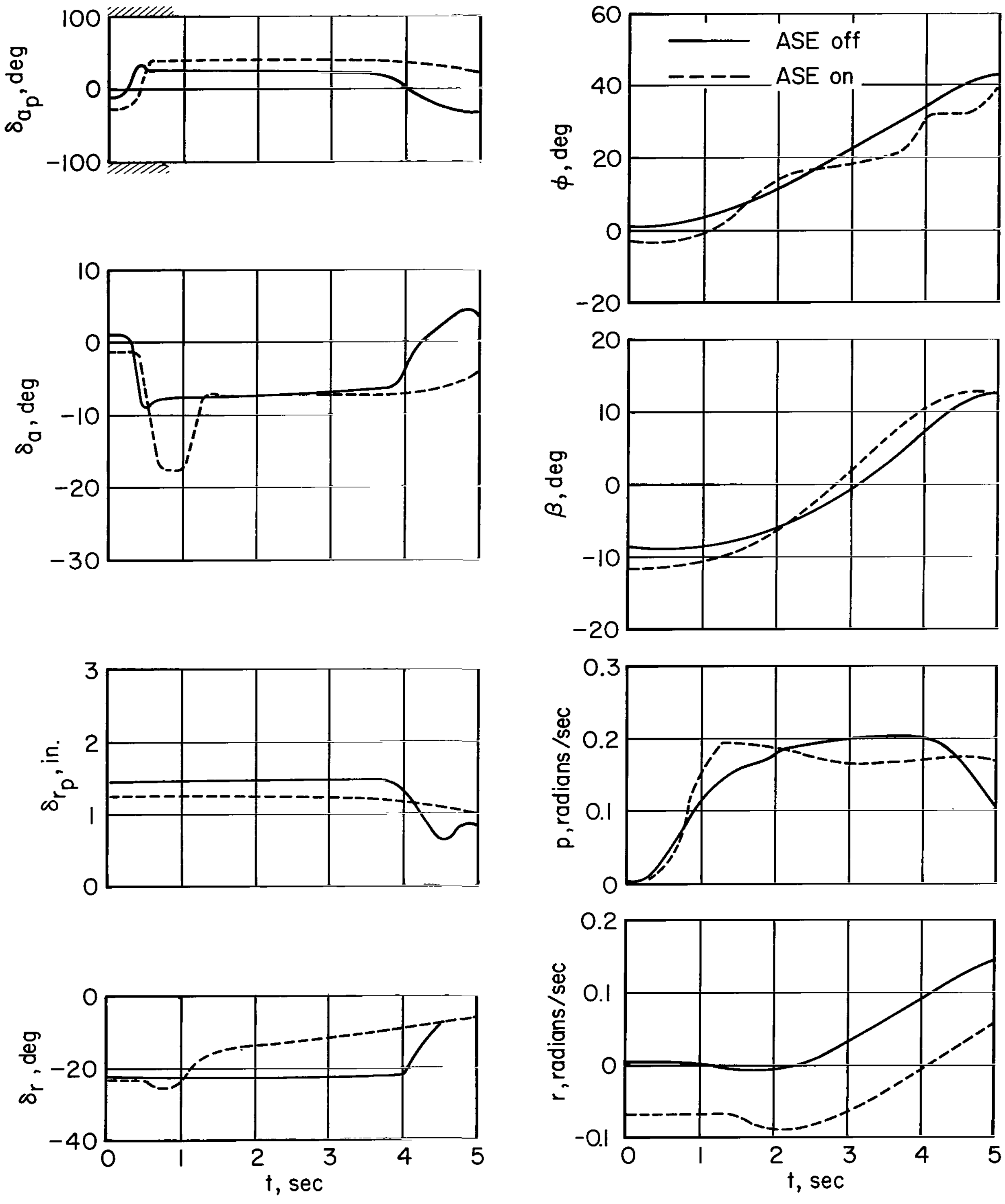


Figure 19.- Comparison of response due to aileron step with ASE on and off, in flight.

NASA-Langley, 1965 A-2082

3/12/85

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Technical information generated in connection with a NASA contract or grant and released under NASA auspices.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

TECHNICAL REPRINTS: Information derived from NASA activities and initially published in the form of journal articles.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities but not necessarily reporting the results of individual NASA-programmed scientific efforts. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546