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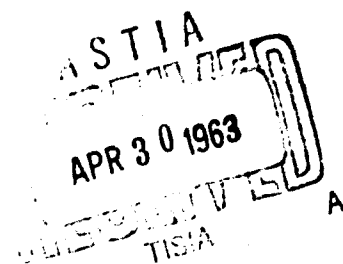
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A SIMULATOR STUDY
OF TILT-WING HANDLING QUALITIES

by

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March 1963



Approved by: *Charles E. Mack, Jr.*
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FOREWORD

The study of tilt-wing handling qualities reported herein was sponsored by the Bureau of Naval Weapons and conducted at the Grumman Aircraft Engineering Corporation, Bethpage, New York, during the period June 1960 to May 1962 under Contract No. N0w 60-0396-c.

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ABSTRACT

An experimental investigation was performed to study handling qualities of tilt-wing type VTOL aircraft. A flight simulator consisting of a cockpit free to pitch and roll, and an optical display system providing a visual illusion of motion in the remaining four degrees of freedom was employed in this program. Qualified pilots operated both a longitudinal three degree of freedom and a six degree of freedom mechanization of a simulated 15,000 pound tilt-wing type VTOL airplane. Four pilots evaluated over 350 configurations at hover and during continuous transitions in calm air and under visual flying conditions.

Control sensitivity and rate damping requirements about each axis at hover were investigated relative to the performance of maneuvering tasks that require, in general, more positive control applications than "trimming" and more finely coordinated multiple control utilization than single degree of freedom "move and stop maneuvers." That handling qualities requirements depend upon the maneuver in which they are measured and the degree of simulator sophistication is clearly suggested by comparing the results of the present study with published NASA data representing the extremes in the "maneuver spectrum."

Control response-time characteristics, as well as control, aerodynamic rate, and gyroscopic coupling effects were also investigated at hover. The results of the control response-time variations are most interesting, for they suggest that the criterion upon which present helicopter specifications are based (i.e., time to reach proper direction of acceleration) is inadequate.

Transition handling qualities are discussed primarily with regard to whether satisfaction of hover derived criteria is sufficient to ensure good handling qualities for the performance of the transition maneuver. That is, "do handling qualities remain acceptable during a transition maneuver if rate damping and control sensitivity, which are allowed to vary in typical fashion, always remain within the acceptable hover boundaries?" Several parameters unique to VTOL designs (e.g., wing tilt rate) are also discussed in light of their effects on transition handling qualities.

The critical result here is that handling qualities criteria derived from hover or steady flight experimentation cannot, in general, be stretched to include nonsteady (e.g., transition) flight.

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LIST OF SYMBOLS

a	distance between rotating body pivot point and rotating body cg
$A_1, A_2, \dots$	constant coefficients used in the functional representation of the dependence of the inertia properties of the vehicle on wing incidence
b	distance between rotating body pivot point and fixed body cg
g	acceleration due to gravity
GC_H	ratio of $(I_E^\Omega)_H$ to the pitch inertia
GC_V	ratio of $(I_E^\Omega)_V$ to the pitch inertia
i_W	wing incidence angle
I_E	moment of inertia of rotating gyroscopic mass
$(I_E^\Omega)_H$	angular momentum of rotating gyroscopic mass about the x body axis
$(I_E^\Omega)_V$	angular momentum of rotating gyroscopic mass about the z body axis
I_x	total vehicle moments and product of inertia referred to total vehicle body axes
I_y	
I_z	
I_{xz}	
I_{x_w}	principal moments of inertia of rotating body
I_{y_w}	
I_{z_w}	

I_{x_f}	
I_{y_f}	
I_{z_f}	moments and product of inertia of fixed body referred to axes at the fixed body cg and parallel with the total vehicle body axes
I_{xz_f}	
$L_1, L_2, \dots$	constant coefficients in equation of roll motion
L_p	roll rate damping to inertia ratio (sec^{-1})
L_v	roll acceleration due to side velocity (rad/sec^2)/(ft/sec)
$L_{\delta_{LAS}}$	roll acceleration per inch of lateral control stick motion ($\text{rad/sec}^2/\text{in.}$)
$L_{\delta_{RP}}$	roll acceleration per inch of rudder pedal motion ($\text{rad/sec}^2/\text{in.}$)
$M_0, M_1, M_2, \dots$	constant coefficients in equation of pitch motion
M_f	mass of the fixed body (fuselage and tail)
M_Q	pitch rate damping to inertia ratio (sec^{-1})
$(M_Q) U^2$	rate of change of M_Q with U^2 ($1/\text{sec}$)/(ft/sec) ²
M_T	total mass of the vehicle
M_W	mass of the rotating body (wing)
$M_{\delta_{cp}}$	pitch acceleration per degree of blade pitch at 45 degrees of wing incidence
$M_{\delta_{LOS}}$	pitch acceleration per inch of longitudinal control stick motion ($\text{rad/sec}^2/\text{in.}$)

$(M_{\delta_{LOS}}) U^2$	rate of change of $M_{\delta_{LOS}}$ with U^2 (rad/sec ² /in.)/(ft/sec) ²
$N_1, N_2, \dots$	constant coefficients in equation of yaw motion
N_P	yaw acceleration due to roll rate (sec ⁻¹)
N_R	yaw rate damping to inertia ratio (sec ⁻¹)
$N_{\delta_{LAS}}$	yaw acceleration per inch of lateral control motion (rad/sec ² /in.)
$N_{\delta_{RP}}$	yaw acceleration per inch of rudder pedal motion (rad/sec ² /in.)
P.R.	pilot rating in units of Cooper pilot opinion scale
P, Q, R	angular velocities about x, y, and z body axes respectively
S	Laplacian operator
t_{cp}, τ_{cp}	time delay and first order time lag in δ_{cp}
t_{LAS}, τ_{LAS}	time delay and first order time lag in δ_{LAS}
t_{LOS}, τ_{LOS}	time delay and first order time lag in δ_{LOS}
t_{RP}, τ_{RP}	time delay and first order time lag in δ_{RP}
t_{WR}, τ_{WR}	time delay and first order time lag in WR
U, V, W	linear velocities along x, y, and z body axes respectively
WR	rate of change of wing incidence angle (positive in the wing up direction)
WR*	rate of change of wing incidence angle when response to wing rate control is instantaneous (i.e., $WR^* = WR$ when $t_{WR} = \tau_{WR} = 0$)

$x_0, x_1, x_2, \dots$	constant coefficients in aerodynamic and control force representations along x body axis
$x \epsilon_{LOS}$	acceleration along x body axis per inch of longitudinal control (ft/sec ² /in.)
$y_0, y_1, y_2, \dots$	constant coefficients in aerodynamic and control force representations along y body axis
$z_0, z_1, z_2, \dots$	constant coefficients in aerodynamic and control force representations along z body axis
β_{cp}	propeller blade pitch angle
$\bar{\epsilon}$	angle between $\bar{b}$ and x body axis taken
$\bar{\epsilon}_{cp}$	effective (lagged or delayed) displacement of collective pitch lever from setting for $\beta_{cp} = 16^\circ$
$\bar{\epsilon}_{LAS}$	effective (lagged or delayed) lateral displacement of control stick
$\bar{\epsilon}_{LOS}$	effective (lagged or delayed) longitudinal displacement of control stick
$\bar{\epsilon}_{RP}$	effective (lagged or delayed) displacement of rudder pedals
$\bar{\delta}_{CP}^*$	displacement of collective pitch lever from setting for $\beta_{cp} = 16^\circ$ (positive, up)
$\bar{\delta}_{LAS}^*$	lateral displacement of control stick (positive, right)
$\bar{\delta}_{LOS}^*$	longitudinal displacement of control stick (positive, rearward)
$\bar{\delta}_{RP}^*$	displacement of rudder pedals (positive, right pedal forward)
ϵ	angle between $\bar{a}$ and principal x axis of the rotating body

ψ
 θ
 ϕ
 Ω

yaw, pitch and roll angles of body axis system
relative to earth axes

rotational speed of rotating gyroscopic mass

INTRODUCTION

Flying a VTOL aircraft is often a hazardous operation. This has been graphically demonstrated in the past several years by the poor natural handling qualities exhibited by many flying test bed VTOL aircraft. One of the major contributions of test bed programs has been to demonstrate the urgent need to specify VTOL flying qualities requirements. The problem is complex, however, and a final set of requirements will not evolve rapidly. As in the development of airplane flying qualities specifications, we can expect that only after much theoretical, simulator, and flight test research will VTOL flying qualities specifications approach maturity, and even then, they will be subject to constant revision, according to experience gained with operational VTOL craft.

In this report, we present the results of a moving base, piloted, simulator research study, performed to obtain data helpful to a basic understanding of the problems associated with piloting VTOL airplanes. In so doing, we hope to hasten the precise specifying of VTOL flying qualities requirements.

DISCUSSION

Approach to the Problem

Many studies of handling qualities have been performed by various investigators (Refs. 1 through 7). They range from the mathematical analysis of linear systems approximating the pilot by a transfer function (Ref. 1) to experimentation with real, variable stability aircraft (Ref. 7). Between these is a wide variety of studies with flight simulators of all types (Refs. 2 through 6). Most of the VTOL work has been concerned with the two "maneuver spectrum" extremes, characterized by the tight trimming tasks studied by Salmirs and Tapscott (Ref. 7) and the gross, single degree of freedom, attitude changes investigated by Faye (Ref. 3). There has been a dearth of information regarding VTOL handling qualities requirements for the performance of precision maneuvering tasks (for example constant altitude, zero forward speed lateral displacement from one hovering spot to another). Such maneuvers, performed in calm air under visual flying conditions, represent the everyday flying that might be encountered in VTOL craft at hover. They require precisely coordinated applications of attitude and power controls accompanied by continuous attention to trimming with the remaining controls.

In general, tight trimming tasks tend to exaggerate vehicle stability requirements, while gross attitude-change tasks tend to exaggerate control requirements. Precision maneuvering tasks, on the other hand, afford a realistic test of stability and control requirements in combination. Furthermore, it would seem that only the commonly performed maneuvers need be made easy by the provision of good handling qualities, and that the less frequent extremes in the maneuver spectrum do not demand ease of performance unless some operational mission is dependent upon them.

The transition in a VTOL aircraft is a most dramatic flight regime, different from anything experienced in helicopters or ordinary airplanes. Handling qualities during transition have not been investigated nearly as much as those at hover, probably because the transition is a maneuver that does not lend itself to established methods of analysis. It is an acceleration or deceleration between zero and perhaps 150 knots, during which the vehicle configuration is changed drastically, forces and moments vary nonlinearly with speed and angle of attack, and the pilot must continuously exercise the controls.

In some studies (e.g., Ref. 2) the transition maneuver has been analyzed with reference to oscillatory characteristics, expressed in terms of natural frequency and time to half-amplitude. It is recognized that oscillatory characteristics have a profound effect on flyability and that such studies are therefore valuable. But the question does arise as to whether VTOL motion characteristics are truly separable into oscillatory and aperiodic parts. If so, we might further question whether natural frequency and time to half-amplitude, which are defined only for controls fixed linear perturbations about steady state flight conditions, afford a true representation of oscillatory characteristics during a transition maneuver.

This study avoided the problem by experimenting directly with those aerodynamic and control terms which usually exhibit profound effects on vehicle motion and handling qualities, and with parameters unique to VTOL designs which could affect handling qualities. Thus, the transition study was reduced to a study of the variation of control sensitivity and rate damping with forward velocity, and of several unique VTOL parameters such as wing rate, wing rate control response-time characteristics, pitching moment due to collective pitch, etc. The static aerodynamics were not varied because they were coupled and highly nonlinear over the transition speed range, making meaningful parameterization impossible.

It was hoped thus to learn whether acceptable hover-defined boundaries on the pitch rate damping, control sensitivity plane were valid for the transition maneuver, i.e., would flight characteristics, acceptable by hover criteria, be made unacceptable by their variation during transition? It was further desired to learn the effect on these results of parameters unique to VTOL designs. Based upon fixed static aerodynamics, however, the results would only apply to the general class of tilt-wing aircraft unless it could be shown that the handling qualities in transition are independent of static aerodynamics or that other VTOL configurations exhibit similar characteristics.

The Simulator

The moving base simulator employed in this study comprised a cockpit free to roll and pitch and an optical display system providing a visual illusion of motion in the remaining four degrees of freedom.

The cockpit was equipped with a set of primary flight controls, with rudder pedal travel of ± 2 inches and control stick travel of ± 5 inches longitudinally and ± 5 inches laterally. A collective pitch lever was also provided, and a longitudinal trim button on the control stick was used as the wing tilt control.

Cockpit instrumentation was provided to display collective pitch setting, wing tilt position, vehicle pitch attitude, forward velocity, altitude, and rate of climb. Figure 1 shows the cockpit in a rolled and pitched attitude. On a screen (measuring 8 ft by 13 ft and placed 8 ft in front of the cockpit) the visual display system projected a moving roadway and a fixed horizon. Shape, position, and orientation of the projected roadway were changed in proper perspective to depict vertical, transverse, and directional motions of the vehicle. The illusion of forward and backward velocity was provided by the motion of tabs along the edge of the roadway. Figures 2, 3, 4, and 5 show the realistic visual illusion provided.

The complete device afforded simulated freedom of motion within the following limits:

Altitude	$+8$ to $+300$ feet (measured at the pilot's eye)
Transverse displacement	± 150 feet from centerline of roadway
Roll (ϕ)	± 25 degrees
Pitch (θ)	± 15 degrees
Yaw (ψ)	± 40 degrees
Velocities	± 100 knots parallel to the roadway
	± 20 ft/sec both vertically and laterally

Detailed information on the simulator acceleration capabilities and response characteristics can be found in Ref. 8. For this study, they were more than adequate.

Equations of Motion

This section of the report discusses the analytical development of the analog computer working equations (see Table I) for the complete six degrees of freedom motion of a 15,000 pound tilt-wing VTOL vehicle. The choice of the tilt-wing design for evaluation was primarily influenced by the abundance of existing experimental static aerodynamic data for two, tilt-wing aircraft.

The static aerodynamic data utilized in this formulation are those wind tunnel data accumulated by Vertol (in collaboration with NASA) using a 1/4-scale powered model of the Vertol 76 aircraft (Refs. 9 and 10). For the purpose of representing a generalized tilt-wing vehicle design, these data were compared (via a scaling process) to those obtained from the Hiller X-18 model tests (Ref. 11). The comparison was favorable, indicating that basic tilt-wing vehicle aerodynamic behavior for a class of tilt-wing vehicles could be formulated in a general fashion, with the help of appropriate scaling factors, from the Vertol 76 model data. Hovering, ascent, and descent data were estimated from available data at low forward speed ascent and descent conditions.

Analytical expressions representing static aerodynamic properties were developed from the data by the "Forward Doolittle" method (Ref. 12), with the aid of a special digital computer program (Ref. 13). These expressions were developed in the form of polynomials giving the total forces and moments relative to body axes. This eliminates the problem of handling cumbersome (and usually nonlinear) conventional aerodynamic coefficients and removes the need for determining angle of attack (undefined at hover), permitting a unified simulation of hovering, transition, and airplane mode flight.

Rate damping effects were considered to be primary variables, and each was represented by a fixed hover value and a variation in transition roughly proportional to dynamic pressure. This variation was based on an unpublished theoretical analysis which showed pitch rate damping to vary as the square of velocity in the speed range from 0 to 140 knots. Although experimental data could not be found to check this, it will be shown that for the results of this study the velocity-squared variation is conservative. Aerodynamic cross coupled rate effects were estimated and assumed not to vary with flight condition.

Control data were also obtained mainly from the 1/4-scale powered model windtunnel experiments, and were similarly represented by a hover value (tail rotor or reaction controls) and a forward velocity variation. Coupled control effects (e.g., yaw due to roll control) from the phasing of aerodynamic surface and propeller controls during transitional flight were represented as functions of wing incidence and forward velocity. Variable delays and first order time lags were included in the control representation, as depicted in part G of Table I. Rudder pedal and lateral stick force gradients were constant at 5-pounds per inch and 1-pound per inch respectively. Longitudinal stick force gradient, however, was 1-pound per inch for the first inch and 1/2-pound per additional inch.

The rates of change of angular momentum, including rotating mass gyroscopic effects, are shown in Part B of Table I, and Part E shows the dependence of total vehicle moments and products of inertia on wing tilt position and vehicle geometry. Supplemental analysis showed that angular momentum changes and wing mounted engine gyroscopic moments resulting from wing tilting could be neglected. These deletions make the equation form for the rates of change of angular momentum (Part B of Table I) analogous to that presented in Ref. 14.

Table II gives the values assigned to the coefficients in the equations of motion presented in Table I.

Test Procedure

Qualified pilots were asked to perform specified maneuvering tasks with various simulated tilt-wing VTOL aircraft configurations in still air under visual flight conditions, and to quantify their evaluation of each configuration in terms of the Cooper pilot opinion numerical rating scale (Ref. 15). Three helicopter pilots and a conventional airplane pilot (whose backgrounds are listed in Table III) participated in the evaluation of over 350 separate configurations at hover and during transition. Because none of the pilots had ever participated in a study of this nature, each was required to fly several hours of indoctrination. This consisted of both hovering and transitional flight in which exposure to a wide range of vehicle parameters helped familiarize them with the extremes of flyability that they would be expected to evaluate. Not until the pilots had demonstrated proficiency in flying the simulated craft did experimentation begin. As a

check on how well the indoctrination phase had served its purpose, the time that each pilot had logged in the simulator prior to making each evaluation was recorded during the first experimental period. Analysis of these data indicated that the pilots' learning had substantially reached saturation during the indoctrination phase. This conclusion was confirmed by the results of some repeated experiments made, unknown to the pilots, during the first period; re-evaluation never changed a report by more than one unit on the pilot rating scale, and no trend either to upgrade or downgrade was exhibited. These results were considered convincing, and no further checks of the phenomenon were made.

Five different maneuvering tasks were used in the evaluation of handling qualities about the roll, pitch, and yaw axes at hover and in accelerating and decelerating transitions. These tasks were:

- | | |
|---------|---|
| TASK HP | From hover over the center of the runway, perform a constant altitude acceleration to 10 knots. |
| TASK HR | From hover over the center of the runway, perform a constant altitude, zero forward speed lateral displacement to hover over the edge of the runway. |
| TASK HY | From hover over the center of the runway but directionally misaligned with it ($\psi = \pm 20^\circ$), perform a pure directional change so as to align the vehicle with the runway. |
| TASK TA | Perform a constant altitude transition from hover (wing incidence 86°) to forward flight (wing incidence 30°). |
| TASK TD | From a trimmed flight condition of 80 knots forward speed, 40° wing incidence at an altitude of 200 ft, descend at 500 ft per minute to an altitude of 100 ft, flare and decelerate at constant altitude to hover. |

As is obvious from their definition, TASKS HP, HR, and HY were concerned with hovering handling qualities about the pitch, roll, and yaw axes respectively, while TASKS TA and TD were concerned with handling qualities during accelerating and decelerating transitions. In each, the pilots were required to perform the appropriate maneuver at least twice before assigning a rating to a configuration. Most often they performed it three to four times. To augment the Cooper scale definitions the pilots gave written comments as well as numerical ratings for virtually all of the configurations evaluated.

In addition to the pilot opinion data collected, pilot control and vehicle motion time histories were recorded on magnetic tape. Unfortunately, however, time has so far not permitted analysis of this information.

Data Analysis

During the roll and yaw axis experimentation at hover (TASK HR and HY), and during the decelerating transition (TASK TD) pilot opinion data were taken, averaged, and plotted in a straightforward manner. This was not the case, however, for the data taken during the pitch axis experimentation at hover (TASK HP) and during the accelerating transition (TASK TA). Here, fractional experimental design techniques were used to select the experimental test points, and a response surface technique was used to analyze the data taken. To provide a uniform subcovering of the experimental spaces considered, the "Random Balance" method of F.E. Satterthwaite (Ref. 16) was used to select the test points. Response surfaces were generated by a least squares fitting technique mechanized for digital computer calculation (Ref. 13). This technique determined, from the experimental data, least squares coefficients for a polynomial model expressing pilot opinion as a function of linear, quadratic, and first order interaction effects of the experimental variables. The computer program determined coefficients for only those polynomial terms with a preassigned value of statistical significance.

The response surface method of data analysis allowed the experimental results of TASKS HP and TA to be summarized by single functions relating pilot rating to the experimental variables. From these functions any desired "cross section" plots could be made within the range of experimentation considered.

EXPERIMENTATION AND RESULTS

Longitudinal Handling Qualities at Hover

Longitudinal handling qualities at hover were studied with only the three longitudinal degrees of freedom operating (pitch, altitude, and forward velocity). All 4 pilots performed TASK HP, examining 46 configurations in which pitch rate damping M_Q , pitch control sensitivity $M_{\delta_{LOS}}$, forward acceleration due to pitch control coupling $X_{\delta_{LOS}}$, and longitudinal control system delay t_{LOS} , and first order time lag τ_{LOS} , were varied. The following ranges of investigation were considered.

$$0.00 \leq M_Q \leq 2.50 \text{ sec}^{-1}$$

$$0.05 \leq M_{\delta_{LOS}} \leq 0.50 \text{ rad/sec}^2/\text{in.}$$

$$-2.00 \leq X_{\delta_{LOS}} \leq 0.00 \text{ ft/sec}^2/\text{in.}$$

$$0.00 \leq t_{LOS} \leq 0.30 \text{ sec}$$

$$0.00 \leq \tau_{LOS} \leq 0.30 \text{ sec}$$

Five levels of each of the five variables were chosen. The 46 configurations were obtained as 46 random combinations of these (Ref. 16).

The control system response-time characteristics, t_{LOS} and τ_{LOS} , were simulated on the analog computer by combinations of

linear elements. Thus a true time delay could not be represented exactly, although the lag, a first order linear effect, was correct. The approximation actually provided is shown in Fig. 6 for various combinations of delay t_{LOS} and first order time lag τ_{LOS} .

Pilot ratings of the 46 configurations were averaged, and a polynomial in the 5 experimental variables was fit to the data (see Table IV). It turned out that the rating assigned to each of the configurations tested by any one pilot never varied from the average rating of the four pilots by more than one unit on the pilot opinion scale, and the between-pilot differences were consistent; some pilots always rating a little above the average, some always a little below. Graphical representation of the results, as in Figs. 7 through 14, are obtained from "cross-sectional" evaluation of the multivariable polynomial, and as such can show only faired curves since there is little likelihood that many of the randomly selected experimental points would fall exactly on a specific cross section.

In Fig. 7, the $M_Q, M_{\delta_{LOS}}$ plane is divided into regions of acceptability by lines of constant pilot opinion. This figure represents the "basic" case, in which vehicle response to control input is pure and instantaneous ($x_{\delta_{LOS}} = t_{LOS} = \tau_{LOS} = 0$), i.e., all variables zero except those on the coordinates. Figure 8 compares these results with similar results obtained by NASA

investigators Salmirs and Tapscott (Ref. 7) and Faye (Ref. 3). Although the differences are large, we feel they can be mostly attributed to differences in degree of sophistication of the "simulators" employed and of the tasks the pilots performed in making their evaluations; Salmirs and Tapscott's pilots performed an extremely tight trimming task, on instruments, in a real helicopter, while (for the data shown in Fig. 8) Faye's pilots performed large pitch attitude changes (15°) in a single degree of freedom, moving base simulator. Pilots in the present study performed a constant altitude, forward acceleration to 10 knots, in a moving base longitudinal three degree of freedom simulation.

Figure 9 shows how the basic region of acceptability depicted in Fig. 7 changes when response to control input is degraded by incorporation of the first order time lag τ_{LOS} . The effect is profound, especially when viewed in light of the requirement for longitudinal response to control input specified for helicopters in MIL-H-8501A (Ref. 17), and considered for V/STOL aircraft in Ref. 18, which requires that there be no objectionable delay in $\dot{\theta}$ following control displacement and that $\ddot{\theta}$ be in the proper direction within 0.2 second after control displacement. The present results show that the helicopter requirement is not adequate in two respects for VTOL craft at hover. First, as is evident in Fig. 9, degradation of handling qualities by first

order time lag is not independent of damping and control sensitivity, and second, but perhaps more important, the requirement for time to achieve proper direction of acceleration is at best incomplete since all values of the lag considered here gave instantaneous acceleration in the proper direction, reaching at least 63 per cent of the commanded value in time τ_{LOS} . Thus the requirement of MIL-H-8501A was always met no matter what the value of τ_{LOS} .

Figure 10 shows the variation of pilot rating with τ_{LOS} at the four combinations of $M_{\phi_{LOS}}$ and M_Q labeled 1, 2, 3, 4 in Fig. 9. This is another way to show the effect of τ_{LOS} on longitudinal handling qualities, and it is useful for comparison with other lag effects discussed later in the report.

The effect of "delay" t_{LOS} the other time factor described earlier and illustrated in Fig. 6, on handling qualities is shown in Fig. 11, where acceptable regions for different values of "delay" are compared with the basic acceptable regions of Fig. 7. The effect of t_{LOS} is smaller than that of τ_{LOS} (Fig. 9) and appears to saturate. These results are shown in Fig. 12 in a manner analogous to that of Fig. 10, with pilot rating plotted against t_{LOS} for the four values of M_Q and $M_{\phi_{LOS}}$ labeled 1, 2, 3, and 4 in Fig. 12. Here, the saturation, or leveling-off, of pilot rating with increasing t_{LOS} is more graphic. It should

be noted that handling qualities are most affected by τ_{LOS} (Figs. 9 and 10) and t_{LOS} (Figs. 11 and 12) when control sensitivity is high and rate damping low.

The variation of $X_{\delta_{LOS}}$ was included in the experimentation to simulate a cyclic pitch type of longitudinal control, where linear accelerations accompany commanded angular accelerations. Figure 13 shows how this factor shifts the basic acceptable region in the $M_Q, M_{\delta_{LOS}}$ plane, first expanding it slightly, then shrinking it drastically. It can be seen that for values of $X_{\delta_{LOS}}$ from 0 to $-0.5 \text{ ft/sec}^2/\text{in.}$ the acceptable boundary actually grows somewhat in the low damped region, but for smaller $X_{\delta_{LOS}}$ the whole acceptable region shrinks, vanishing for $X_{\delta_{LOS}} = -2 \text{ ft/sec}^2/\text{in.}$ (Grumman Design No. 242, a tilt-wing entry in the tri-service VTOL competition, was calculated to have $X_{\delta_{LOS}} = -0.33 \text{ ft/sec}^2/\text{in.}$) The effect of this coupling can be seen more clearly in Fig. 14, where the variation of pilot rating with $X_{\delta_{LOS}}$ is shown for the three combinations of M_Q and $M_{\delta_{LOS}}$ labeled 1, 2, and 3 on Fig. 13. It is important to remember here that the pilot was attempting to accelerate to a specific speed at constant altitude when evaluating these configurations. Thus, it would be expected that increasing a coupling which minimized the pitch attitude required would be beneficial until the coupling became too pronounced for close control of speed.

At this point, it is apropos to return briefly to Fig. 8 for further hypothesis about the apparent discrepancy between the results of the three studies. In the work of Salmirs and Tapscott an actual helicopter was used in which control sensitivity was varied by changing the gain of a servo system controlling cyclic pitch. For this type of control, we might reasonably expect a certain amount of forward acceleration coupling and less than instantaneous response to control application. So, it may be that the acceptable region defined by Salmirs and Tapscott is for a system containing some forward acceleration coupling and, particularly in the high control sensitivity region, a lag. This becomes interesting when we recall that for both $\tau_{LOS} > 0$ and $X_{\delta_{LOS}} < \dots 0.5 \text{ ft/sec}^2/\text{in.}$ The acceptable boundary determined in the present study moves toward the boundary determined by Salmirs and Tapscott, and that the largest discrepancy occurs between the boundary of Salmirs and Tapscott and those of the two zero lag, pure control, simulator studies.

Lateral Handling Qualities at Hover

Handling qualities in roll at hover were studied with the full six degree of freedom simulation. Three pilots participated in performing TASK HR to evaluate 80 different configurations (40 were evaluated by 2 pilots only). Experimental variables were roll control sensitivity $L_{\delta_{LAS}}$, roll rate damping L_p , roll

control system delay t_{LAS} and first order time lag τ_{LAS} , gyroscopic coupling GC_V (mass rotating about the z-body axis), yaw acceleration due to roll rate N_p , pitch acceleration lateral control coupling $M_{\delta_{LAS}}$, and yaw acceleration lateral control coupling $N_{\delta_{LAS}}$.

The following range of investigation were considered:

$$0.05 \leq L_{\delta_{LAS}} \leq 1.0 \text{ rad/sec}^2/\text{in.}$$

$$0 \leq L_p \leq 6 \text{ sec}^{-1}$$

$$0 \leq \tau_{LOS} \leq 0.6 \text{ sec}$$

$$0 \leq \tau_{LOS} \leq 0.6 \text{ sec}$$

$$0 \leq GC_V \leq 4 \text{ sec}^{-1}$$

$$0 \leq N_p \leq 0.8 \text{ sec}^{-1}$$

$$0 \leq M_{\delta_{LAS}} \leq 0.16 \text{ rad/sec}^2/\text{in.}$$

$$0 \leq N_{\delta_{LAS}} \leq 0.50 \text{ rad/sec}^2/\text{in.}$$

The more sophisticated, "optimized," experimental design techniques used for the longitudinal study were replaced here by a conventional "planar" setup which allowed the presentation of individual test points on the graphs.

Figure 15 shows, in a manner analogous to the longitudinal case (Fig. 7), the "basic" (all variables zero except those on

the coordinates) regions of handling qualities acceptability on the $L_{\tau_{LAS}}, L_p$ plane. Also shown on this plot are many of the experimental points, coded to show the average pilot evaluation of each.

Figure 16 compares the results of this study with those of Salmirs and Tapscott (Ref. 7) and Fay (Ref. 3). As before, we take note of the differences in type of maneuver performed by the pilots in the different studies and offer it as partial explanation for the differences in the boundaries. As before, these tasks were (for the data shown), a tight trimming task performed in a helicopter (Salmirs and Tapscott), a large attitude change (15° ; roll) in a single degree of freedom, moving base simulator (Faye), and a constant altitude, zero forward speed, lateral displacement from hover over one spot to another, in a moving base, six degree of freedom simulation (the present study).

Figure 17 shows the variation of average pilot rating with first order time lag (τ_{LAS}) in the lateral control for points 1, 2, and 3 on Fig. 16. The character of the effects of lateral and longitudinal first order time lag on lateral and longitudinal handling qualities, respectively (Figs. 17 and 10), are similar for comparable values of lateral and longitudinal control sensitivity and rate damping, but the longitudinal effect is slightly more pronounced.

Figure 18 shows the effect of lateral control "delay" t_{LAS} on lateral handling qualities for points 1, 3, and 4 on Fig. 16. It happens that the data at points 3 and 4 exhibited larger between-pilot differences than any other data taken in the study. For each pilot, however, ratings increased with increasing t_{LAS} , in the general manner shown. The values plotted are for the pilot who gave the best (lowest numerical) rating. The reader is cautioned again as to the meaning of "delay" as defined here (illustrated in Fig. 6). As in the case of first order time lags, there is a strong resemblance between longitudinal and lateral delay effects (Fig. 18 compared with Fig. 12). In this case, however, the effect on lateral handling qualities is more pronounced. The military helicopter specification (MIL-H-8501A, Ref. 17) for roll control requires that there be no objectionable or excessive delay in $\dot{\phi}$ in response to lateral or directional control displacements and that $\ddot{\phi}$ be in the proper direction within 0.2 sec for all flight conditions. As in the longitudinal case, for all values of first order time lag τ_{LAS} considered in this study, the helicopter requirement is met in the sense that $\ddot{\phi}$ is always in the proper direction instantaneously, indicating that time for $\ddot{\phi}$ to attain the correct sense is not an adequate VTOL performance criterion. Furthermore, if "delays" of the type considered here were allowed to become as large as 0.2 sec, they would seriously de-

grade flying qualities for some combinations of control sensitivity and damping.

It is interesting to note again for roll, as was true for pitch, that acceptable configurations are least susceptible to handling qualities degradation due to control system delay or first order time lag when rate damping is relatively high and control sensitivity relatively low (Figs. 17 and 18).

The effect of gyroscopic coupling GC_V on handling qualities is shown in Fig. 19 for the combinations of $L_{\delta_{LAS}}$ and L_p labeled 5, 6, 7, and 8 in Fig. 16. Handling qualities obviously deteriorate rapidly with increased gyroscopic coupling, and the effect appears to be quite independent of rate damping or control sensitivity at the levels considered.

Other parameters varied in this part of the study N_p , $M_{\delta_{LAS}}$ and $N_{\delta_{LAS}}$ produced only small, spurious and inconsistent variations in pilot rating, which is attributed at least partially to the nature of the maneuver considered (TASK HY), in which roll rates and roll control applications never become large.

Directional Handling Qualities at Hover

Directional handling qualities at hover were studied with the full six degree of freedom simulation. Three pilots participated in performing TASK HY to evaluate 70 different configurations (35 by 2 pilots only). Variables in these experiments were

yaw control sensitivity, $N_{\delta_{RP}}$, yaw rate damping, N_R , delay t_{RP} and first order time lag, τ_{RP} , in vehicle response to yaw control inputs, and gyroscopic coupling caused by a mass rotating about the x body axis, GC_H .

The following ranges of investigation were considered.

$$0.25 \leq N_{\delta_{RP}} \leq 6.0 \text{ rad/sec}^2/\text{in.}$$

$$0 \leq N_R \leq 8 \text{ sec}^{-1}$$

$$0 \leq t_{RP} \leq 0.6 \text{ sec}$$

$$0 \leq \tau_{RP} \leq 0.6 \text{ sec}$$

$$0 \leq GC_H \leq 4 \text{ sec}^{-1}$$

As in the lateral case conventional experimental design and data analysis were used. Figure 20 shows the "basic" (all variables zero except those on the coordinates) region of acceptability on the $N_{\delta_{RP}}$, N_R plane, and includes many of the test points, coded to show the average pilot evaluation of each.

Figure 21 again compares the results of the present study with those of Salmirs and Tapscott (Ref. 7) and Faye (Ref. 3). Here, however, there is a strong correspondence between the present results and Faye's. This is attributed to the maneuver (TASK HY) which required the use of directional control for directional change only, creating no out-of-trim forces or moments and demanding little pilot attention to other degrees of freedom.

The only difference between Faye's maneuver and TASK HY was Faye's requirement that the maneuver be performed as rapidly as possible, which might account for the displacement between the two boundaries that occurs in the low control sensitivity region.

Figures 22 and 23 give the effect of control system delay, t_{RP} , and first order time lag, τ_{RP} , on the average pilot rating at the four combinations of $N_{\delta_{RP}}$ and N_R labeled 1, 2, 3, and 4 in Fig. 21. A marked difference between these results and the corresponding ones for pitch and roll control systems (Figs. 10, 12, 17, and 18) is apparent. Here, for all practical purposes, pilot rating is independent of t_{RP} and τ_{RP} . This, again, is attributable to the task, where only a directional change was required and precise coordination between rudder pedal and other controls was unnecessary.

Figure 24 shows the effect of gyroscopic coupling GC_H on average pilot rating of directional handling qualities at points 5, 6, 7, and 8 in Fig. 21. As can be seen, the gyroscopic effect is strong and appears equally detrimental at all points in the $N_{\delta_{LAS}}$, N_R plane. Although the simple maneuver (TASK HY) required only directional changes, the introduction of gyroscopic coupling produced large pitching and rolling moments so that trimming of these degrees of freedom became extremely difficult, affecting the pilot's opinion accordingly.

Handling Qualities in Accelerating Transition

This portion of the study involved the three longitudinal degrees of freedom only, with two pilots rating 121 configurations in the performance of TASK TA. A prefatory check was first made on the applicability of hover data (TASK HP) to a forward flight condition in transition. Here, the pilots flew configurations with various amounts of M_Q and $M_{\dot{\alpha}_{LOS}}$ through a maneuver requiring a change in altitude from 200 feet to 100 feet while maintaining a constant speed (80 knots) and wing incidence (40°), which demanded the same kind of coordination between the power control and pitch control as was required in TASK HP. This revealed that values of damping and control sensitivity acceptable at hover remain so at 80 knots (wing incidence 40°). Thus the over-all question seemed reducible to: "How applicable to varying-speed maneuvers are hover-derived criteria?", or, for example, "Do handling qualities remain acceptable when damping and control sensitivity vary in typical fashion within the acceptable hover boundaries?" Accordingly, subsequent experimentation took the form of transition maneuvers in which values of damping and control sensitivity always began at the same typical point in the acceptable hover region but moved to other points in that region according to divers levels of variation with velocity squared. Unfortunately, time did not allow the study of more than one starting, (hover) configuration.

In Fig. 25 are shown the quadratic variations of M_Q and $M_{\delta_{LOS}}$ with U for the largest absolute values of $(M_Q)_{U^2}$ and $(M_{\delta_{LOS}})_{U^2}$ considered. The conservative nature of the M_Q variation (as mentioned on page 5) is evident in comparison with a linear variation (dashed line in Fig. 25) creating the same change in M_Q during transition, say to a value of 2 sec^{-1} at 84 knots. The quadratic variation lies below the linear de-emphasizing the effect of change in M_Q .

As in the hovering study the effect of several other parameters was included (in this case wing rate, WR , first order time lag, τ_{WR} , and delay, t_{WR} , in wing rate, pitching acceleration collective pitch coupling, $M_{\delta_{cp}}$, and delay, t_{cp} , and first order time lag, τ_{cp} , in collective pitch). Parameter variation covered the following ranges:

$$\begin{aligned} -0.5000 &\leq (M_Q)_{U^2} && \leq +0.500 \times 10^{-4} [(1/\text{sec})/(\text{ft}/\text{sec})^2] \\ +0.0500 &\leq (M_{\delta_{LOS}})_{U^2} && \leq +0.2500 \times 10^{-4} [(\text{rad}/\text{sec}^2/\text{in.})/(\text{ft}/\text{sec})^2] \\ 0 &\leq M_{\delta_{cp}} && \leq +0.875 \text{ rad}/\text{sec}^2/\text{in. (or rad}/\text{sec}^2/\beta_{cp}) \\ 2 &\leq WR && \leq 10^\circ/\text{sec} \\ 0.01 &\leq \tau_{WR} && \leq 1.00 \text{ sec} \\ 0 &\leq t_{WR} && \leq 0.60 \text{ sec} \\ 0.01 &\leq \tau_{cp} && \leq 0.60 \text{ sec} \\ 0 &\leq t_{cp} && \leq 0.60 \text{ sec} \end{aligned}$$

To ensure adequate control margin in the presence of longitudinal trim change with wing incidence (see Fig. 26), only positive (increasing) values of control sensitivity change with velocity were employed. For the experiments considered here, control margin was always in excess of 25 per cent. The net coupling term $M_{\delta_{cp}}$ was a function of wing incidence, expressed as:

$$M_{\delta_{cp}}(i_w) = M_{\delta_{cp}} \sin 2 i_w .$$

Initial (hover) values of longitudinal control sensitivity and damping were, respectively, $0.10 \text{ rad/sec}^2/\text{in.}$, and $+1.0 \text{ sec}^{-1}$. Longitudinal control delay and first order time lag were both fixed at 0.1 sec for all flight conditions. The resulting configuration was acceptable at hover, but not optimum (P.R. ≈ 3) according to the criteria defined by the previous analysis. The reader is reminded that this hover configuration remained fixed throughout the transition experiments while the rates of change of control sensitivity and damping with speed $[(M_{\delta_{LOS}})U^2 \text{ and } (M_Q)U^2]$ were varied.

Five levels of each of the 8 parameters were chosen, and 121 different configurations were represented by random combinations of these (Ref. 16). One pilot rated 55 configurations and the other 66. As in the investigation of longitudinal handling qualities at hover, a polynomial in the experimental variables was fit

to the data (see Table V); hence graphical representations of the results appear only as two variable "cross sections" of the multi-variable polynomial on which few, if any, specific data are presentable (see discussion, page 8).

In Fig. 27 the $(M_Q)_{U^2}$, $(M_{\delta_{LOS}})_{U^2}$ plane (for τ_{cp} , t_{cp} , τ_{WR} , t_{WR} and $M_{\delta_{cp}}$ zero) is divided into acceptable and unacceptable regions by lines of constant pilot rating for three different wing rates. It is evident that increasing wing rate sharply narrows the acceptable region. This can be attributed to large trim changes which accompany wing tilting (see Fig. 26) in conjunction with the particular type of tilt control used — on-off command of wing rate. A rapid wing rate, applied in steps, causes abrupt wing tilt changes, hence abrupt longitudinal trim changes which the pilots readily sense and find undesirable. Notably, for high wing rates ($10^\circ/\text{sec}$) the pilots always complained of "pitching-acceleration: wing-rate-control coupling."

Cross sections such as Fig. 27 are interesting but hard to relate to physical situations. The following considerations lead to a more graphic presentation of the results: Each level of $(M_Q)_{U^2}$ or $(M_{\delta_{LOS}})_{U^2}$ corresponds to a change in M_Q or $M_{\delta_{LOS}}$ from a hover value to an end of transition value which depends upon final velocity. In these experiments, final velocity did not vary much and was almost normally distributed about a mean of

84 knots (Fig. 28). This value, in conjunction with various levels of $(M_Q)_{U^2}$, gives increments of pitch damping and control sensitivity which, when added to the previously specified hover values, locate various points on the $M_Q, M_{\delta_{LOS}}$ plane representing end of transition conditions. Figure 29 shows the transition results of Fig. 27 presented in this fashion. Here, the shaded line delimits a region of end points attainable from the single hover point shown, for various combinations of the $(M_Q)_{U^2}$ and $(M_{\delta_{LOS}})_{U^2}$ values used; during a transition, damping and control sensitivity vary along a straight line, of slope $(M_Q)_{U^2}/(M_{\delta_{LOS}})_{U^2}$, from the hover point to some point within the rectangle, as indicated by the typical "track" shown.

It is clear that there are combinations of damping and control sensitivity rates for which a transition can proceed along a track which is entirely within the acceptable hover (hence steady forward flight) region, yet crosses the wing-rate boundary into an unacceptable end of transition region. Conversely it is equally clear that there are damping and control sensitivity variations which can take the configuration far outside the acceptable hover region without making transition handling qualities unacceptable. These are the crucial conclusions of the present study; they imply that handling qualities criteria derived from hovering or steady flight experiments cannot generally be relied upon for the transition regime.

Of particular interest is the fact that for the hover point shown, conventional variations in M_Q and $M_{\bar{\delta}_{LOS}}$ (i.e., increasing with speed) will always result in an acceptable transition configuration, even if end of transition control sensitivities far exceed maximum acceptable hover values. Also notable is the strong dependence of the acceptable end of transition region on wing rate. It is evident that losses in damping (as might result from the phasing out of hover augmentation) are more tolerable at small wing rates. As was noted in the discussion of Fig. 27, however (see page 24), the dependence of handling qualities on wing rate is probably exaggerated by the type of wing tilt control used.

Figure 30 shows the effect of tilt control delay on the region of acceptable end of transition values in the M_Q , $M_{\bar{\delta}_{LOS}}$ plane. Delay is evidently strongly detrimental. This is interesting because it turned out that first order time lag, τ_{WR} , in the response to wing rate control did not produce any such effect on handling qualities for TASK TA. It is believed that these peculiarities stem from the pitching moment variation with wing position in conjunction with the previously discussed abruptness of the wing tilt control response. The pilots learn to coordinate each application of wing rate control with the proper longitudinal control change for maintenance of trim. A first order time lag (exponential response) in the tilt control, therefore, need not be detri-

mental if, as is the case, it tends to smooth the onset of out of trim moments resulting from control applications. A delay, however, leaves trim changes just as abrupt but displaced in time, making the necessary coordination between wing rate and longitudinal controls difficult.

Pitch acceleration due to collective-pitch coupling, $M_{\delta_{cp}}$, affects handling qualities only weakly unless its magnitude becomes unrealistically large. In Fig. 31 for example, the upper boundary represents an $M_{\delta_{cp}}$ of $-1.0 \text{ rad/sec}^2/\text{deg}$ which is about 100 times the amount of coupling determined by the powered model wind tunnel experiments upon which the present study was based. Time delay and first order lag in collective pitch control response were equally ineffectual (no data are presented). Apparently, collective pitch coupling and response-time characteristics were not bothersome to the pilot. Quite possibly this can be attributed to the nature of the engine control system simulated, which was assumed to keep propeller rpm constant by providing automatic power changes. Thus, it turned out that collective pitch changes by the pilot were rarely needed (see Fig. 32, a time history of a typical accelerating transition); hence peculiarities in the control response, being seldom perceived, did not produce significant changes in pilot rating.

Handling Qualities in Decelerating Transition

The decelerating transition was also studied with the full six degree of freedom simulation. Two pilots participated in performing TASK TD to evaluate 50 different configurations. Primarily, these experiments were performed to determine the effect of collective pitch control response and response-time characteristics in a maneuver requiring relatively bold applications of collective pitch. Experimental variables were pitch-acceleration due to collective-pitch-control coupling, $M_{\delta_{cp}}$, first order time lag in vehicle response to collective pitch control, τ_{cp} , wing rate, WR, and first order time lag in vehicle response to wing rate control, τ_{WR} .

The following ranges of investigation were considered:

$$\begin{aligned} 0 &\leq M_{\delta_{cp}} \leq 0.75 \text{ rad/sec}^2/\text{in.} \\ 0.01 &\leq \tau_{cp} \leq 1.00 \text{ sec} \\ 3 &\leq WR \leq 20 \text{ deg/sec} \\ 0.01 &\leq \tau_{WR} \leq 1.00 \text{ sec} \end{aligned}$$

Variations in these parameters were made at each of three fixed combinations of M_Q and $M_{\delta_{LOS}}$ lying close to the acceptable handling qualities boundary developed for hover and confirmed for the forward flight condition that is the starting point

for TASK TD. The location of these three points is shown in Fig. 33. The results of this part of the study are presented in Figs. 34, 35, 36, and 37, in which average pilot rating is plotted against $M_{\bar{c}_{cp}}$, τ_{cp} , WR, and τ_{WR} respectively.

None of the parameters had any pronounced effect on handling qualities. The only one that appeared to affect handling qualities at all, $M_{\bar{c}_{cp}}$, becomes, as in the accelerating transition (TASK TA), influential only for extreme values. Several peculiarities of the simulation may have been the basic cause for these somewhat surprising results. The typical profound wing stall characteristics possessed by test bed, tilt-wing aircraft was not included in the simulation, and there was no structural limitation on the rapidity with which the wing could be tilted to the hover position. Because of this, the pilots found that they could utilize, in one burst, the maximum wing rate provided (as high as $20^\circ/\text{sec}$), and then control collective pitch and pitch attitude to maintain height as the vehicle decelerated rapidly to hover (see Fig. 38). This obviously negated any possible effects of WR and τ_{WR} , and gave the pilot two nearly independent ways (collective pitch and pitch attitude) to control altitude, essentially removing τ_{cp} from the picture. In effect, the decelerating maneuver (TASK TD) was basically a velocity dissipation problem only and did not call for the sort of caution

demanded by the accelerating maneuver (TASK TA), which was a precarious development of flying speed during the transfer from one lifting means to another.

CONCLUSIONS AND RECOMMENDATIONS

In the present study a moving base flight simulator flown by qualified pilots was employed to investigate VTOL handling qualities in still air at hover and during transitions.

Hover

1. Comparison of the present results with the work of other investigators reveals that the acceptable regions on the rate-damping: control-sensitivity plane for roll, pitch and yaw all depend strongly upon the maneuvering task performed in the experimentation.

The demand for vehicle "stability" increases, as shown by increases in required damping levels, when the task varies from one of gross attitude change, to one of precision maneuvering, and finally to one of precise control of a given flight condition.

In general the minimum acceptable control sensitivity appears to be independent of task, while the maximum acceptable value is strongly task dependent and is drastically delimited in tight trimming tasks.

2. Control system response-time characteristics have a large effect on handling qualities in pitch and roll, but none at all in yaw. This is attributed to thrust vector direction change with control application, which occurs in pitch and roll but not in yaw.

In general the effect of control system delays and first order time lags is to increase the damping required for acceptable handling qualities; the increase in required damping being largest when control sensitivity is high.

Conversely it is seen that the handling qualities of configurations with relatively high values of rate damping and low values of control sensitivity appear almost insensitive to variations in control system response-time characteristics.

3. The present helicopter flying qualities requirements do not guarantee good VTOL control response characteristics. The present requirement on time to reach proper direction of acceleration is inadequate since it fails to quantify any limit on a first order time lag. It is effective however for time delays and the limit of 0.2 second seems reasonable for this case. Apparently a more complete requirement is needed to quantify limits on a more general class of response characteristics.
4. Forward-acceleration due to longitudinal-control coupling, $-X_{\delta_{LOS}}$, has a strong effect on handling qualities. For the particular maneuver considered in this research (TASK HP, see p. 7) small values of coupling were mildly beneficial but larger values became drastically detrimental. The following tolerable range is suggested as a tentative limit on this type of coupling: $0 \leq -X_{\delta_{LOS}} \leq 1.0 \text{ ft/sec}^2/\text{in.}$
5. Gyroscopic coupling, in all cases examined, produced a strong degradation of handling qualities. Even small amounts were generally not acceptable and VTOL flying qualities requirements would not be overly cautious in allowing no gyroscopic coupling at hover.

Transition

1. The most important result here is the clear cut demonstration that handling qualities criteria derived from hover or steady flight experimentation cannot, in general, be stretched to include nonsteady (e.g., transition) flight.
2. Two parameters unique to VTOL type craft, wing rate, and its response-time characteristic, strongly affect transition handling qualities. This is probably closely associated with the particular type of wing rate control used and the nature of the trim changes occurring during transition.
3. More work is needed to specify quantitative transition handling qualities criteria. In the interim, unfortunately, the use of hover criteria apparently will not suffice.

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TABLE I

Tilt-Wing Six-Degree-of-Freedom Equations of Motion

(A) FORCE REPRESENTATION ALONG THE BODY AXES

Rates of Change of Linear Momentum	Aerodynamic Forces	Gravitational Forces	Control Forces
$m_1(\dot{u}-vR+wQ)$	$= X_A$	$- m_1 g \sin \theta$	$+ X_C$
$m_1(\dot{v}-wP+uR)$	$= Y_A$	$+ m_1 g \cos \theta \sin \phi$	$+ Y_C$
$m_1(\dot{w}-uQ+vP)$	$= Z_A$	$+ m_1 g \cos \theta \cos \phi$	$+ Z_C$

(B) MOMENT REPRESENTATION ABOUT THE BODY AXES

Rates of Change of Angular Momentum	Aerodynamic Moments	Control Moments
$I_x \dot{P} - I_{xz}(\dot{R}+PQ) + (I_z - I_y)QR - (I_E \Omega)_V Q$	$= L_A$	$+ L_C$
$I_y \dot{Q} + I_{xz}(P^2 - R^2) + (I_x - I_z)PR + (I_E \Omega)_H (R) + (I_E \Omega)_V (P)$	$= M_A$	$+ M_C$
$I_z \dot{R} + I_{xz}(QR - \dot{P}) + (I_y - I_x)PQ + (I_E \Omega)_H (Q)$	$= N_A$	$+ N_C$

TABLE I (Cont)

(C) AERODYNAMIC FORCES AND MOMENTS REFERRED TO THE BODY AXES

$$X_A = x_0 + x_1 u + x_2 u \cos i_w + x_3 \sin i_w \cos i_w + x_4 w^2 + x_5 u^2 \cos i_w$$

$$Y_A = v(y_0 + y_1 u)$$

$$Z_A = z_0 \sin i_w + z_1 u \cos i_w + z_2 w$$

$$L_A = v(L_1 + L_2 u \cos 2 i_w + L_3 \sin 2 i_w + L_4 i_w + L_5 w \sin 2 i_w) + (L_6 + L_6 u^2)P + L_9 R$$

$$M_A = M_0 + M_1 \sin i_w + M_2 \cos i_w + M_3 w + M_4 u^2 w + (M_5 + M_6 u^2)Q$$

$$N_A = v(N_1 u + N_2 \cos 2 i_w + N_3 w \cos 2 i_w + N_4 u w \sin 2 i_w + N_5 u w \cos 2 i_w) + (N_6 + N_7 u^2)R + N_8 P$$

TABLE I (Cont)

(D) CONTROL FORCES AND MOMENTS REFERRED TO THE BODY AXES

$$X_c = (x_6 u^2 \cos i_w) \delta_{cp} + x_7 \delta_{los}$$

$$Y_c = (y_2 + y_3 u^2) \delta_{rp}$$

$$Z_c = (z_3 \sin i_w) \delta_{cp} + z_4 \delta_{los}$$

$$L_c = (L_{10} + L_{11} u^2) \delta_{las} + (L_{12} + L_{13} u^2) \delta_{rp}$$

$$M_c = (M_7 + M_8 u^2) \delta_{los} + (M_9 \sin i_w \cos i_w) \delta_{cp} + (M_{10} + M_{11} u^2) \delta_{las}$$

$$N_c = (N_9 + N_{10} u^2) \delta_{rp} + (N_{11} \sin i_w \cos i_w) \delta_{las}$$

TABLE I (Cont)

(E) VARIATION OF INERTIA PROPERTIES WITH WING INCIDENCE

$$I_x = A_1 + 2A_2 \sin i_w - A_3 \cos 2 i_w + A_4 \sin 2 i_w$$

$$I_y = A_5 - 2A_6 \cos i_w + 2A_2 \sin i_w$$

$$I_z = A_7 - 2A_6 \cos i_w + A_3 \cos 2 i_w - A_4 \sin i_w$$

$$I_{xz} = A_8 - A_2 \cos i_w + A_6 \sin i_w - A_4 \cos 2 i_w - A_3 \sin 2 i_w$$

TABLE I (Cont)

(F) COMPUTATION OF COEFFICIENTS A_1 THROUGH A_8

$$A_1 = \frac{m_F m_W}{m_T} (b^2 \sin^2 \delta + \frac{1}{2} a^2) + l_{x_F} + \frac{1}{2} (l_{x_W} + l_{z_W})$$

$$A_2 = \frac{m_F m_W}{m_T} ab \sin \delta$$

$$A_3 = \frac{1}{2} [(l_{z_W} - l_{x_W}) \cos 2\epsilon + \frac{m_F m_W}{m_T} a^2]$$

$$A_4 = \frac{1}{2} (l_{z_W} - l_{x_W}) \sin 2\epsilon$$

$$A_5 = \frac{m_F m_W}{m_T} (a^2 + b^2) + l_{y_F} + l_{y_W}$$

$$A_6 = \frac{m_F m_W}{m_T} ab \cos \delta$$

$$A_7 = \frac{m_F m_W}{m_T} (b^2 \cos^2 \delta + \frac{1}{2} a^2) + l_{z_F} + \frac{1}{2} (l_{z_W} + l_{x_W})$$

$$A_8 = l_{xz_F} + \frac{m_F m_W}{m_T} b^2 \sin \delta \cos \delta$$

TABLE I (Concluded)

(G) CONTROL EQUATIONS

$i_w(s) = \frac{wR^*}{s^2(1 + \tau_{WR}s)} + \frac{i_{w0}}{s}$	; INPUT DELAYED BY τ_{WR}
$\delta_{LOS}(s) = \frac{\delta_{LOS}^*}{s(1 + \tau_{LOS}s)}$	; INPUT DELAYED BY τ_{LOS}
$\delta_{LAS}(s) = \frac{\delta_{LAS}^*}{s(1 + \tau_{LAS}s)}$	; INPUT DELAYED BY τ_{LAS}
$\delta_{RP}(s) = \frac{\delta_{RP}^*}{s(1 + \tau_{RP}s)}$	; INPUT DELAYED BY τ_{RP}
$\delta_{CP}(s) = \frac{\delta_{CP}^*}{s(1 + \tau_{CP}s)}$	; INPUT DELAYED BY τ_{CP}

TABLE II

COEFFICIENT VALUES FOR TILT-WING SIX DEGREE OF FREEDOM EQUATIONS OF MOTION

COEFF.	UNITS	COMPUTER CHECK VALUE	VALUES USED				
			TASK HF	TASK HR	TASK HY	TASK TA	TASK TD
M_T	slugs	467.25	CC*	CC	CC	CC	CC
$(I_E)_{\dot{V}}$	slug-ft ² /sec	5250	0	V*	0	0	0
$(I_E)_H$	slug-ft ² /sec	5250	0	0	V	0	0
A_1	slug-ft ²	23334.5	CC	CC	CC	CC	CC
A_2		436.6					
A_3		665.6					
A_4		105.2					
A_5		35341.2					
A_6		120.5					
A_7		50516					
A_8		5170.4					
X_0	lb	710.22					
X_1	lb/(ft/sec)	-56.5					
X_2	lb/(ft/sec)	33.76					
X_3	lb	3051.69					
X_4	lb/(ft/sec) ²	-.8937					
X_5	lb/(ft/sec) ²	.0555					
X_6	$\frac{1b/(ft/sec)}{(in. \text{ of pot.})_{cp}}$	.1386					
X_7	lb/(in. of pot.) _{LOS}	0	V	0	0	0	0
Y_0	lb/(ft/sec)	-17.28	0	CC	CC	0	CC
Y_1	lb/(ft/sec) ²	-.3718		CC	CC		
Y_2	lb/(in. of pot.) _{RP}	-160		0	0		
Y_3	$\frac{1b/(ft/sec)^2}{(in. \text{ of pot.})_{RP}}$	-.0160		0	0	0	
Z_0	lb	-15126.1	CC	CC	CC	CC	
Z_1	lb/(ft/sec)	-54.73					
Z_2	lb/(ft/sec)	-182.43				-93.45	
Z_3	lb/(in. of pot.) _{cp}	-2361.81				-875.5	
Z_4	lb/(in. of pot.) _{LOS}	471.68				CC	

TABLE II (Cont.)

COEFF.	UNITS	COMPUTER CHECK VALUE	VALUES USED				
			TASK HP	TASK HR	TASK HY	TASK TA	TASK TD
L ₁	ft-lb/(ft/sec)	1439.0	0	CC	0	0	CC
L ₂	ft-lb/(ft/sec) ²	-10.22			CC		
L ₃	ft-lb/(ft/sec)	-710.27			0		
L ₄	ft-lb/(ft/sec)-rad	-1224.7			0		
L ₅	ft-lb/(ft/sec) ²	5.71			CC		
L ₆	ft-lb-sec/(ft/sec) ²	-1.0		0	0		0
L ₈	ft-lb-sec	-50000		V	-49000		-49000
L ₉	ft-lb-sec	25000		0	0		3000
L ₁₀	ft-lb/(in. of pot.) _{LAS}	40000		V	29390		34310
L ₁₁	$\frac{\text{ft-lb}/(\text{ft/sec})^2}{(\text{in. of pot.})_{\text{LAS}}}$	2		0	0		0
L ₁₂	ft-lb/(in. of pot.) _{RP}	-6607			V		
L ₁₃	$\frac{\text{ft-lb}/(\text{ft/sec})^2}{(\text{in. of pot.})_{\text{RP}}}$	-1.3333			0		
M ₀	ft-lb	-86308	CC	CC	CC	CC	CC
M ₁	ft-lb	75519					
M ₂	ft-lb	67269					
M ₃	ft-lb/(ft/sec) ²	157.97					
M ₄	ft-lb/(ft/sec) ³	-0.0182					
M ₅	ft-lb-sec	-36000	V	-36200	-36200	-36200	V
M ₆	ft-lb-sec/(ft/sec) ²	-1.8	0	0	0	V	0
M ₇	ft-lb/(in. of pot.) _{LOS}	27100	V	13843	13843	13843	V
M ₈	$\frac{\text{ft-lb}/(\text{ft/sec})^2}{(\text{in. of pot.})_{\text{LOS}}}$	1.0	0	0	0	V	0
M ₉	ft-lb/(in. of pot.) _{cp}	68750	CC	0		V	V
M ₁₀	ft-lb/(in. of pot.) _{LAS}	13280	0	V		0	0
M ₁₁	$\frac{\text{ft-lb}/(\text{ft/sec})^2}{(\text{in. of pot.})_{\text{LAS}}}$	1.66		0			0
N ₁	ft-lb/(ft/sec) ²	2.16		CC	CC		CC
N ₂	ft-lb/(ft/sec)	-67.35					
N ₃	ft-lb/(ft/sec) ²	-20.39					
N ₄	ft-lb/(ft/sec) ³	-0.0372					

TABLE II (Cont.)

COEFF.	UNITS	COMPUTER CHECK VALUE	VALUES USED				
			TASK HP	TASK HR	TASK HY	TASK TA	TASK TD
N ₅	ft-lb/(ft/sec) ³	.1350	0	CC	CC	0	CC
N ₆	ft-lb-sec	-250000	0	-300000	V	0	-300000
N ₇	ft-lb-sec/(ft/sec) ²	-5		0	0		0
N ₈	ft-lb-sec	-50000		V	0		-3840
N ₉	ft-lb/(in. of pot.) _{RP}	160000		160000	V		160000
N ₁₀	$\frac{\text{ft-lb}/(\text{ft/sec})^2}{(\text{in. of pot.})_{\text{RP}}}$	4		0	0		0
N ₁₁	ft-lb/(in. of pot.) _{LAS}	20000		V			CC
t _{WR}	sec	.10		0		V	V
t _{WR}							0
t _{cp}			CC				V
t _{cp}			CC				0
t _{LOS}			V			.1	.1
t _{LOS}			V			.1	.1
t _{LAS}			0	V	.05	0	0
t _{LAS}			0	V	.05	0	0
t _{RP}				.05	V		
t _{RP}				.05	V		
i _w	deg/sec	10		0	0	V	V

* CC - Indicates computer check value.

† V - Indicates that parameter was a variable in the study.

TABLE III
PARTICIPATING PILOTS

<u>Pilot</u>	<u>Experience</u>
A	Commercial licensed helicopter pilot. Naval Reserve Officer with considerable fixed wing experience also. Logged flying time 2400 hours.
B	Commercial licensed helicopter pilot and instructor. Marine Corps service also included considerable fighter type experience. Logged flying time 3000 hours.
C	Commercial licensed helicopter pilot and instructor with instrument rating. Naval Reserve Officer with fighter type experience also. Logged flying time 1500 hours.
D	Commercial licensed pilot and instructor with instrument and multi- and single-engine land and sea ratings. Naval Reserve Officer with majority of experience in single-engine aircraft. Logged flying time 2000 hours.

TABLE IV

PILOT RATING FUNCTION FOR LONGITUDINAL HANDLING QUALITIES AT HOVER(TASK HP)

$$\begin{aligned}
\text{P.R.} = & 12.94 - 57.09 M_{\delta_{\text{LOS}}} - 7.36 M_Q - 6.89 t_{\text{LOS}} + 4.83 t_{\text{LOS}} + 4.37 X_{\epsilon_{\text{LOS}}} + 100.33 (M_{\epsilon_{\text{LOS}}})^2 \\
& + 0.36 M_{\delta_{\text{LOS}}} M_Q + 41.29 M_{\epsilon_{\text{LOS}}} t_{\text{LOS}} + 21.02 M_{\epsilon_{\text{LOS}}} t_{\text{LOS}} - 7.26 M_{\epsilon_{\text{LOS}}} X_{\epsilon_{\text{LOS}}} + 2.71 (M_Q)^2 \\
& - 4.72 M_Q t_{\text{LOS}} - 9.10 M_Q t_{\text{LOS}} - 0.91 M_Q X_{\epsilon_{\text{LOS}}} + 20.61 (t_{\text{LOS}})^2 + 62.02 t_{\text{LOS}} t_{\text{LOS}} \\
& + 3.20 t_{\text{LOS}} X_{\delta_{\text{LOS}}} - 13.67 (t_{\text{LOS}})^2 - 0.025 t_{\text{LOS}} X_{\epsilon_{\text{LOS}}} + 1.58 (X_{\delta_{\text{LOS}}})^2
\end{aligned}$$

TABLE V
PILOT RATING FUNCTION FOR HANDLING QUALITIES DURING ACCELERATING TRANSITION

(TASK 1A)

$$\begin{aligned}
 P.R. = & 1.842 - 1.784 M_{\epsilon_{cp}} - 2.094 (M_Q) U^2 + 5.852 t_{WR} + 6.302 t_{cp} - 2.282 t_{cp} + 0.831 (M_{\epsilon_{cp}})^2 \\
 & + 0.235 M_{\epsilon_{cp}} (WR) - 0.493 M_{\epsilon_{cp}} t_{WR} + 5.070 [(M_Q) U^2]^2 - 0.234 (M_Q) U^2 (WR) - 5.042 (M_Q) U^2 t_{WR} \\
 & - 0.419 (WR) t_{WR} + 0.651 (WR) (M_{\epsilon_{LOS}}) + 4.997 t_{WR} t_{WR} - 2.927 t_{WR} t_{cp} - 6.362 (t_{WR})^2 \\
 & - 6.575 t_{WR} t_{cp} + 13.273 t_{WR} (M_{\epsilon_{LOS}}) - 7.296 (t_{cp})^2 + 6.558 (t_{cp})^2 - 9.538 t_{cp} (M_{\epsilon_{LOS}}) U^2 \\
 & - 2.900 [(M_{\epsilon_{LOS}}) U^2]^2
 \end{aligned}$$



Fig. 1 From 3/1 View of Motion Platform in a Right Roll Nose Down Attitude

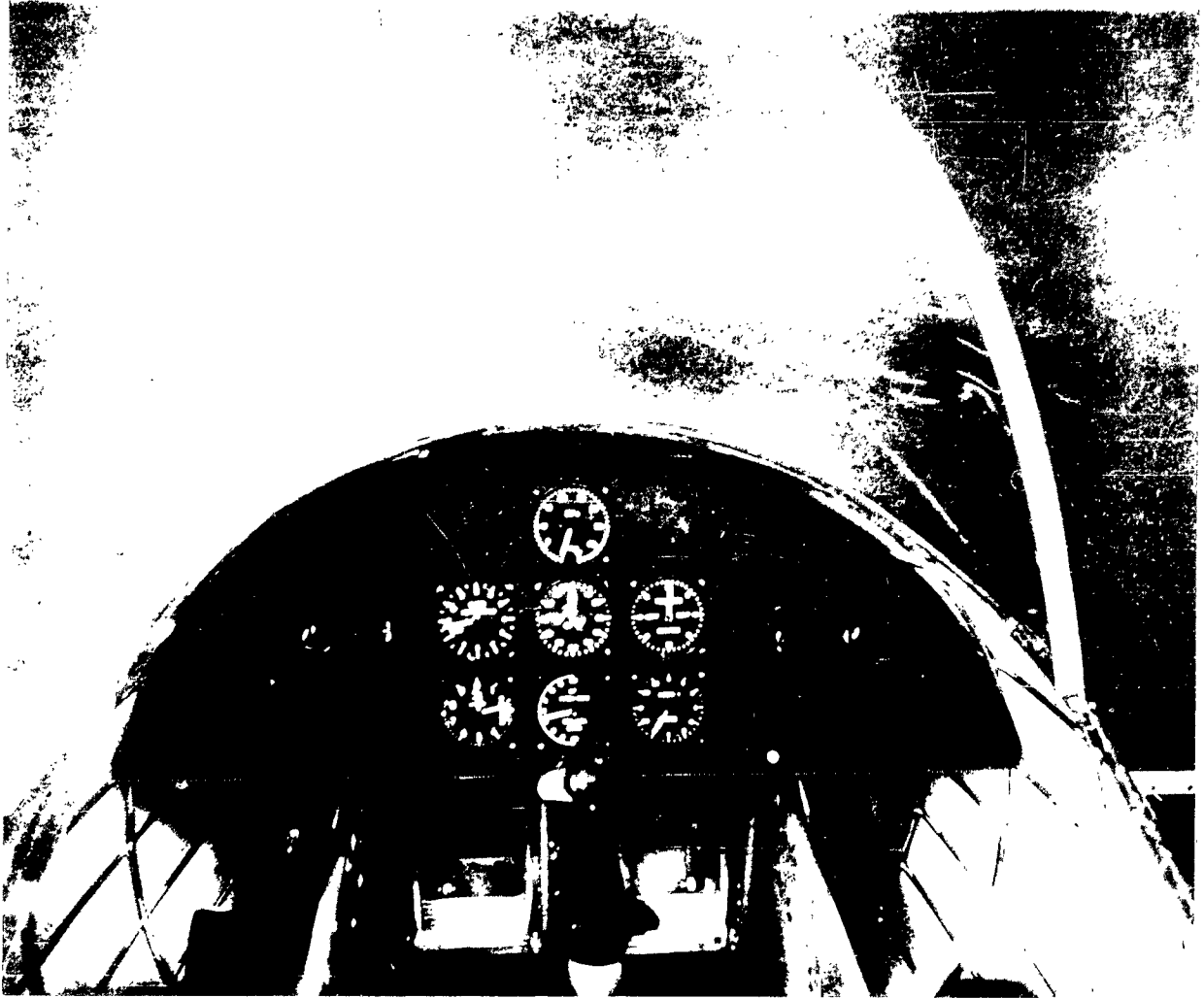


Fig. 2 View from Cockpit Showing Typical Yawed Flight at Medium Altitude

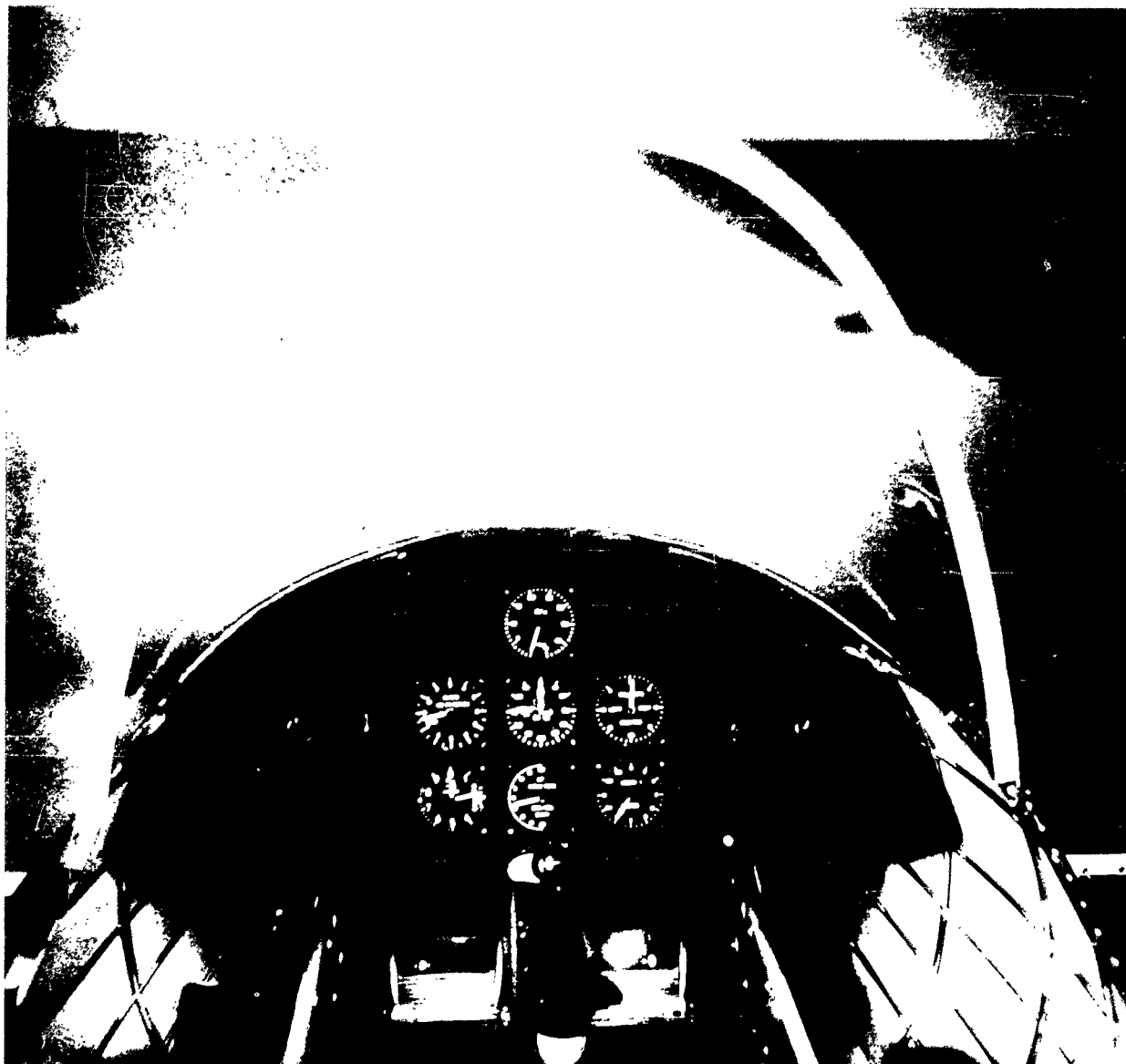


Fig. 3 View from Cockpit Showing Typical Straight-On Flight at Low Altitude



Fig. 4 View from Cockpit Showing Typical Straight-On Flight at High Altitude



Fig. 5. View of cockpit showing Typical Side Displacement in flight. (code)

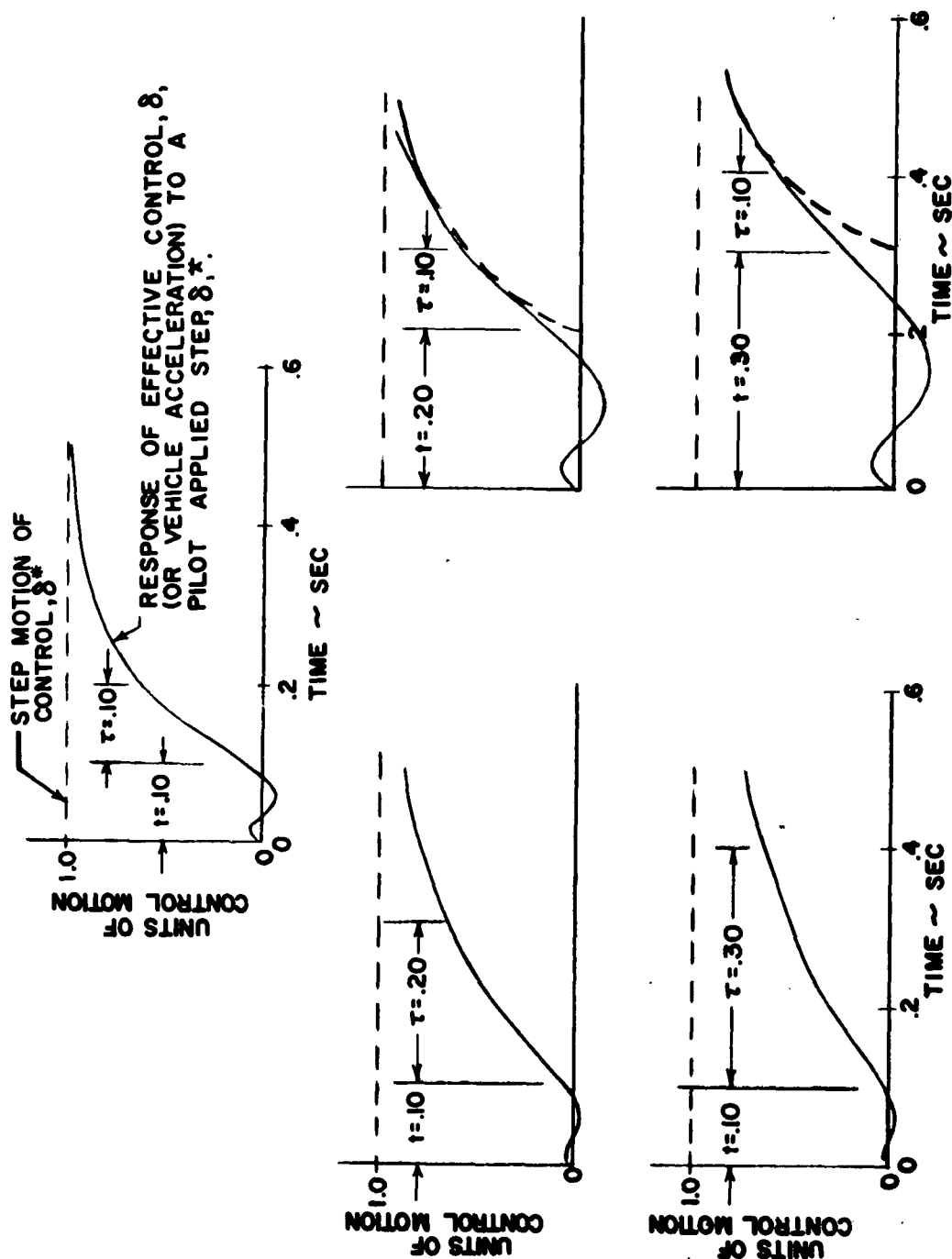
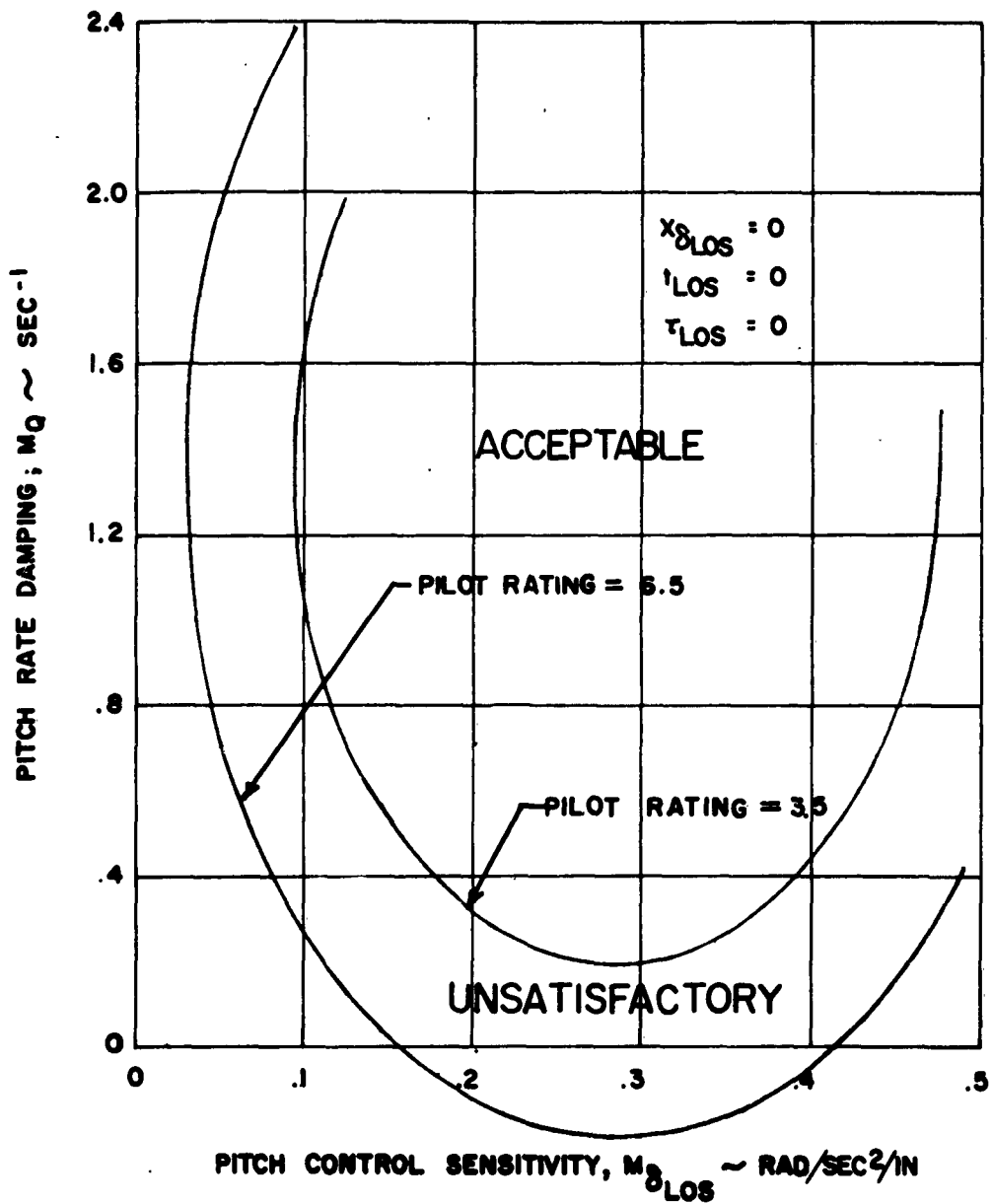
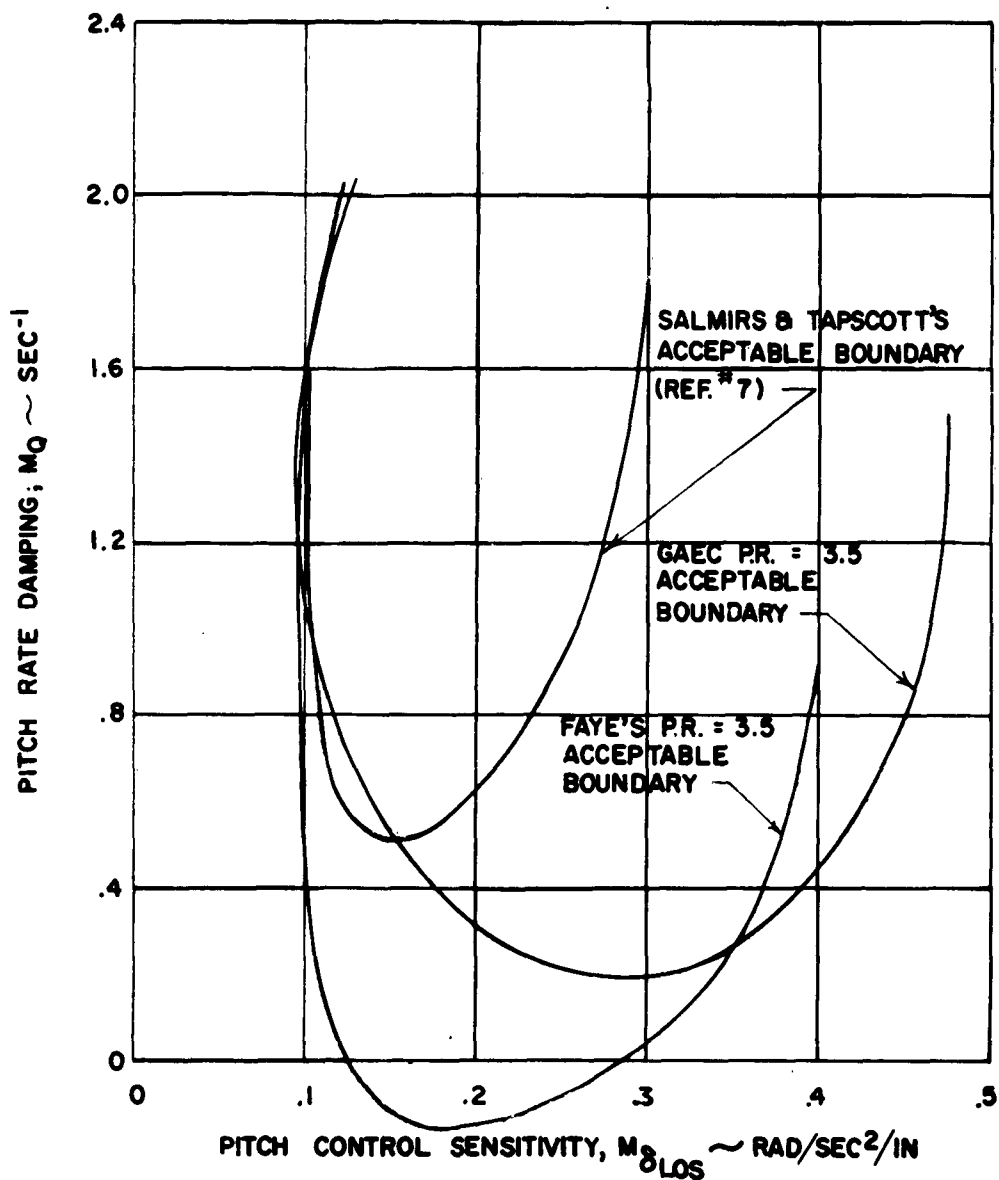


Fig. 6 Pictorial Definition of Control System Response Time Characteristics



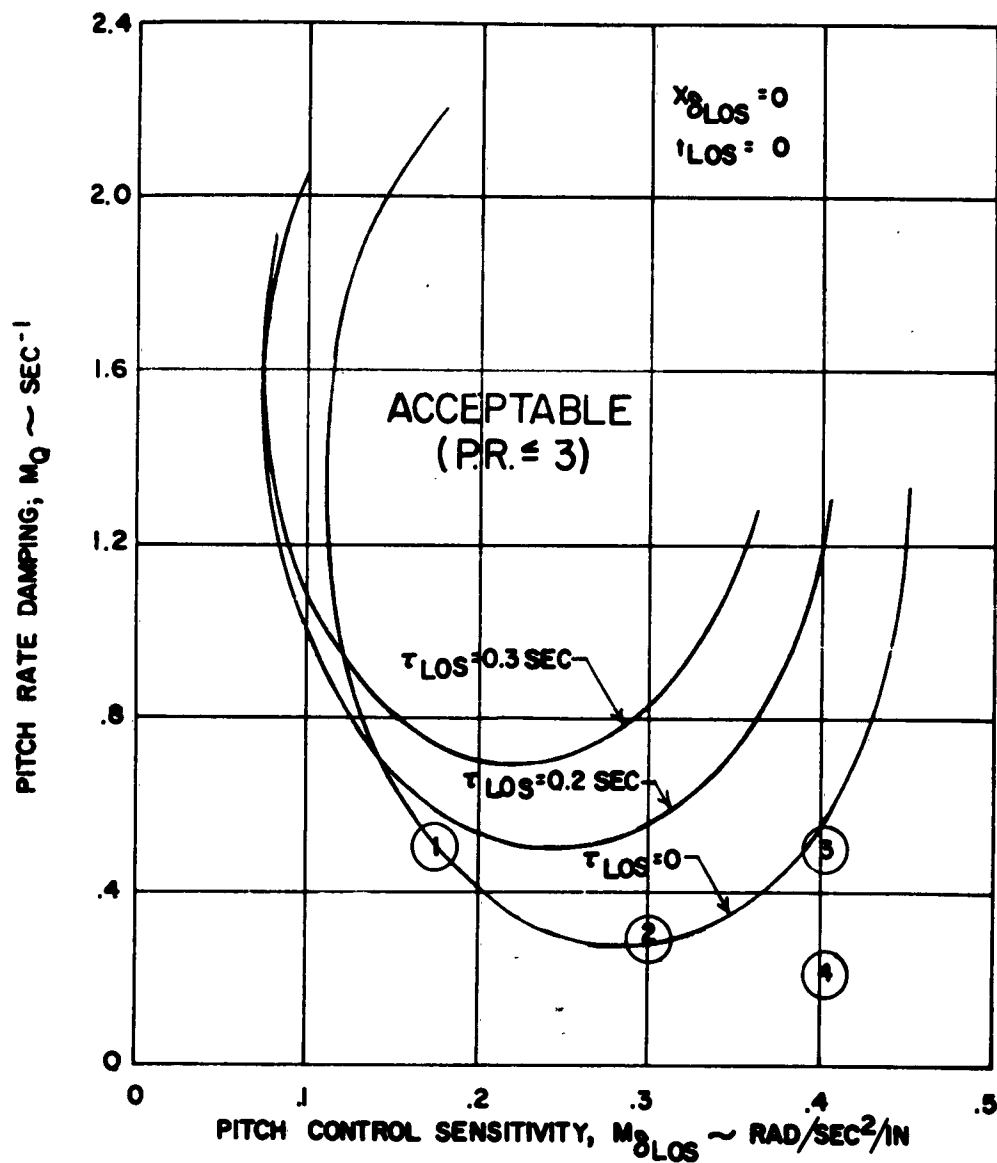
LONGITUDINAL HANDLING QUALITIES AT HOVER

Fig. 7 Basic Damping and Control Sensitivity Boundaries



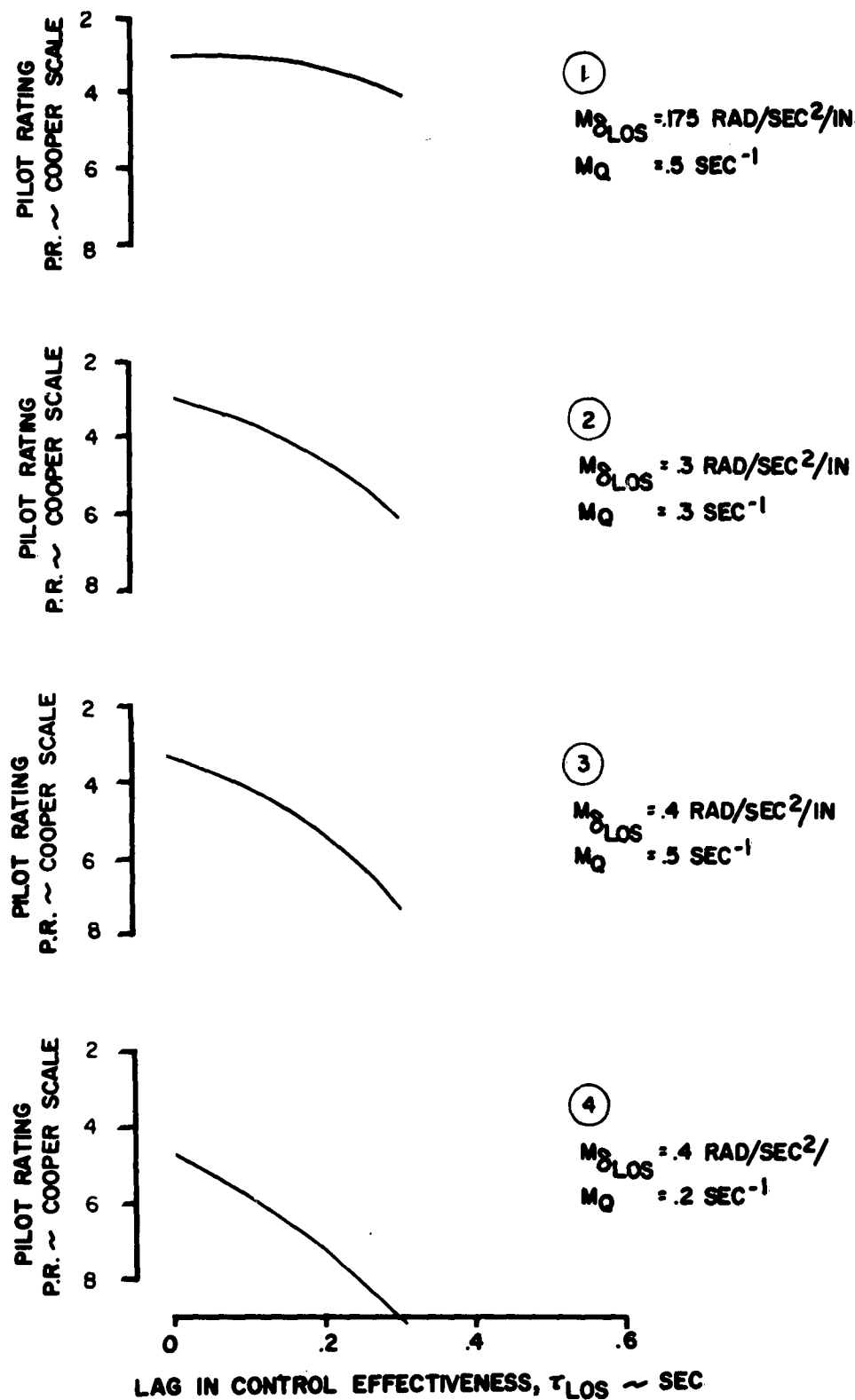
LONGITUDINAL HANDLING QUALITIES AT HOVER

Fig. 8 Comparison of Basic Acceptable Boundaries Obtained by Three Investigators



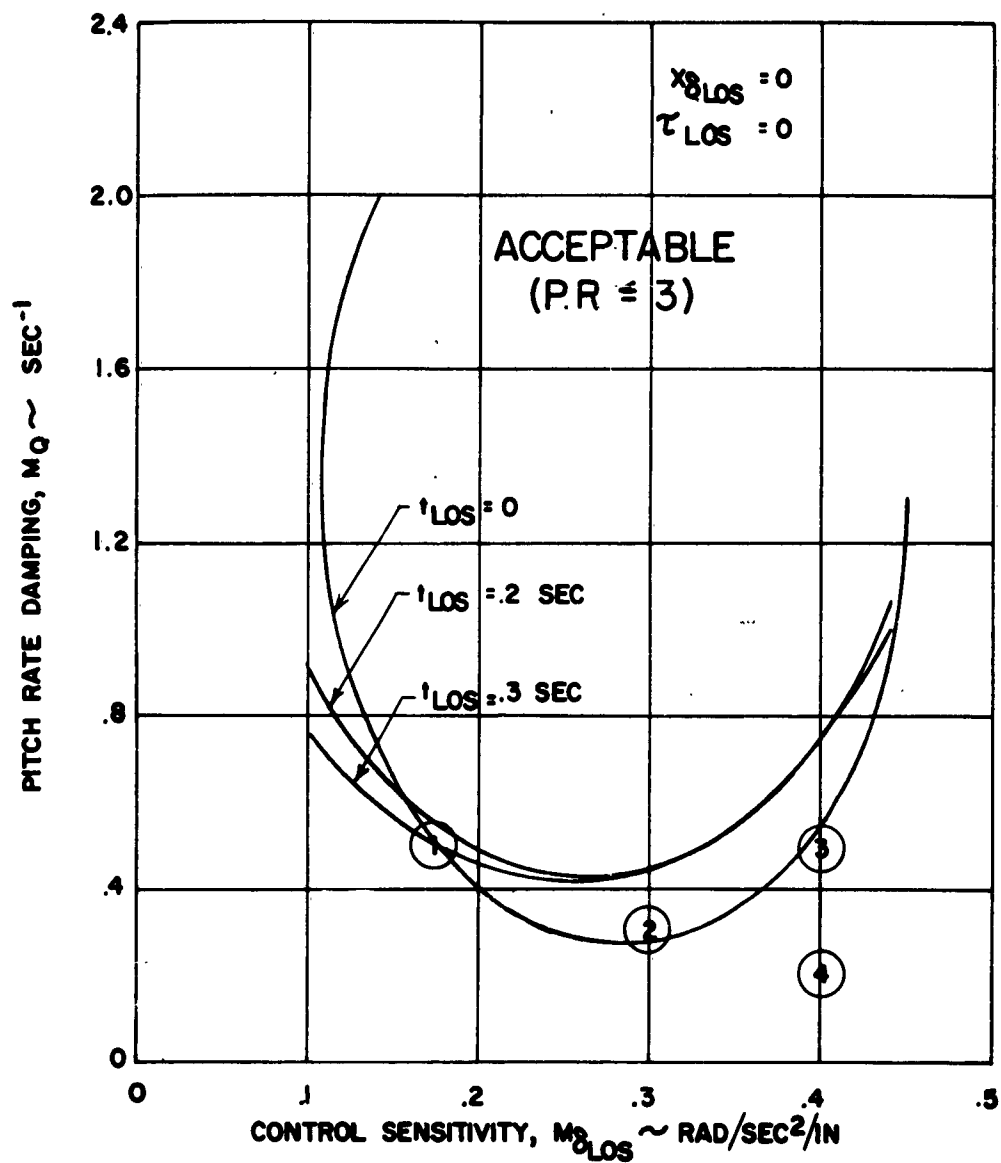
LONGITUDINAL HANDLING QUALITIES AT HOVER

Fig. 9 Effect of First-Order Control Lag on Basic Acceptable Boundary



LONGITUDINAL HANDLING QUALITIES AT HOVER

Fig. 10 Variation of Pilot Rating with First-Order Control Lag for the Four Points Indicated on Fig. 9



LONGITUDINAL HANDLING QUALITIES AT HOVER

Fig. 11 Effect of Control Time Delay on Basic Acceptable Boundary

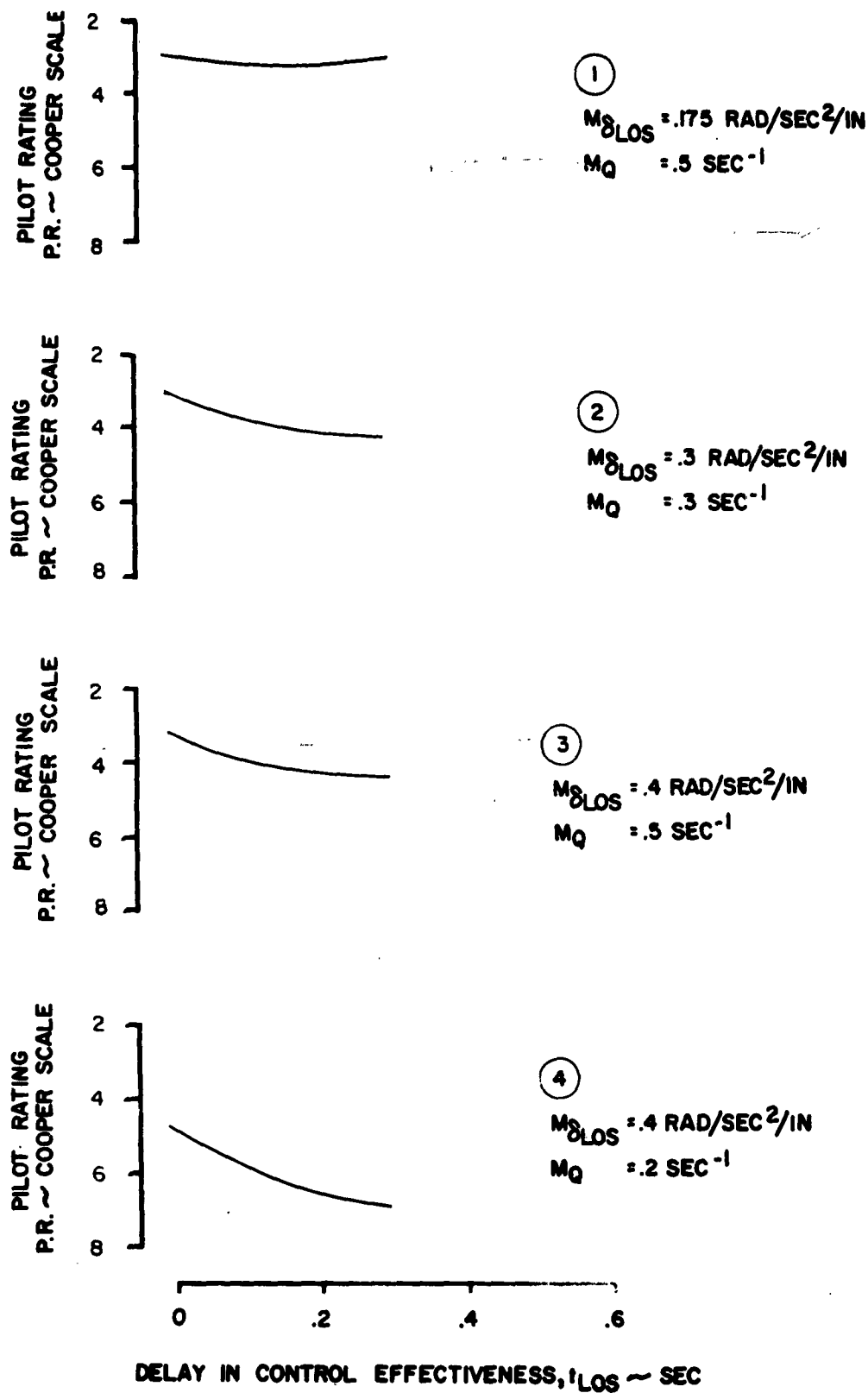
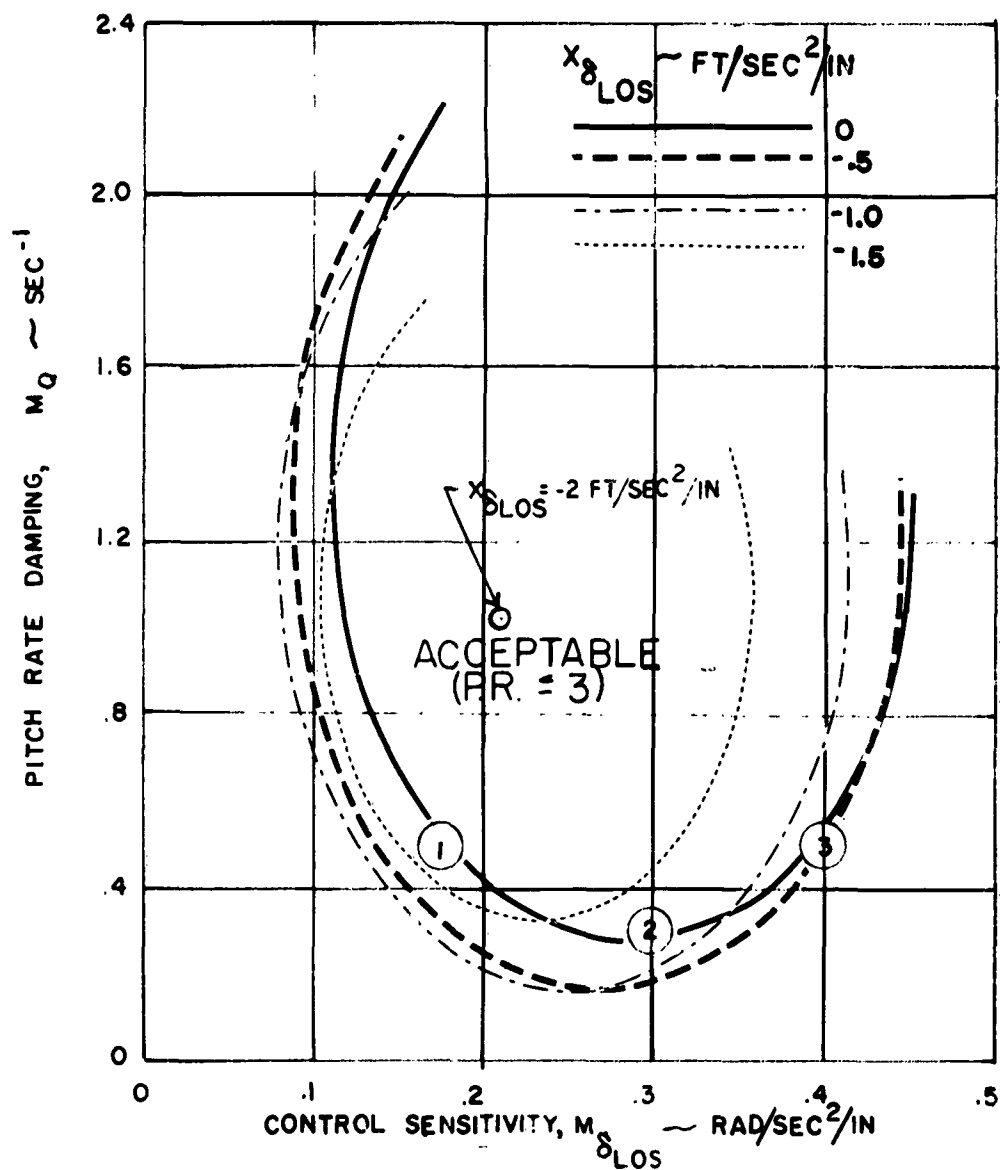
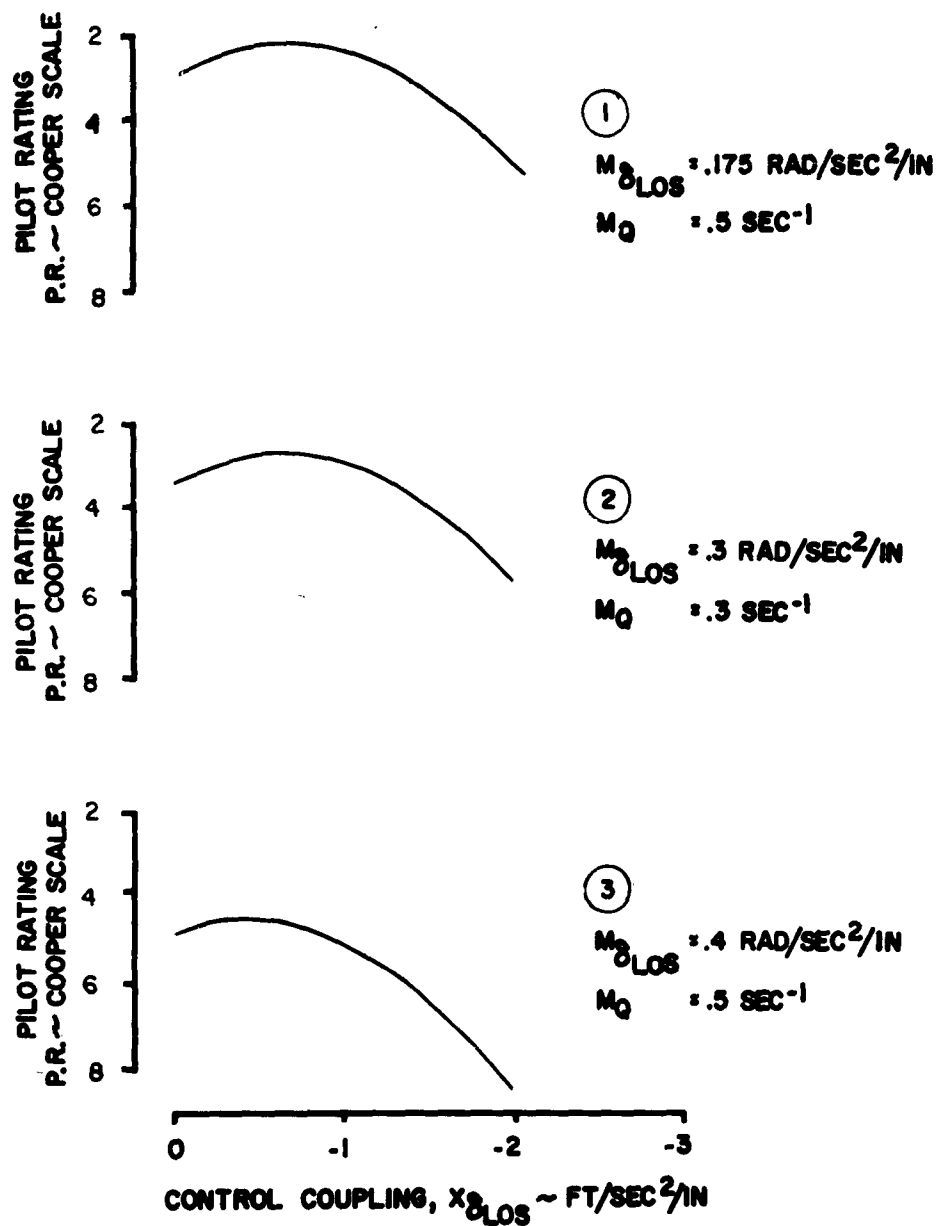


Fig. 12 Variation of Pilot Rating with Control Time Delay for the Four Points Indicated on Fig. 11



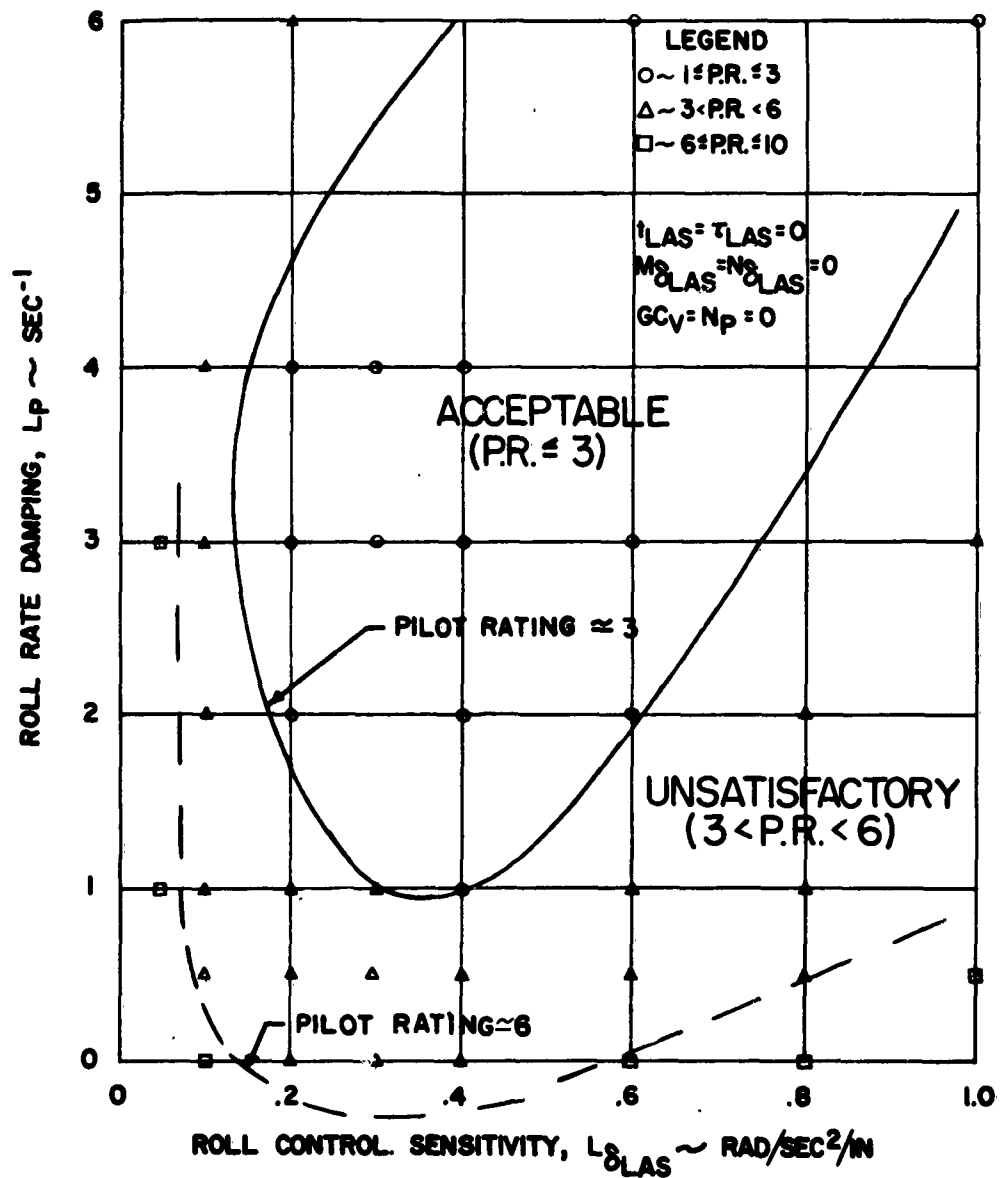
LONGITUDINAL HANDLING QUALITIES AT HOVER

Fig. 13 Effect of Forward-Acceleration: Control-Motion Coupling on Basic Acceptable Boundary



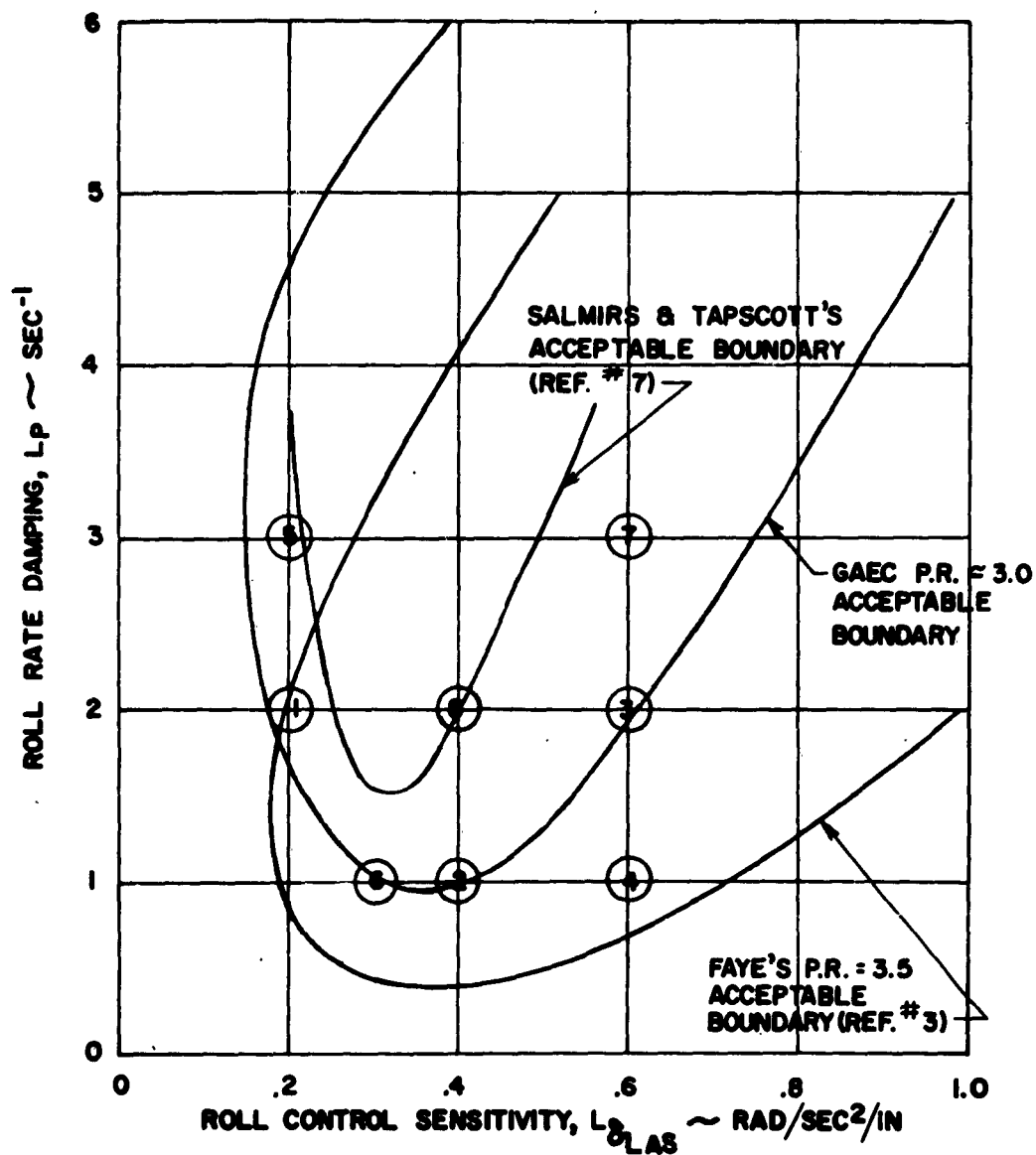
LONGITUDINAL HANDLING QUALITIES AT HOVER

Fig. 14 Variation of Pilot Rating with Forward-Acceleration:
Control-Motion Coupling for the Three Points
Indicated on Fig. 13



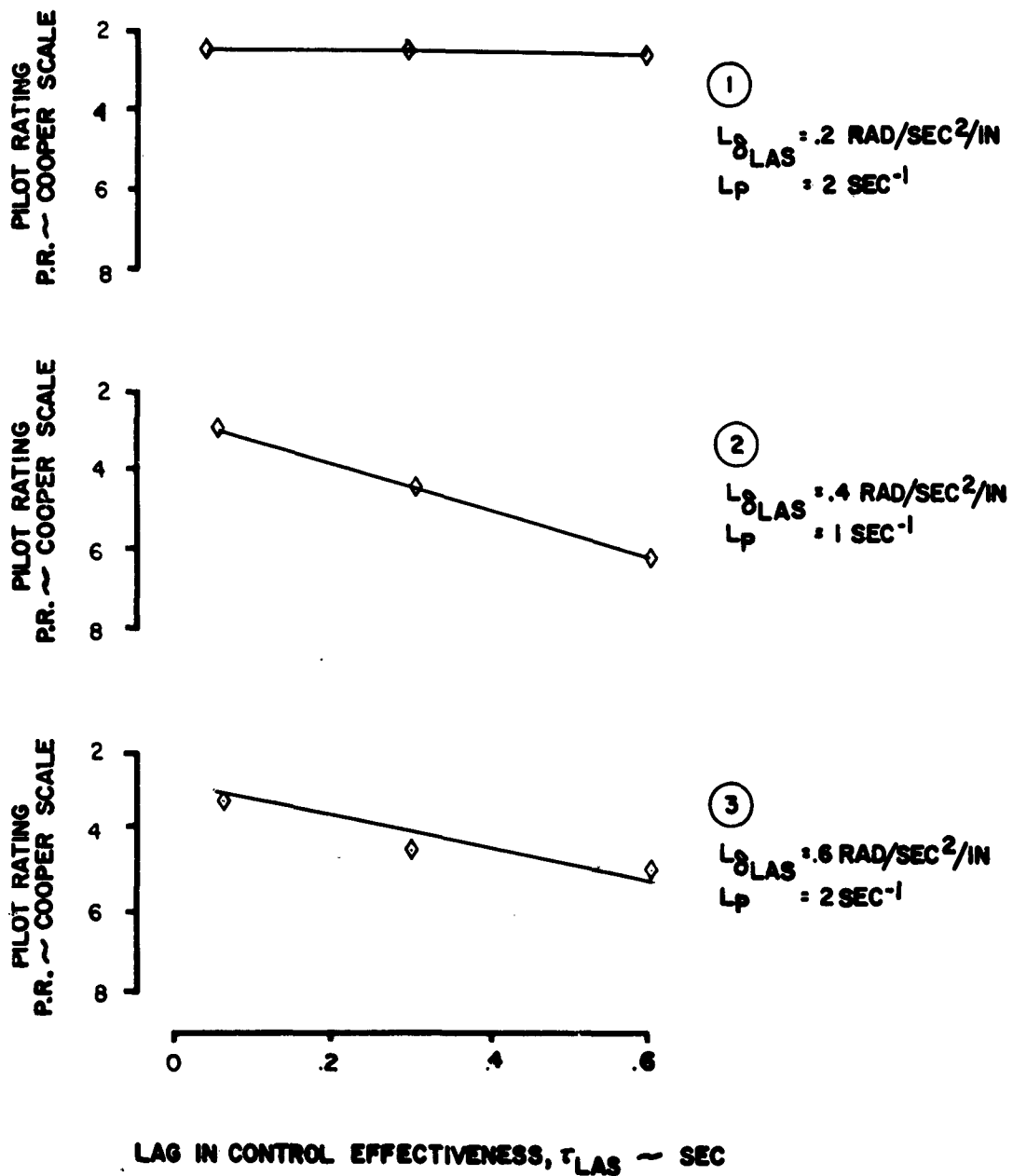
LATERAL HANDLING QUALITIES AT HOVER

Fig. 15 Basic Damping and Control Sensitivity Boundaries



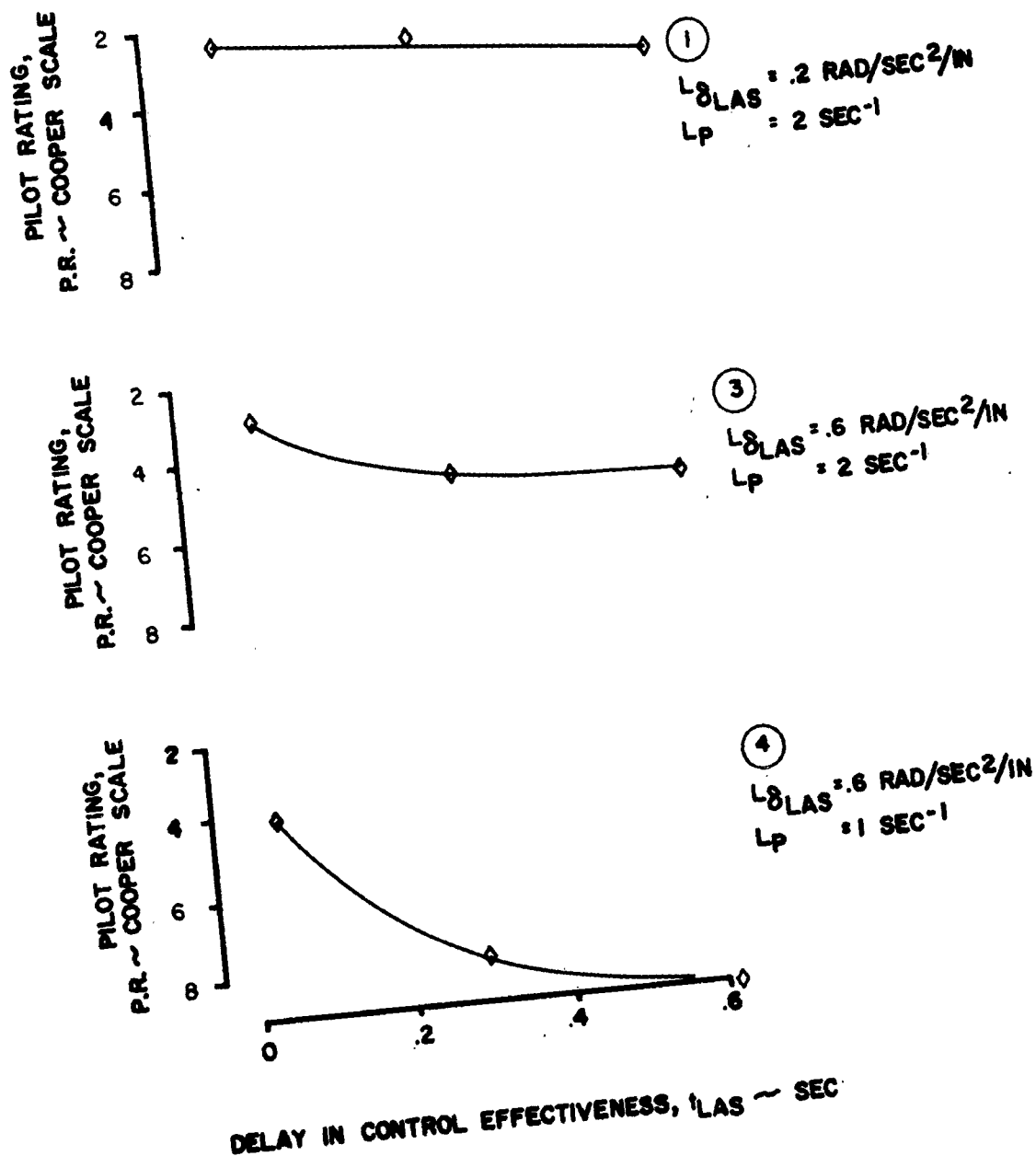
LATERAL HANDLING QUALITIES AT HOVER

Fig. 16 Comparison of Basic Acceptable Boundaries Obtained by Three Investigators

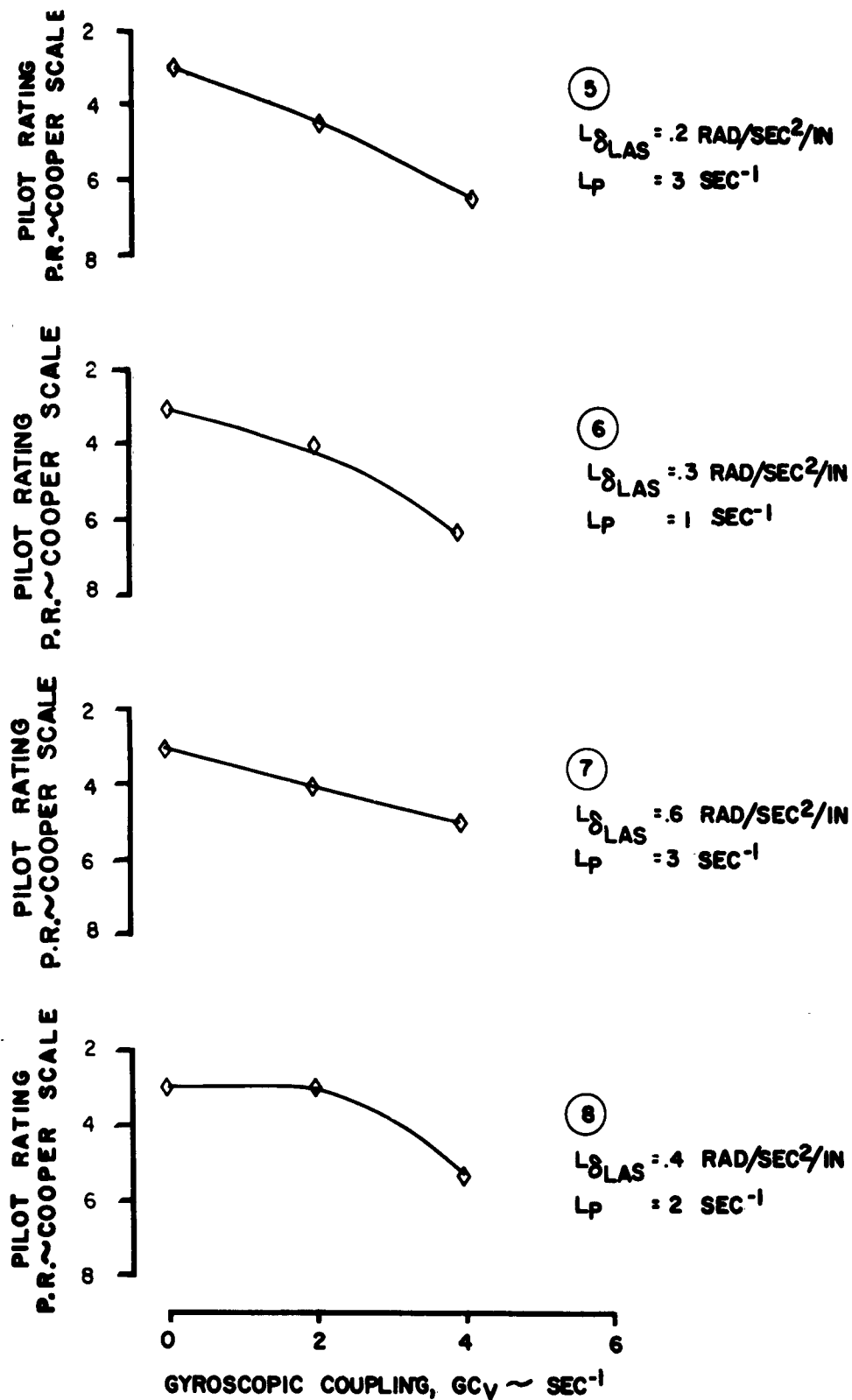


LATERAL HANDLING QUALITIES AT HOVER

Fig. 17 Variation of Pilot Rating with First-Order Control Lag for Three of the Points Indicated on Fig. 16

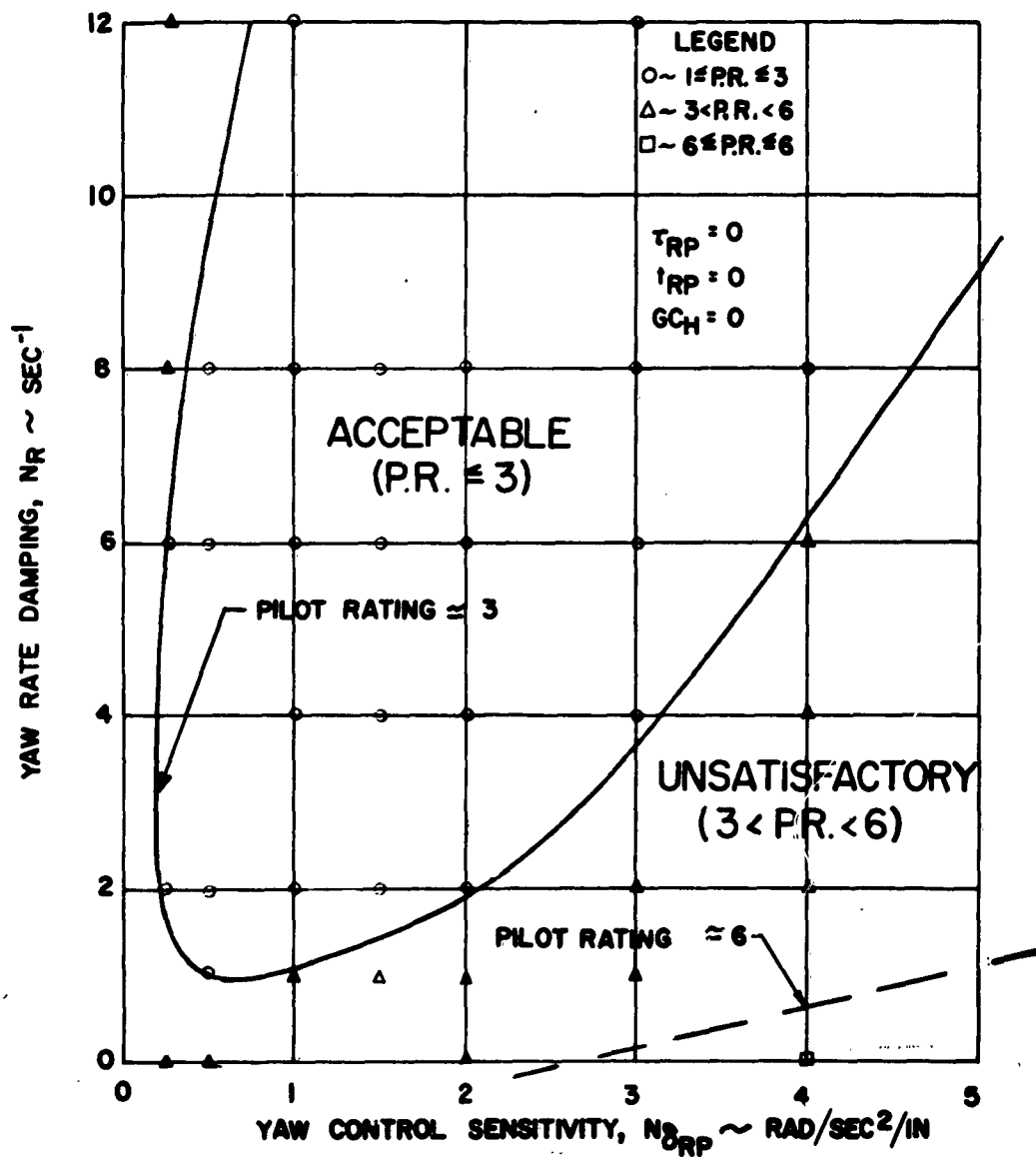


LATERAL HANDLING QUALITIES AT HOVER
 Fig. 18 Variation of Pilot Rating with Control Time Delay
 for Three of the Points Indicated on Fig. 16.



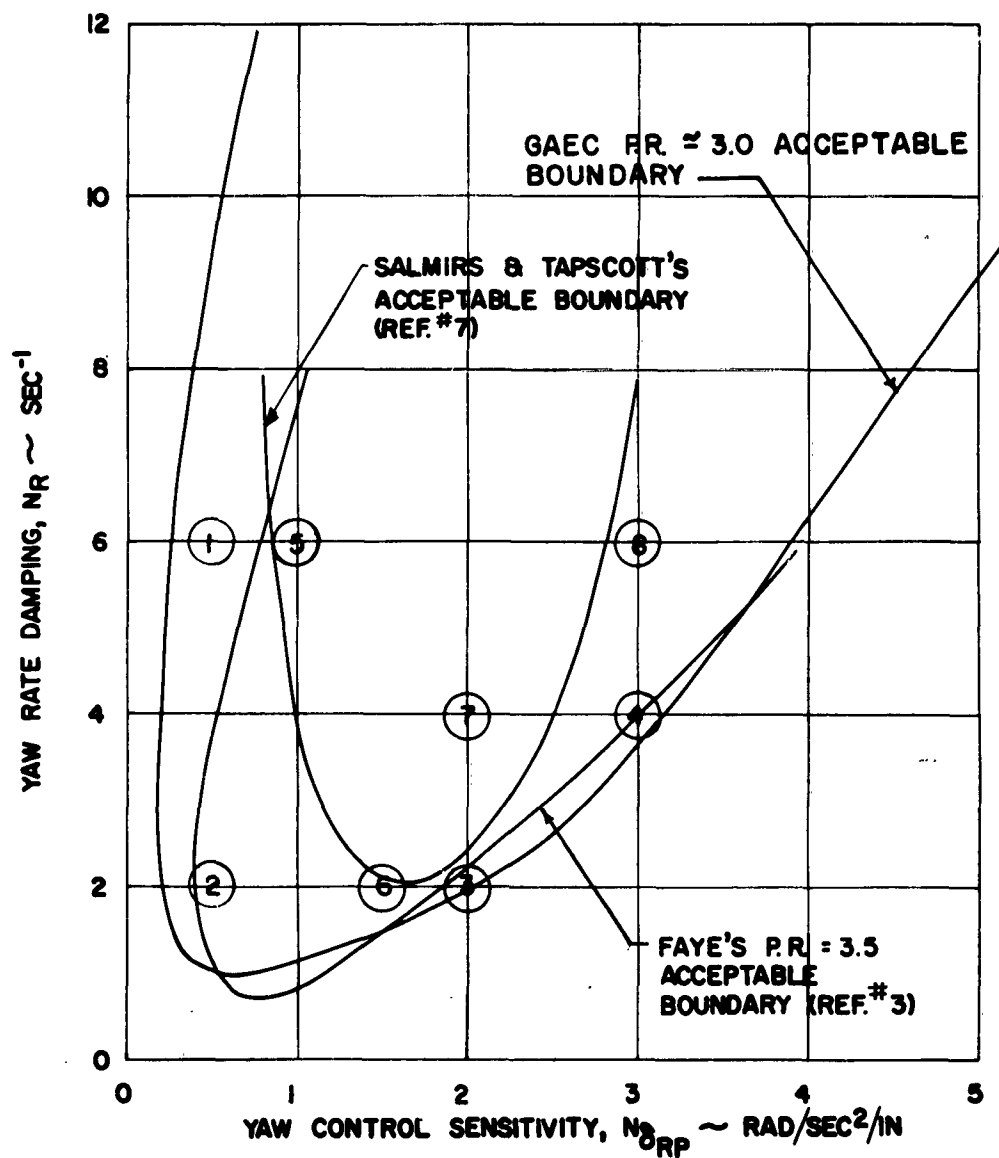
LATERAL HANDLING QUALITIES AT HOVER

Fig. 19 Variation of Pilot Rating with Gyroscopic Coupling for Four of the Points Indicated on Fig. 16



DIRECTIONAL HANDLING QUALITIES AT HOVER

Fig. 20 Basic Damping and Control Sensitivity Boundaries



DIRECTIONAL HANDLING QUALITIES AT HOVER

Fig. 21 Comparison of Basic Acceptable Boundaries Obtained by Three Investigators

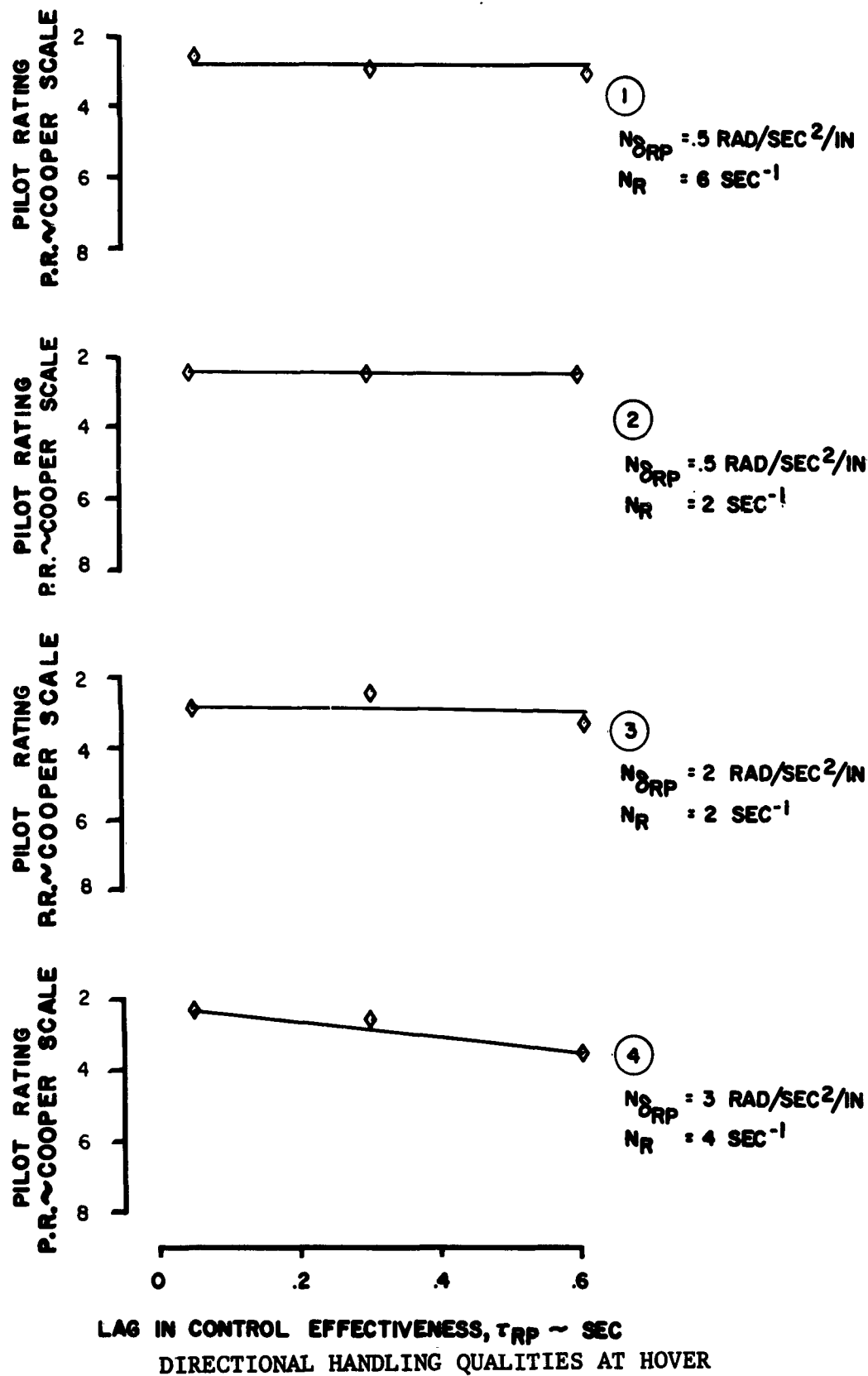
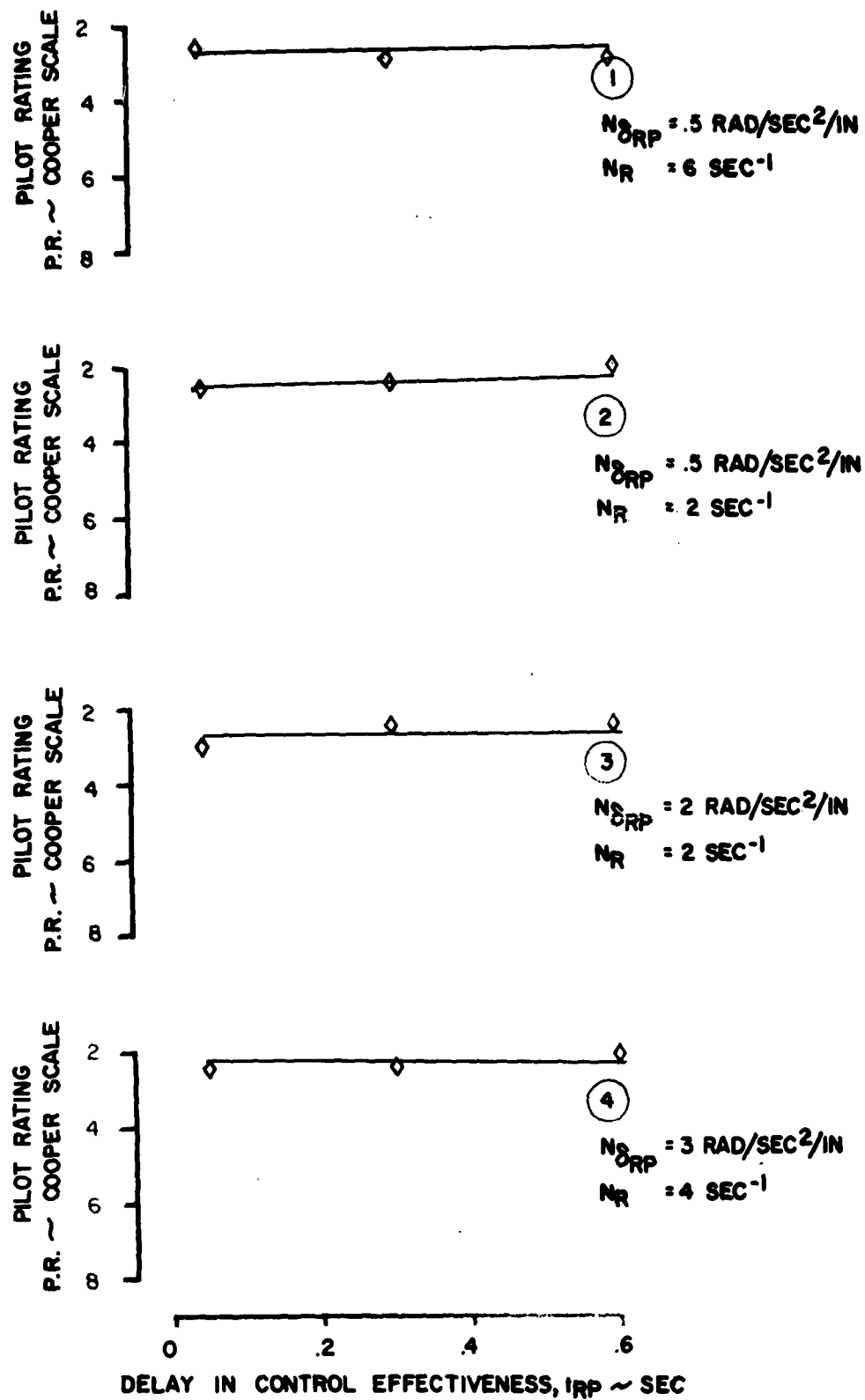
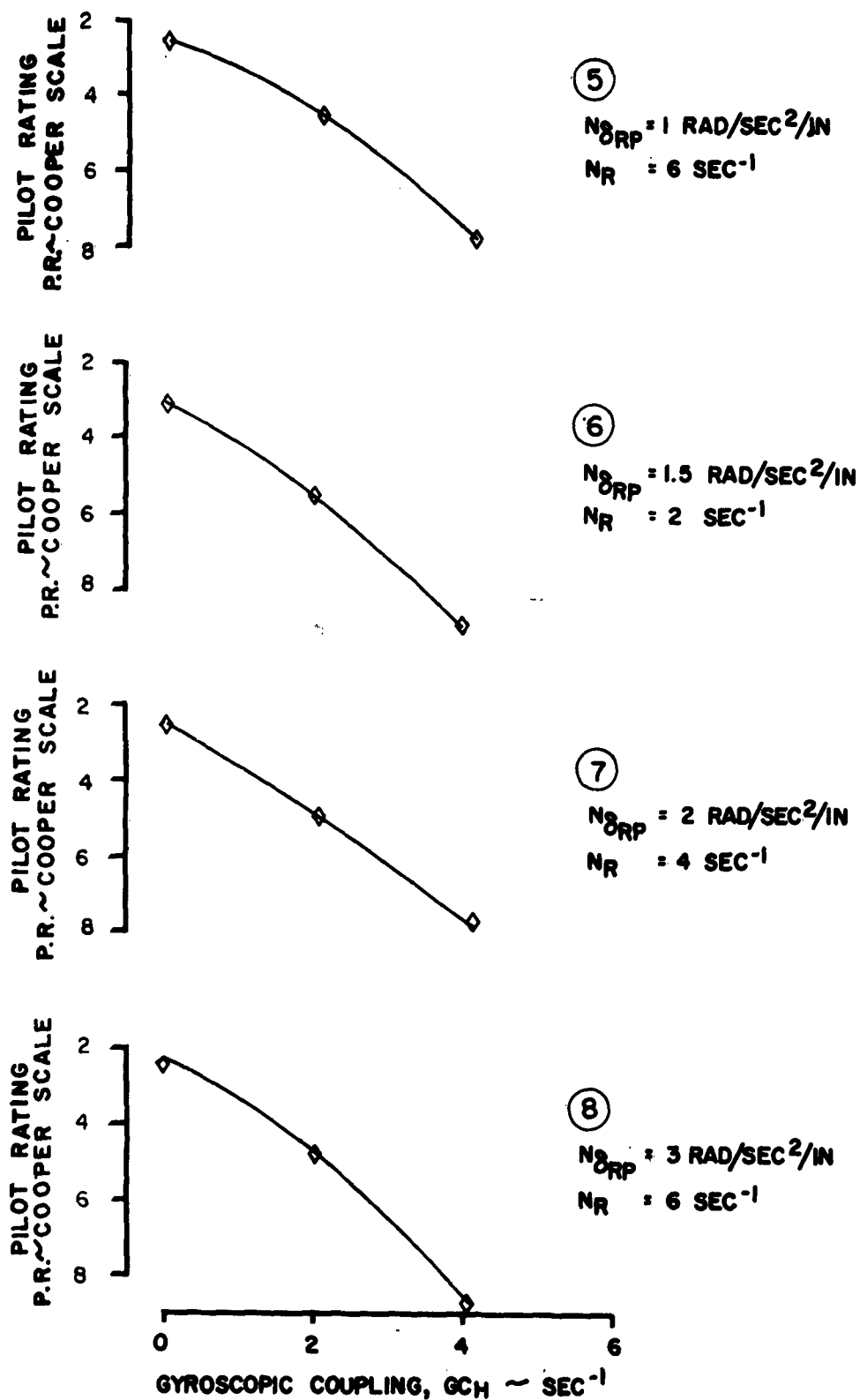


Fig. 22 Variation of Pilot Rating with First-Order Control Lag for the Four Points Indicated on Fig. 21



DIRECTIONAL HANDLING QUALITIES AT HOVER

Fig. 23 Variation of Pilot Rating with Control Time Delay for the Four Points Indicated on Fig. 21



DIRECTIONAL HANDLING QUALITIES AT HOVER

Fig. 24 Variation of Pilot Rating with Gyroscopic Coupling for Four of the Points Indicated on Fig. 21

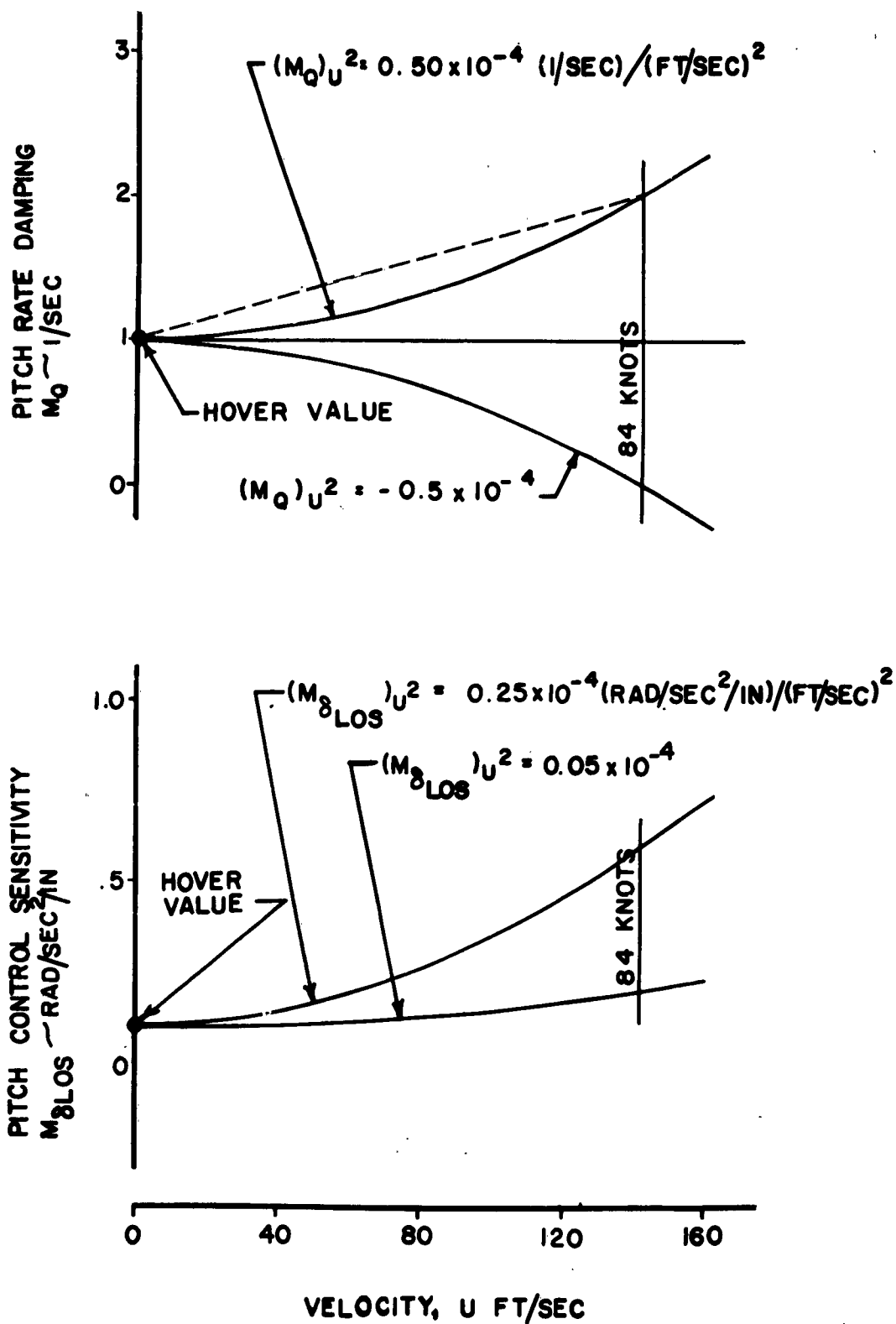
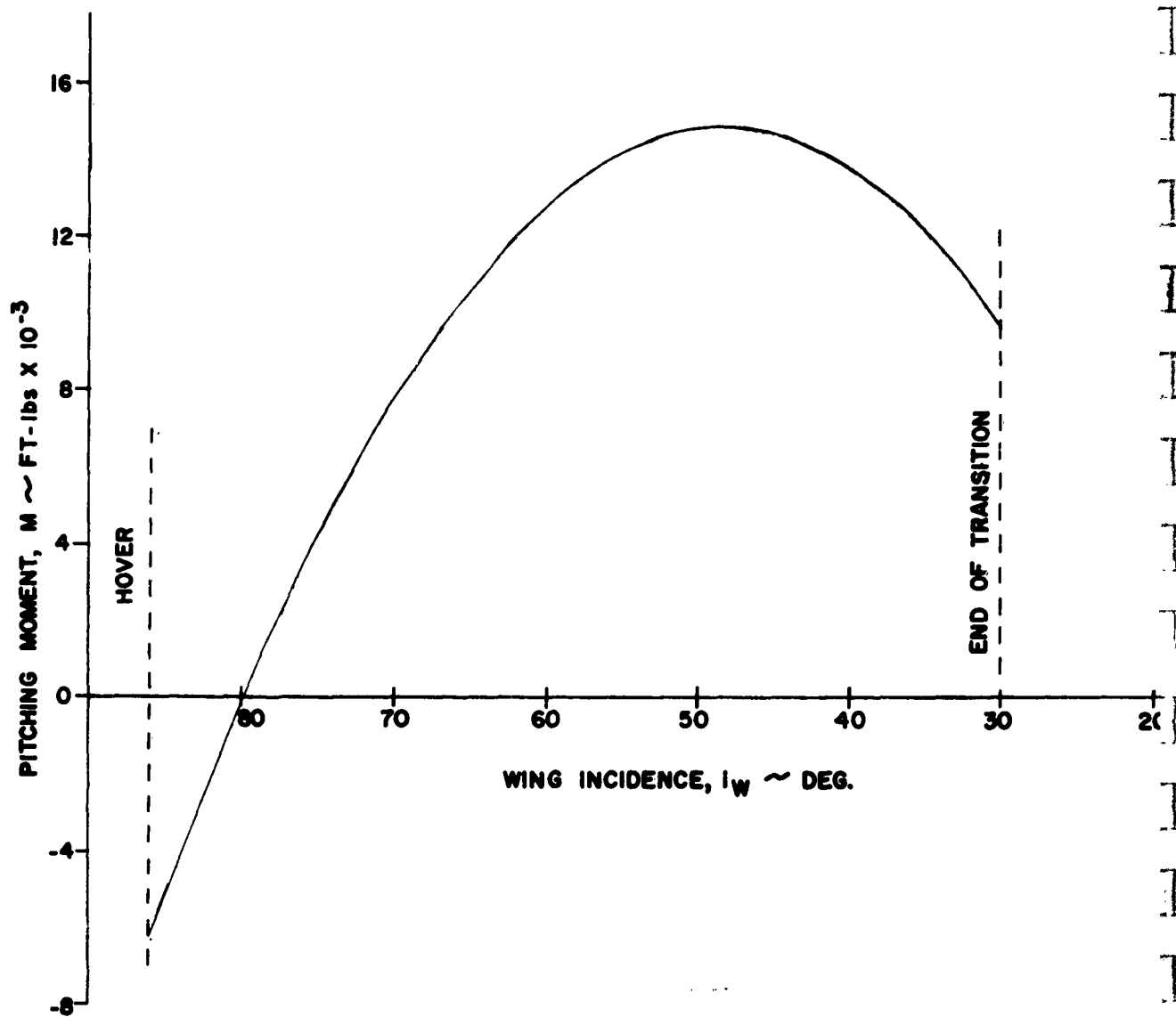
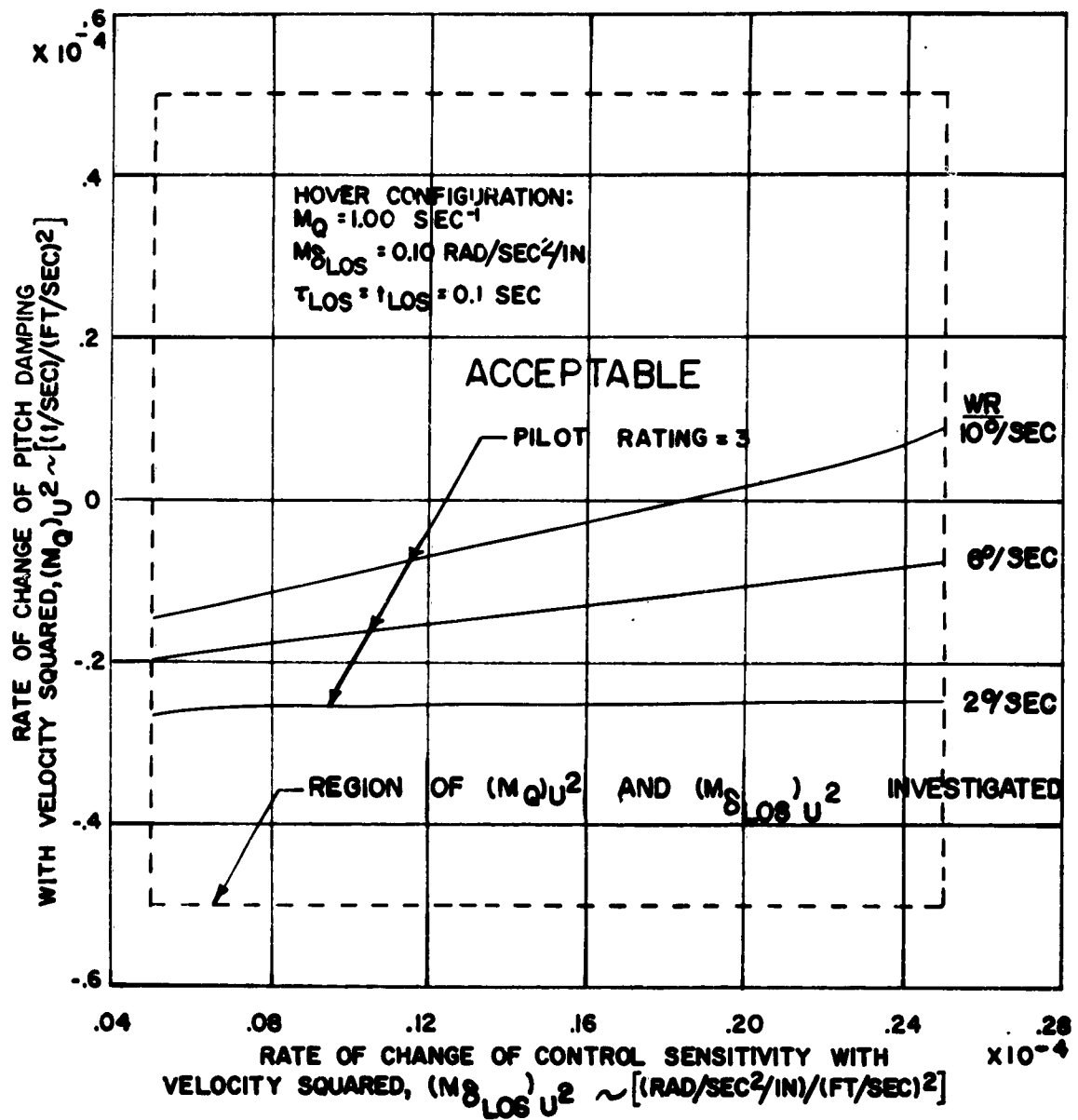


Fig. 25 Typical Variations of Damping and Control Sensitivity during Accelerating Transition



DIRECTIONAL HANDLING QUALITIES AT HOVER

Fig. 26 Variation of Static Pitching Moment with Wing Incidence for Fuselage Angle of Attack α_F Zero



LONGITUDINAL HANDLING QUALITIES IN ACCELERATING TRANSITION
 Fig. 27 Acceptable Boundaries of $(M_Q)_U^2$ and $(M_{\delta_{LOS}})_U^2$ for Various Wing Rates.

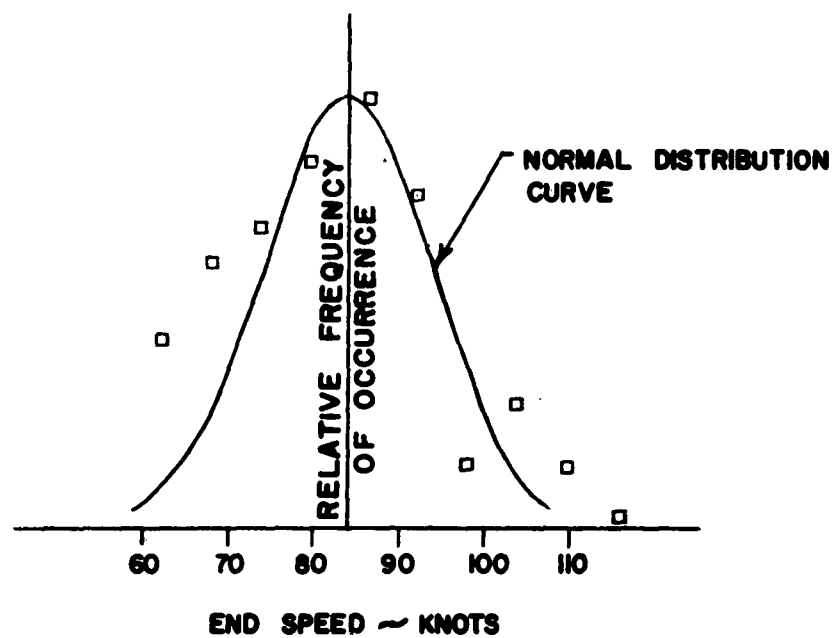
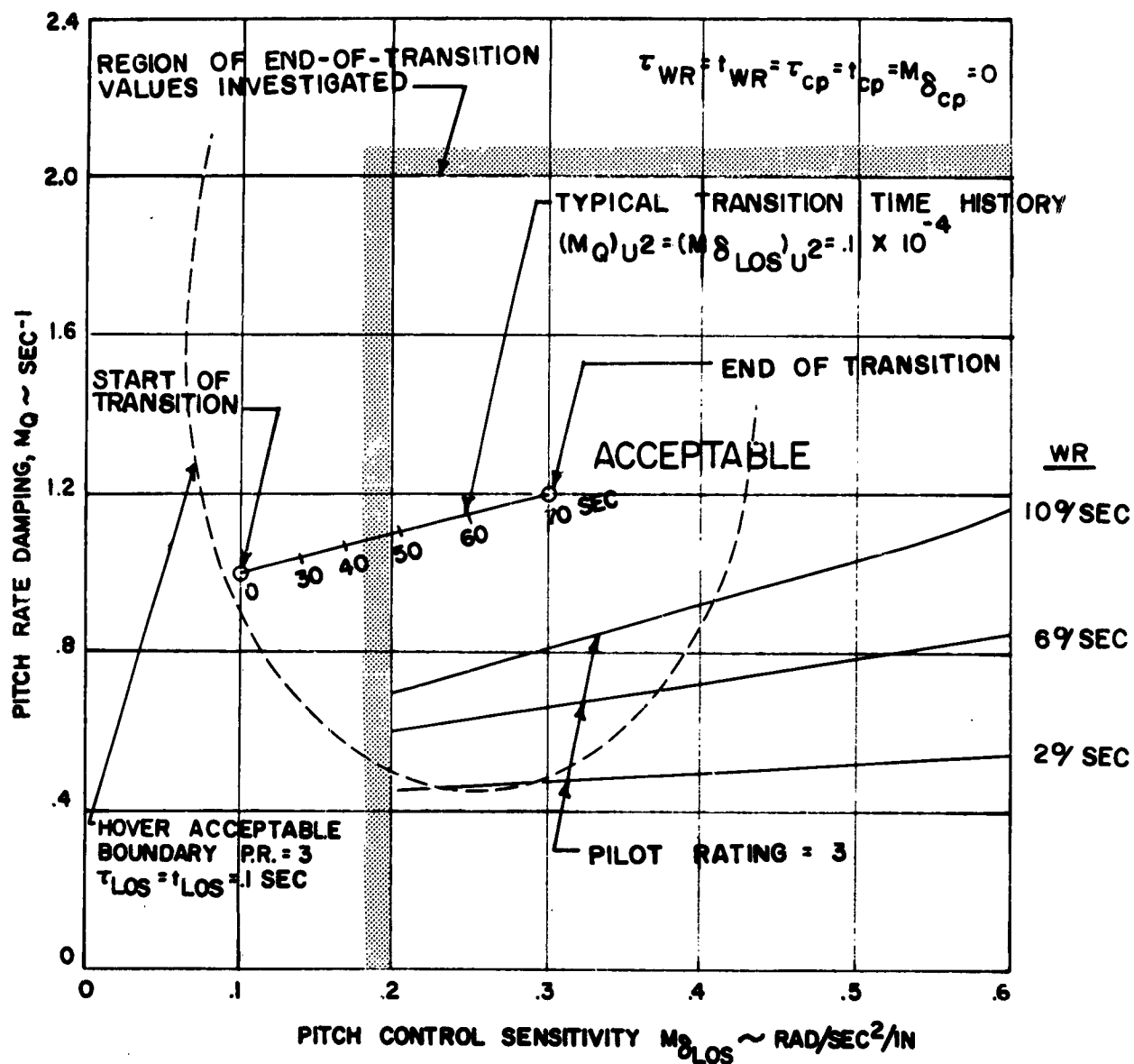
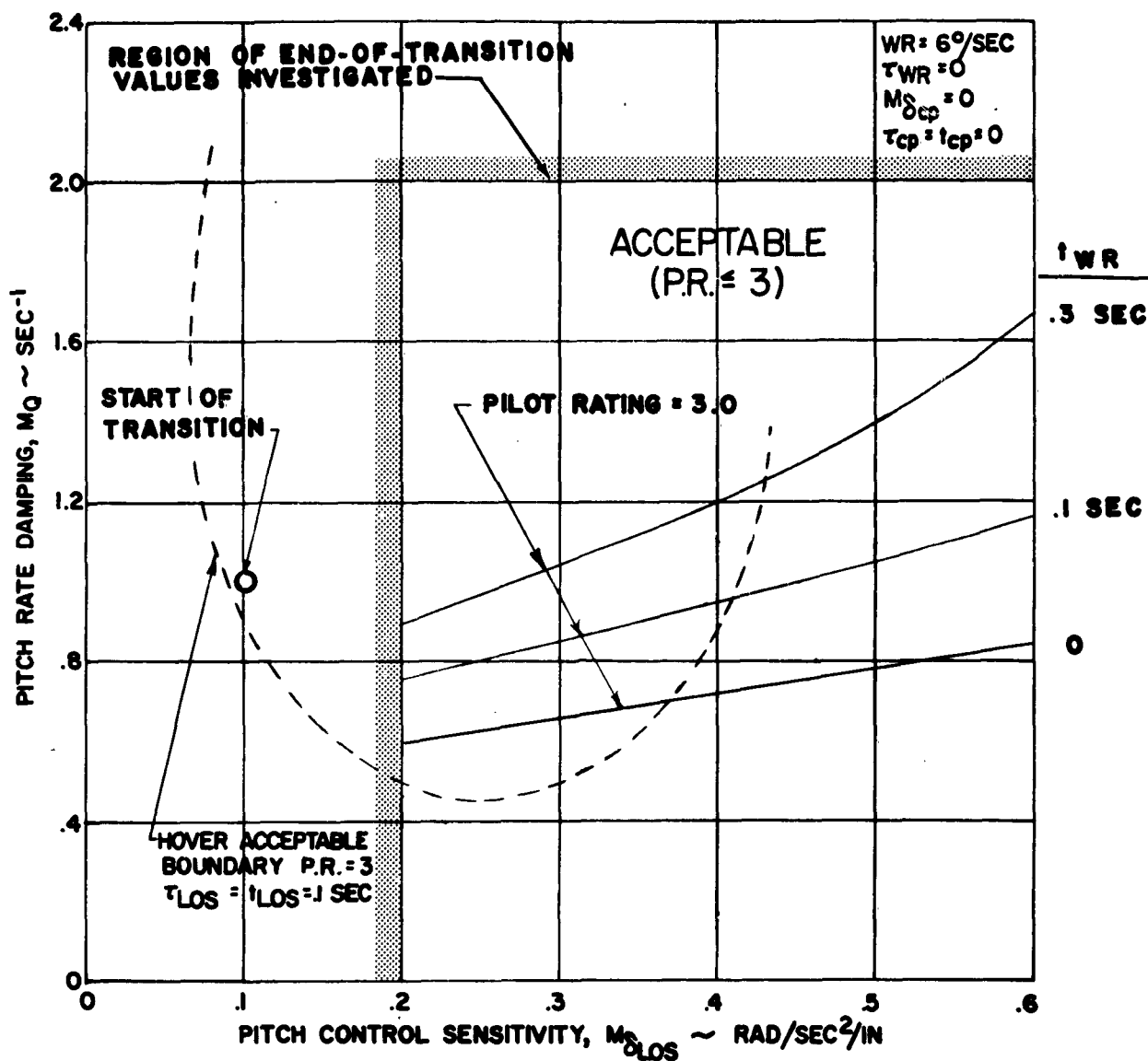


Fig. 28 Frequency Distribution of Speed at the End of Accelerating Transitions



LONGITUDINAL HANDLING QUALITIES IN ACCELERATING TRANSITION

Fig. 29 Acceptable Boundaries, for Various Wing Rates, of End-of-Transition Sensitivity, Based on Start-of-Transition Point Shown



LONGITUDINAL HANDLING QUALITIES IN ACCELERATING TRANSITION

Fig. 30 Effect of Wing Rate Control Time Delay on Acceptable End-of-Transition Boundary

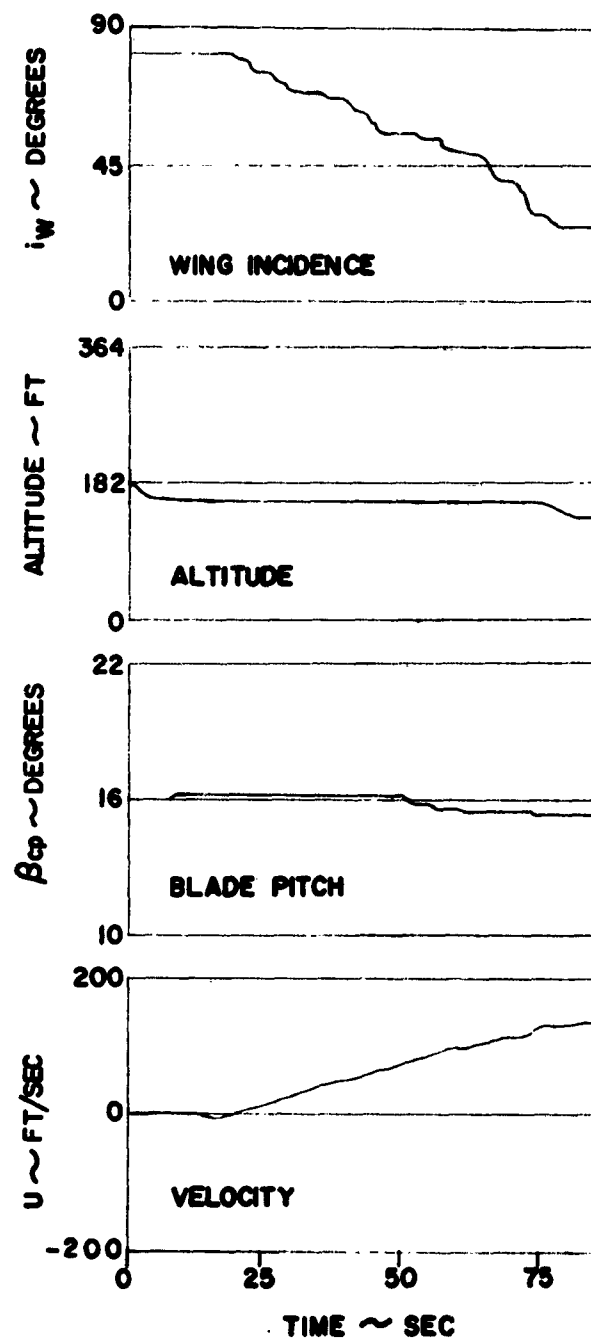


Fig. 32 Time History of a Typical Accelerating Transition

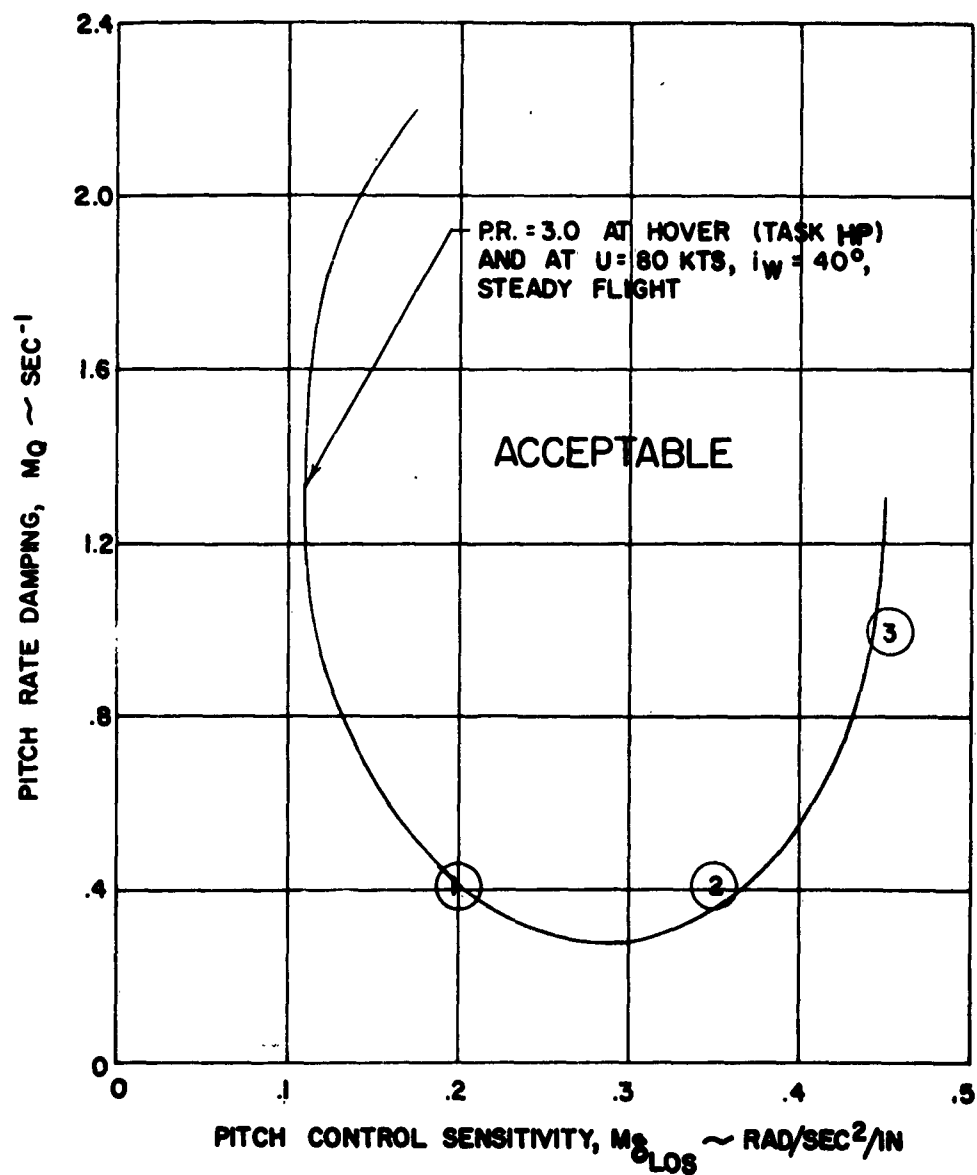
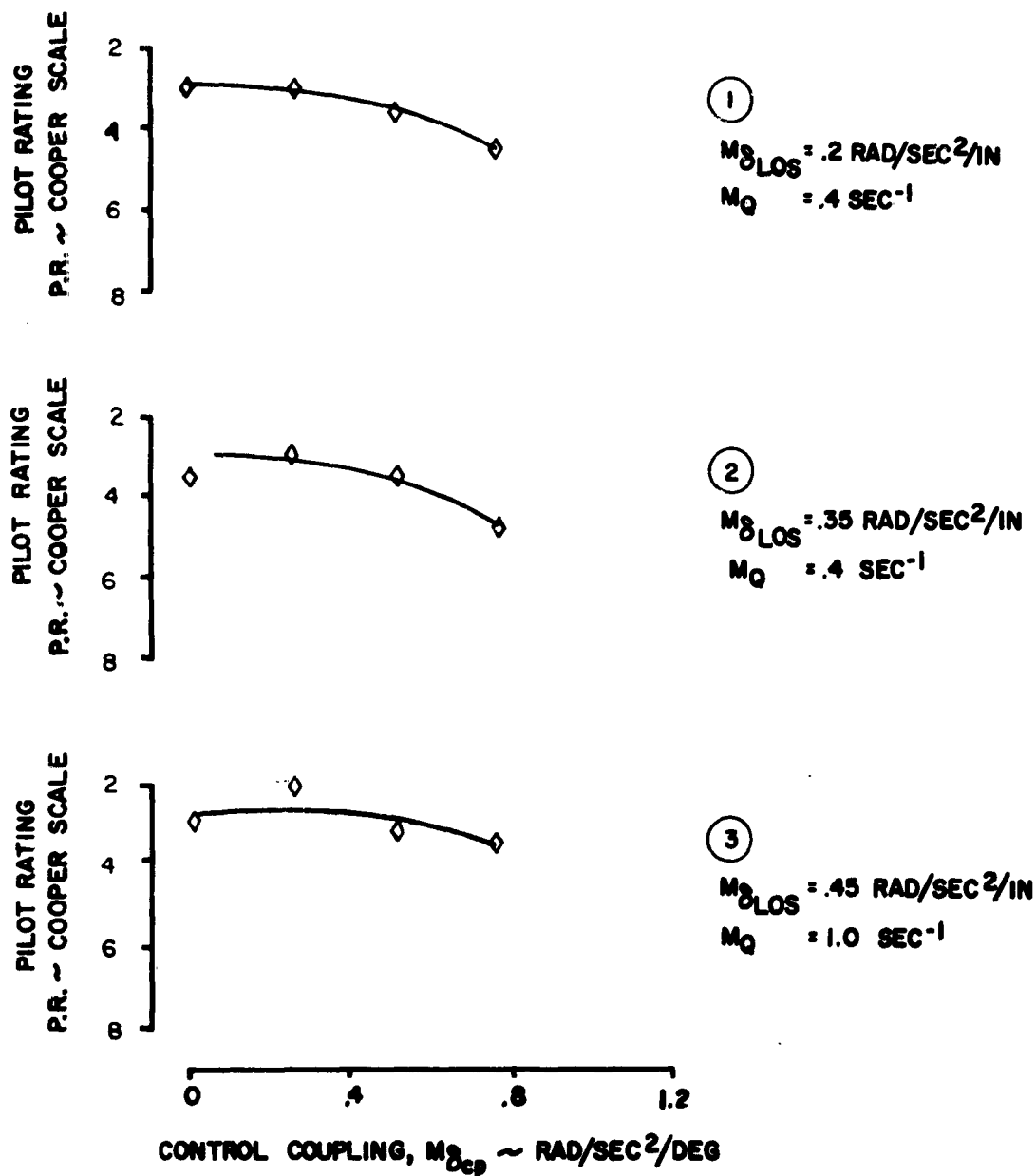
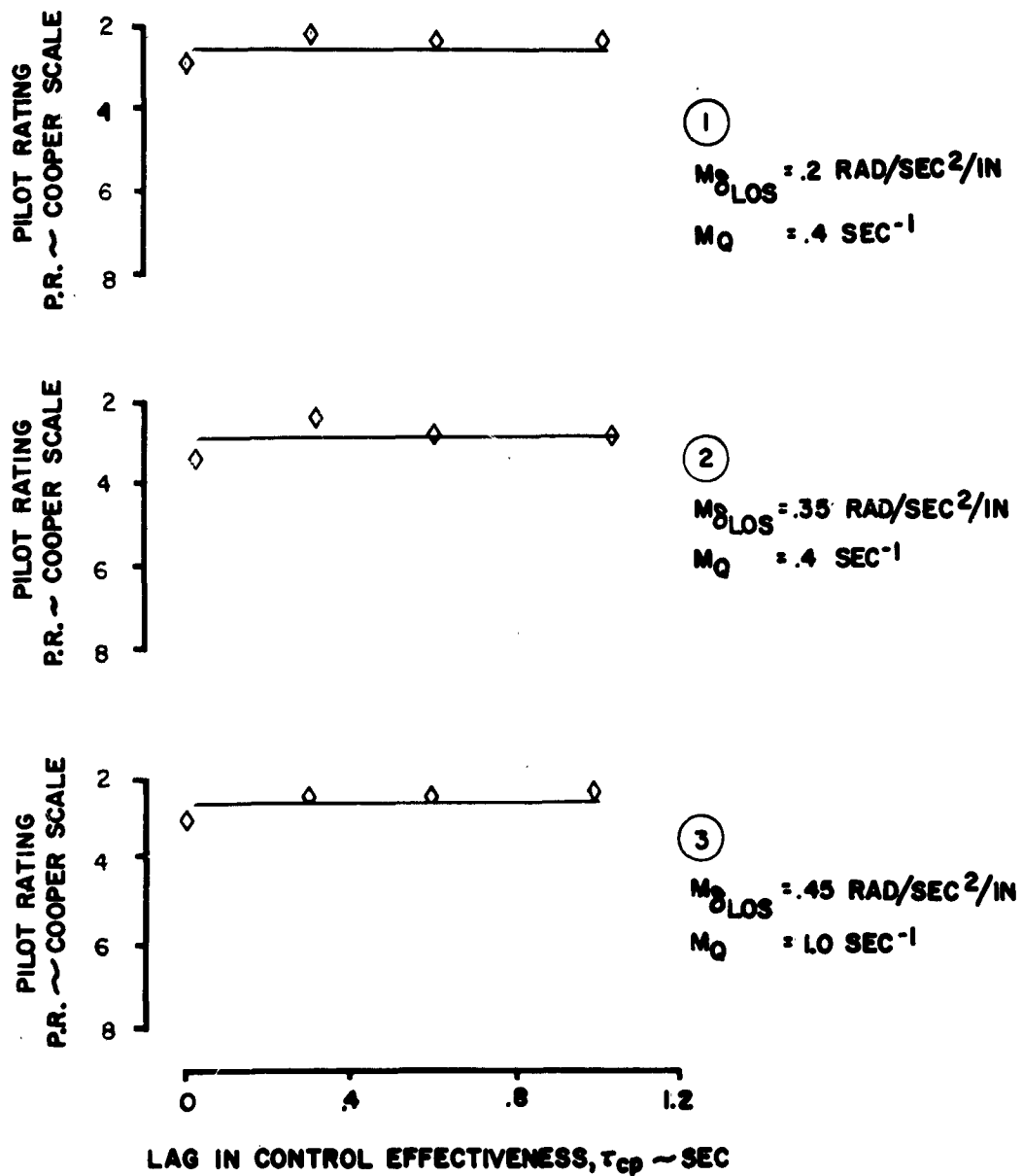


Fig. 33 Values of M_Q and $M_{\delta_{LOS}}$ Used in the Decelerating Transition



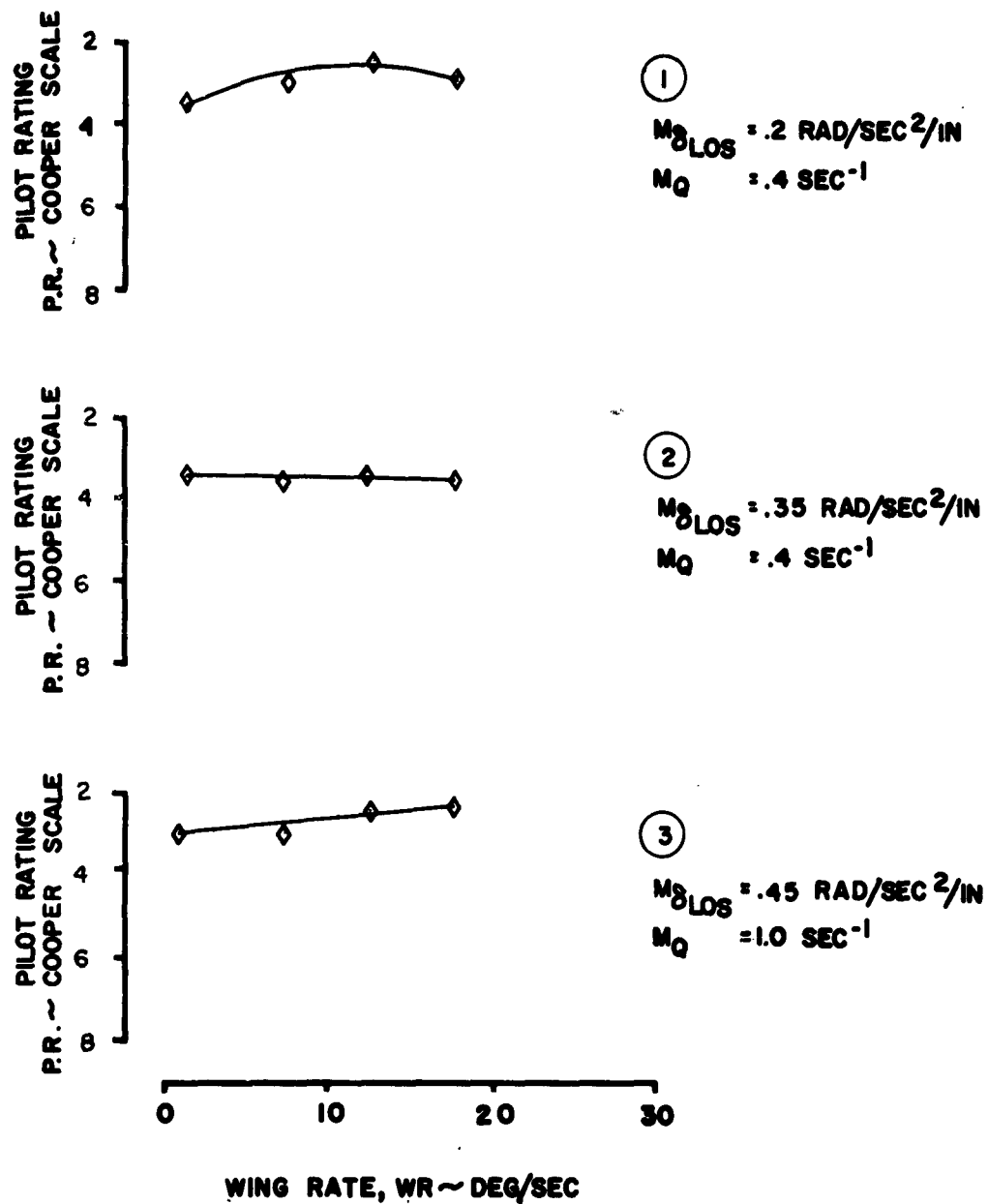
LONGITUDINAL HANDLING QUALITIES IN DECELERATING TRANSITION

Fig. 34 Variation of Pilot Rating with Pitching-Acceleration: Control-Motion Coupling for the Three Points Indicated on Fig. 33



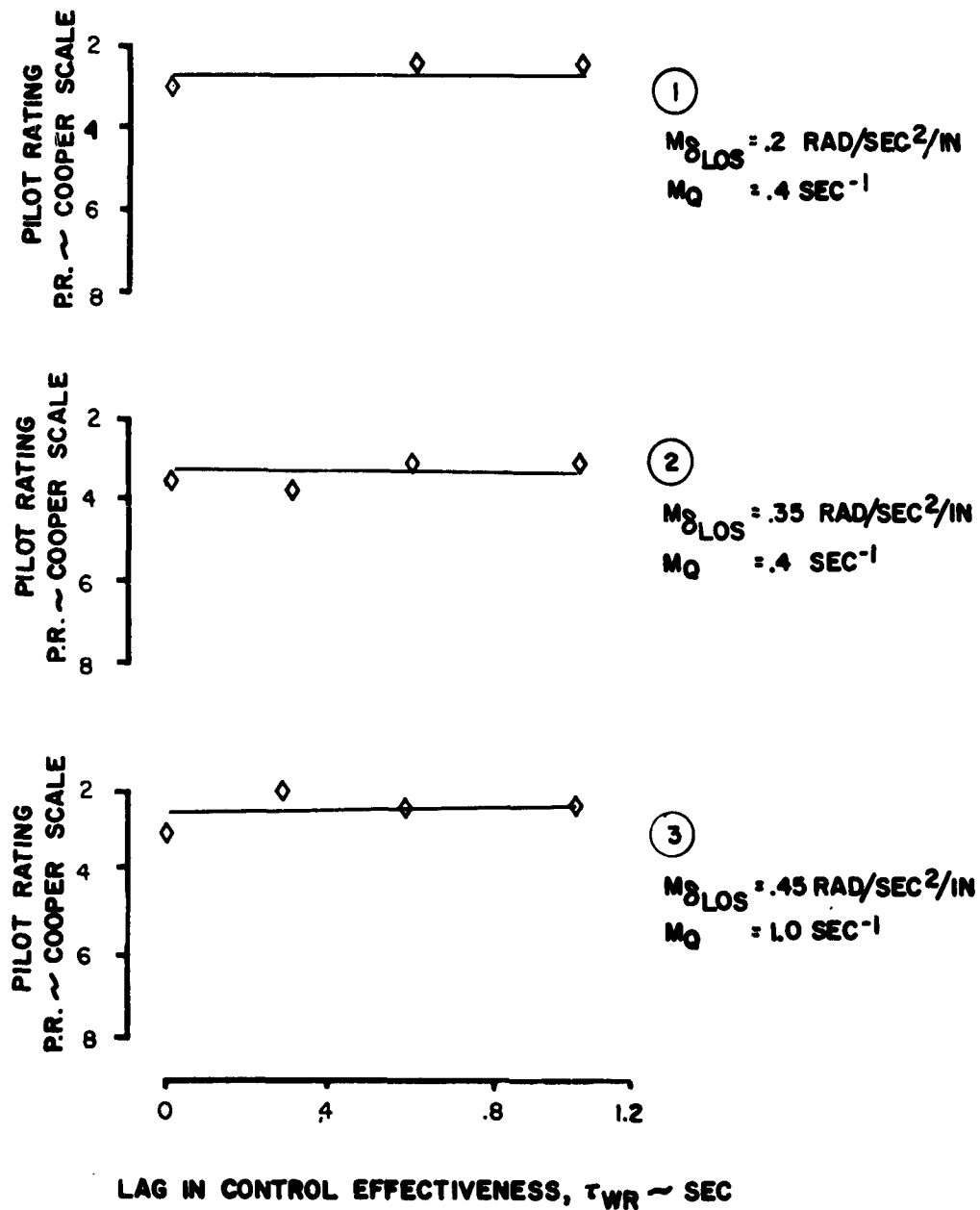
LONGITUDINAL HANDLING QUALITIES IN DECELERATING TRANSITION

Fig. 35 Variation of Pilot Rating with First-Order Pitch Control Lag for the Three Points Indicated on Fig. 33



LONGITUDINAL HANDLING QUALITIES IN DECELERATING TRANSITION

Fig. 36 Variation of Pilot Rating with Wing Rate for the Three Points Indicated on Fig. 33



LONGITUDINAL HANDLING QUALITIES IN DECELERATING TRANSITION

Fig.37 Variation of Pilot Rating with First-Order Wing-Rate Control Lag for the Three Points Indicated on Fig. 33

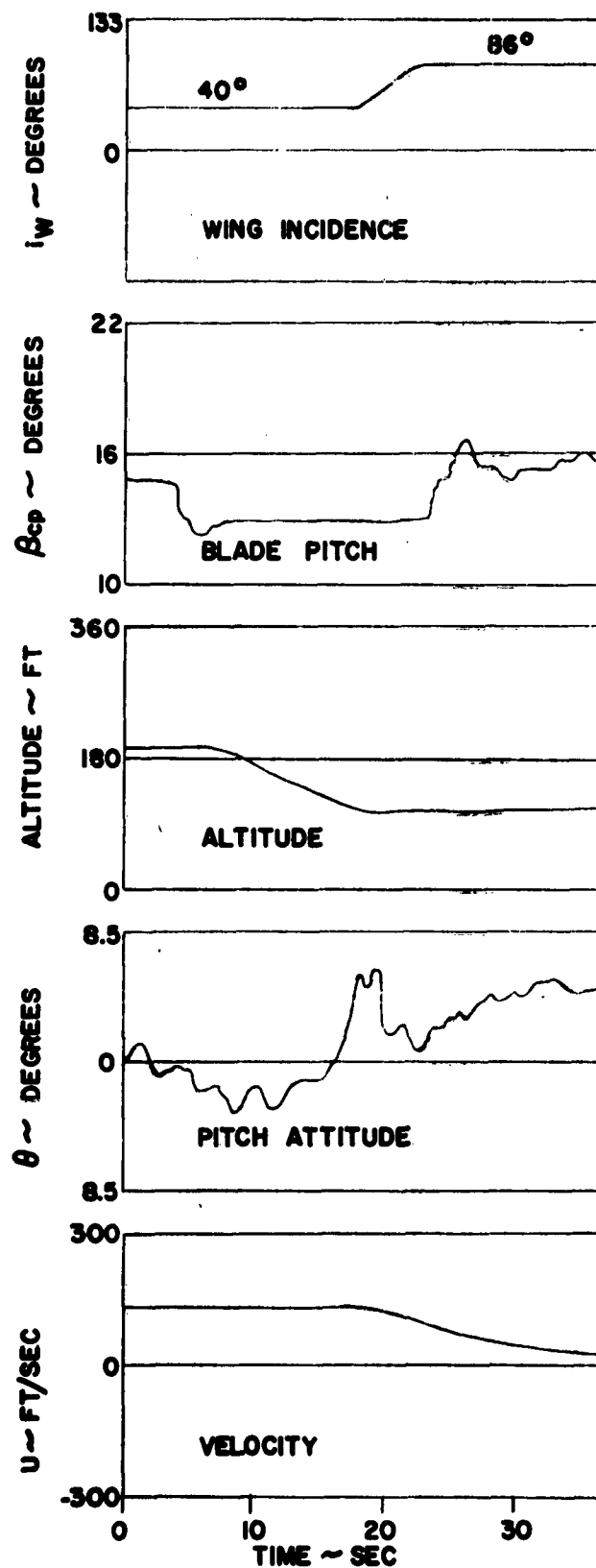


Fig. 38 Time History of a Typical Decelerating Transition