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CALCULATED AND FLIGHT-MEASURED HANDLING-QUALITIES FACTORS OF THREE SUBSONIC JET TRANSPORTS

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Moffett Field, Calif.

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SUMMARY

As part of an NASA intercenter study of jet transport stability and control problems in severe turbulence, several calculated and flight-measured handling-qualities factors of three current jet transports have been reviewed, and compared with various handling-qualities criteria.

The longitudinal and lateral handling-qualities parameters were calculated by means of a digital computer program, for several typical flight conditions within the normal operating envelopes, using aerodynamic and physical data supplied by the manufacturers of the aircraft as the most reliable information available. The calculations did not take account of effects of yaw dampers and automatic pitch trim devices.

On the basis of the current military specification and other published criteria, all three transports had satisfactory or acceptable predicted or flight-measured longitudinal short-period frequency and damping characteristics in the flight conditions of interest. Except for some cases of speed instability associated with disengagement of Mach trim compensation devices, acceptable longitudinal phugoid characteristics also were calculated for these transports. The lateral-directional oscillatory (Dutch roll) characteristics varied from satisfactory for normal operation to unacceptable with dampers inoperative. According to the current military specification, the predicted roll control characteristics were generally acceptable for two of the three transports.

INTRODUCTION

In recent years, several large jet transport aircraft have suffered loss of control during scheduled operation. In some cases, recovery was not effected and destruction of the airplane resulted. In addition to the class of airplane, these incidents had two factors in common: the aircraft were being operated under instrument conditions and in severe storm turbulence.

In December 1963, a cooperative NASA study was initiated, involving research teams from the Ames, Langley, and Flight Research Centers, to investigate all pertinent aspects of this problem. Reference 1 summarizes the overall program and presents some of the key observations resulting from a limited analysis at the Ames Research Center of the handling qualities of three current jet transports.

In this report, the results of the handling-qualities analysis are discussed in greater detail and in terms of existing or recommended numerical criteria. Comparisons of the calculated characteristics with these criteria are not used as bases for conclusions as to the acceptability of a given airplane because of inconsistencies among some of the criteria and a lack of clearly established applicability of the criteria to the jet upsets. Rather, the criteria are included to provide a structure for presentation of representative behavior and to serve as indicators of gross inadequacies. Some comparisons between computed characteristics and flight measurements are also included.

NOTATION

b wing span, ft

$\bar{c}$ wing mean aerodynamic chord, ft

C_D drag coefficient, $\frac{\text{drag}}{q_\infty S}$

C_{D_α} $\frac{\partial C_D}{\partial \alpha}$, $\frac{1}{\text{rad}}$

$C_{D_{\delta_e}}$ $\frac{\partial C_D}{\partial \delta_e}$, $\frac{1}{\text{rad}}$

C_{D_M} $\frac{\partial C_D}{\partial M}$

C_L lift coefficient, $\frac{\text{lift}}{q_\infty S}$

C_{L_α} $\frac{\partial C_L}{\partial \alpha}$, $\frac{1}{\text{rad}}$

$C_{L_{\dot{\alpha}}}$ $\frac{\partial C_L}{\partial(\dot{\alpha}\bar{c}/2V)}$, $\frac{1}{\text{rad}}$

$C_{L_{\delta_e}}$ $\frac{\partial C_L}{\partial \delta_e}$, $\frac{1}{\text{rad}}$

C_{L_M} $\frac{\partial C_L}{\partial M}$

C_l rolling-moment coefficient, $\frac{\text{rolling moment}}{q_\infty Sb}$

C_{l_β} $\frac{\partial C_l}{\partial \beta}$, $\frac{1}{\text{rad}}$

$C_{l_{\delta_a}}$ $\frac{\partial C_l}{\partial \delta_a}$, $\frac{1}{\text{rad}}$

$C_{l_{\delta_r}}$ $\frac{\partial C_l}{\partial \delta_r}$, $\frac{1}{\text{rad}}$

C_{l_p} $\frac{\partial C_l}{\partial(pb/2V)}$, $\frac{1}{\text{rad}}$

C_{l_r} $\frac{\partial C_l}{\partial(rb/2V)}$, $\frac{1}{\text{rad}}$

C_m pitching-moment coefficient, $\frac{\text{pitching moment}}{q_\infty S\bar{c}}$

C_{m_α} $\frac{\partial C_m}{\partial \alpha}$, $\frac{1}{\text{rad}}$

$C_{m_{\dot{\alpha}}}$ $\frac{\partial C_m}{\partial(\dot{\alpha}\bar{c}/2V)}$, $\frac{1}{\text{rad}}$

$C_{m_{\delta_e}}$ $\frac{\partial C_m}{\partial \delta_e}$, $\frac{1}{\text{rad}}$

C_{m_M} $\frac{\partial C_m}{\partial M}$

C_{m_q} $\frac{\partial C_m}{\partial(q\bar{c}/2V)}$, $\frac{1}{\text{rad}}$

C_n yawing-moment coefficient, $\frac{\text{yawing moment}}{q_\infty Sb}$

C_{n_β} $\frac{\partial C_n}{\partial \beta}$, $\frac{1}{\text{rad}}$

$C_{n_{\delta_a}}$ $\frac{\partial C_n}{\partial \delta_a}$, $\frac{1}{\text{rad}}$

$C_{n_{\delta_r}}$ $\frac{\partial C_n}{\partial \delta_r}$, $\frac{1}{\text{rad}}$

C_{n_p} $\frac{\partial C_n}{\partial (pb/2V)}$, $\frac{1}{\text{rad}}$

C_{n_r} $\frac{\partial C_n}{\partial (rb/2V)}$, $\frac{1}{\text{rad}}$

C_Y side-force coefficient, $\frac{\text{side force}}{q_\infty S}$

C_{Y_β} $\frac{\partial C_Y}{\partial \beta}$, $\frac{1}{\text{rad}}$

$C_{Y_{\delta_a}}$ $\frac{\partial C_Y}{\partial \delta_a}$, $\frac{1}{\text{rad}}$

$C_{Y_{\delta_r}}$ $\frac{\partial C_Y}{\partial \delta_r}$, $\frac{1}{\text{rad}}$

C_{Y_p} $\frac{\partial C_Y}{\partial (pb/2V)}$, $\frac{1}{\text{rad}}$

C_{Y_r} $\frac{\partial C_Y}{\partial (rb/2V)}$, $\frac{1}{\text{rad}}$

$C_{1/10}$ cycles to damp to 1/10 amplitude

$C_{1/2}$ cycles to damp to 1/2 amplitude

$f_{n,SP}$ undamped natural frequency of longitudinal short-period mode, cps

h_p pressure altitude, ft

I_X, I_Y, I_Z rolling, pitching, and yawing moments of inertia, respectively, about body reference axes, slug-ft^2

I_{XZ} product of inertia about body reference axes, slug-ft^2

K constant relating damping criterion to $T_{1/2}$

L_α $\frac{q_\infty S}{mV} C_{L_\alpha}$, $\frac{1}{\text{sec}}$

M Mach number

M_M, M_{NO} maximum permitted Mach number for normal operation, military and civil aircraft, respectively

n_Z normal acceleration, positive upward, g

n_{Z_α} $\frac{\partial n_Z}{\partial \alpha}$, g/rad

p rolling angular velocity, rad/sec

$\left(\frac{pb}{2V}\right)_{SS,max}$ maximum attainable steady-state wing-tip helix angle, rad

$\dot{p}$ $\frac{dp}{dt}$, rad/sec^2

$\dot{p}_{max}$ maximum attainable rolling acceleration, rad/sec^2

P_d Dutch roll oscillation period, sec

P_{PH} longitudinal phugoid oscillation period, sec

q	pitching angular velocity, rad/sec
q_{∞}	dynamic pressure, lb/ft^2
r	yawing angular velocity, rad/sec
s	complex frequency (Laplace operator)
S	wing reference area, ft^2
T	thrust, lb
$\frac{\partial T}{\partial M}$	variation of thrust with Mach number at trim condition, lb
$T_{1/2,d}$	Dutch roll time to damp to half amplitude, sec
$T_{1/2,PH}$	phugoid time to damp to half amplitude, sec
t	time, sec
V	true airspeed, ft/sec
V_c	calibrated airspeed, knots
V_e	equivalent airspeed, knots or ft/sec
V_{NO}	maximum permitted calibrated airspeed for normal operation, knots
α	angle of attack, radians
α_o	trimmed angle of attack, deg
β	angle of sideslip, radians
γ_o	trimmed longitudinal flight-path inclination, positive for climb, deg
δ_a	total aileron deflection, positive for right aileron down, radians
δ_e	elevator deflection, positive trailing edge down, radians
δ_r	rudder deflection, positive trailing edge left, radians
$\zeta_d, \zeta_{PH}, \zeta_{SP}$	damping ratio of the oscillatory Dutch roll, longitudinal phugoid, and longitudinal short-period modes, respectively
τ_{R_1}	single-degree-of-freedom roll time constant, sec
τ_{R_3}	roll-subsidence mode time constant, sec
τ_s	spiral mode time constant, sec
φ	bank angle, radians
$\frac{\lvert\varphi\rvert}{\lvert\beta\rvert}$	ratio of bank amplitude to sideslip amplitude in the oscillatory Dutch roll mode
$\frac{\lvert\varphi\rvert}{\lvert v_e\rvert}$	$\frac{57.3}{V_e}\frac{\lvert\varphi\rvert}{\lvert\beta\rvert}$, $\frac{\text{deg}}{\text{ft/sec}}$

$\omega_d, \omega_{n,PH}, \omega_{n,SP}$ undamped natural frequency of the oscillatory Dutch roll, longitudinal phugoid, and longitudinal short-period modes, respectively, rad/sec

ω_φ frequency of the oscillatory part of the numerator of the $\frac{\varphi}{\delta_a}$ transfer function, rad/sec

METHOD

Computation

Computation of the stability, control, and handling-qualities factors of interest was based on equations of motion that included all six airplane degrees of freedom. The equations were linear and perturbations in velocities and angles were assumed small. The calculations were performed by digital computer programs (hereinafter referred to as the "exact factors" programs),[1] which treated the longitudinal and the lateral-directional sets of equations separately. The programs were written in Fortran IV computer language.

Input Data

The aerodynamic stability derivatives, mass and inertia parameters, and dimensional data for each airplane and flight condition were based largely on wind-tunnel measurements supplemented by flight tests, and were represented by the aircraft manufacturers as the most reliable data available for use in developing operational flight simulators. Theoretical estimates were given for parameters that did not lend themselves to ready experimental measurement (e.g., most of the rotary derivatives). Corrections for the effects of airframe flexibility were included in the data. Yaw dampers and automatic pitch trim devices were assumed inoperative.

The major dimensions of the jet transports are given in table I. The basic flight conditions analyzed are tabulated below.

Condition	V_c, knots	M	Altitude, ft
Climb	280	0.46	5,000
Climb	285	0.62	20,000
Cruise	216 - 250	0.72 - 0.82	40,000
Cruise	264 - 295	0.78 - 0.86	35,000
Maximum V_{NO}	376 - 397	0.844 - 0.90	22,400 - 23,500
Holding	225 - 240	0.45 - 0.48	15,000

The altitudes and calibrated airspeeds for the basic flight conditions are compared with the operational flight envelopes in figure 1. Because all the reported upsets occurred at higher speeds, the take-off and landing

[1]Furnished by Systems Technology, Inc., Hawthorne, California, under Contract NAS2-864.

conditions were not considered. The values for all input parameters corresponding to six basic flight conditions are presented in table II. Four additional conditions, which closely approximated conditions for which flight data were available, were set up for computation. These conditions are described in figure 2 and table III.

Output Data

The results obtained directly from the digital programs were in the form of (1) the roots of the characteristic equation (where complex roots were obtained, they were expressed as natural frequency and damping ratio), and (2) the numerator roots (zeros) and gains of selected airplane transfer functions. One parameter of interest, the bank-to-sideslip ratio $|\varphi|/|\beta|$ of the lateral oscillatory (Dutch roll) mode, was not computed explicitly in the digital program; rather, it was hand calculated by expressing φ/β as the ratio of numerators of bank and sideslip transfer functions (e.g., the φ/δ_r and β/δ_r transfer functions) written as polynomials in terms of the complex frequency s, and evaluated by substituting the roots of the Dutch roll mode. The resulting complex ratio was converted to the amplitude ratio $|\varphi|/|\beta|$ by taking the square root of the sum of squares of the real and imaginary parts. All other output data were directly translatable into currently applicable handling-qualities factors.

RESULTS AND DISCUSSION

The longitudinal and lateral-directional handling-qualities factors computed for the basic conditions are shown in table IV, and in figures 3 through 19. Where applicable, boundaries indicating existing or proposed handling-qualities criteria are included. These criteria are indicated for comparison purposes only, since the builders of civil transports in the United States are not required to comply wit! any definite numerical standards regarding the handling-qualities parameters considered herein. They need satisfy only Part 25 of the Federal Air Regulations, the FAA certification test pilot, and the buyer of the airplane.

Although the three transports have accumulated many thousands of flight hours, no documented pilot comments were available for inclusion in this report.

The handling-qualities factors computed for the additional flight conditions (for comparison with flight measurements) are presented in table V.

Longitudinal Short-Period Characteristics

Basic flight conditions.- The longitudinal short-period natural frequencies and damping ratios are shown in figure 3. The characteristics of all three airplanes are similar, with $f_{n,SP}$ between 0.24 and 0.45 cps and ζ_{SP} between 0.33 and 0.65. The present military specification (ref. 2) is indicated by the rectangular-appearing boundaries at the left. This criterion would be satisfied in all cases.

Figure 3 also shows pilot-opinion boundaries from variable-stability flight tests by Cornell Aeronautical Laboratory in a B-26 airplane (ref. 3). According to this criterion, the three transports as a group would cover the full range from "best tested" to "poor." More recent pilot-opinion data from Cornell (refs. 4 and 5) are not used for comparison because they were obtained in tests of a fighter-type variable-stability airplane, an F-94A, with characteristics markedly different from those of a transport. Another analysis of longitudinal handling qualities resulted in a new set of boundaries in terms of the same two variables, short-period natural frequency and damping ratio (ref. 6). This set of boundaries, shown in figure 4, more nearly represents current thinking among handling-qualities investigators.

The dissimilarity in the nature of the boundaries from references 2, 3, and 6 is of interest. The present military specification says that as long as the period is less than 6 seconds, damping requirements must be met. If the period is 6 seconds or longer, no damping requirements need be satisfied. (The specification states only that residual oscillations shall not be of objectionable magnitude.) On the other hand, the boundaries of reference 3 indicate that, at a natural frequency less than 0.29 cps, poor characteristics should be expected regardless of the damping ratio. Although there may be disagreement as to the precise shape of the boundaries, the proper variable to use as the ordinate, and as to whether (as indicated by the lower boundary of ref. 6) increased damping ratio can compensate for very low natural frequencies, all recent work shows that the low-frequency, low-damping corner should be avoided.

The results of the present study, shown in relation to the proposed boundaries of reference 6 in figure 4, indicate that most of the basic flight conditions would have marginally acceptable characteristics for normal operation. Exceptions would be the maximum speed case for all three transports (which clearly would be acceptable) and the 40,000-foot cruise and holding conditions of transport B (acceptable for emergency).

In figures 3 and 4, the shaded areas denote short-period dynamics estimated for two representative four-engine propeller-driven transports in the 100,000 to 130,000-lb weight class. These characteristics are typical of a class of aircraft not associated with upset incidents. With propeller-driven transports, the consequences of upset (altitude loss and overspeed) would usually be less serious than with current jet transports. Although the short-period damping ratios are somewhat greater for these earlier transports than for the current jets, the frequencies are at about the same level.

Additional flight conditions.- Values of the short-period frequency and damping ratio computed and measured (unpublished results of NASA flight tests) for the additional flight conditions are plotted in figure 5. The boundaries of references 2 and 3 are again presented for comparison. (No flight data were available for transport B; instead, manufacturer's estimates are shown. The two sets of computed characteristics agree well.)

Agreement between computed and flight-measured damping of transport A was generally good. For the high-speed condition at each altitude (especially at 15,000 ft), the predicted frequency was less than that measured in flight. For transport C, the level of damping calculated was consistently greater than that measured in flight; however, all damping values were within what would be considered the "good" range.

Figure 6 shows the above comparisons and the NADC boundaries (ref. 6). Previous comments concerning figure 5 apply here as well.

Other frequency parameters.- In figure 7, the short-period dynamics of the three transports (basic conditions only) are indicated in terms of damping ratio and two parameters, proposed in reference 7, which relate lift or normal acceleration characteristics and natural frequency: L_α/ω_n for $n_{z_\alpha} < 15$ g/rad, and n_{z_α}/ω_n for $n_{z_\alpha} > 15$ g/rad. The boundaries separating satisfactory, acceptable, and unacceptable areas are from reference 7 and were developed largely from the flight-test results of references 4, 5, and 8.

In contrast to the marginal acceptability of the short-period dynamics shown in figures 3 and 4, the dynamics in terms of L_α/ω_n and n_{z_α}/ω_n fit, with only one exception, entirely within the satisfactory regions in figure 7. The short-period characteristics of the two reference propeller transports, shown as shaded areas, are also within these satisfactory regions.

Longitudinal Phugoid Characteristics

Poorly damped or divergent phugoid characteristics could be excited by pilot control inputs if the period of the phugoid mode is sufficiently short, or by a large-scale atmospheric disturbance which is periodic and of a frequency near that of the phugoid. For this reason, the controls-fixed phugoid characteristics of the three transports were examined.

Computed values of phugoid period and damping (reciprocal of time to half or double amplitude) for the basic and additional flight conditions are plotted in figures 8 and 9, respectively. The values of $\partial T/\partial M$ given in tables II and III were used in the computations.

Existing criteria for the phugoid mode are very general, even for military aircraft. In general, if the period is 15 seconds or greater, it is required only that the phugoid not produce "objectionable" flight characteristics. The only numerical requirement for damping, suggested in references 6 and 10, is that the time for an unstable oscillation to double amplitude shall be 55 seconds or greater. Figures 8 and 9 also show this boundary.

At all flight conditions where the phugoid mode was oscillatory, the above numerical criterion was satisfied. Solution of the longitudinal equations of motion produced two real roots, one stable and one unstable, at five flight conditions. For these cases, the reciprocal of the times to half-amplitude and double amplitude of the aperiodic characteristics are plotted in figures 8 and 9 at an infinite phugoid period and are compared with the 55-second criterion even though the unstable modes are not oscillatory. The criterion was not satisfied at two of the basic flight conditions; transports A and B at maximum V_{NO}, and two additional conditions; transport B at $M = 0.82$ and $h_p = 32{,}160$ feet, and transport C at $M = 0.835$ and $h_p = 35{,}000$ feet. T_2 was 63 seconds for transport C in the 40,000 foot cruise condition. It should be noted that the aperiodically divergent characteristics presented in figures 8 and 9 occurred above $M = 0.8$ (in the "tuck" region), where normally some type of automatic pitch trim device is used, and would be expected only in case of disengagement of such a device.

Lateral Oscillatory (Dutch Roll) Characteristics

Basic flight conditions.- The calculated oscillatory damping and bank-to-side velocity characteristics without yaw damper are presented for the basic flight conditions in figure 10. The calculated values of $|\varphi|/|v_e|$ were less than 0.4, a figure generally considered small and not indicative of problems. Included for comparison are the current military specification boundaries (ref. 2) for flight conditions other than the landing approach, and the estimated characteristics of the two reference propeller transports (shaded areas).

All the values of damping indicated for transport A would meet the military specification for normal operation, even with the yaw damper inoperative. Although transports B and C were predicted to be more lightly damped, all but one condition (the high-altitude cruise of transport B) were damped sufficiently to satisfy the dampers-off requirement.

The above calculated results are shown in figure 11 in terms of $K/T_{1/2}$ and $|\varphi|/|v_e|$. The K factor as part of the criterion was first introduced in reference 9: $K = P_d$ for $0 < P_d \leq 2.4$ and $K = 2.4$ for $P_d > 2.4$ sec. The conclusion therein was, in effect, that when the Dutch roll period was relatively long, a parameter proportional to $1/T_{1/2}$ correlated better with pilot opinion. The same criterion is presented as a design guide in reference 10. Because in the present study all periods were greater than 2.4 seconds, $K = 2.4$ is indicated in figures 11 and 15. For all the transports, including the K factor resulted in a less favorable comparison with the boundaries than existed with respect to the military specification.

In figure 12 the calculated Dutch roll characteristics are compared with the proposed frequency-damping requirement of reference 6. Because all predicted values of $|\varphi|/|v_e|$ were less than 0.4, the only normal-operation boundary shown is the one for $0 < |\varphi|/|v_e| \leq 0.4$. In the frequency region of interest here, the solid boundary corresponds approximately to $1/T_{1/2} = 0.3$, or $K/T_{1/2} = 0.72$ with $K = 2.4$.

In figure 12, as in figure 11, the only condition to satisfy the normal-operation criterion was transport A at maximum V_{NO}. Of the remaining conditions, 7 fell between the normal-operation boundary and the boundary for acceptable characteristics with stability augmentation inoperative, and 10 were outside the latter boundary. At least in the frequency-damping region covered by the subject transports, the boundaries in figure 12 (from ref. 6) appear more conservative than those in figure 11 (from ref. 9).

Additional flight conditions.- Calculated and flight-measured Dutch roll periods are plotted versus equivalent airspeed for the additional flight conditions in figure 13 and the agreement is considered satisfactory. The flight values for transports A and B were underestimated by only 7 to 21 percent.

The calculated and flight-measured damping and $|\varphi|/|v_e|$ are compared in figures 14, 15, and 16 with the boundaries of references 2, 9, and 6, respectively. Except for transport A at $M = 0.77$ and $h_p = 15{,}000$ ft and at $M = 0.86$ and $h_p = 35{,}000$ ft, and transport B at $M = 0.82$ and $h_p = 32{,}160$ ft, the calculated damping levels agree well with those measured in flight. The flight $|\varphi|/|v_e|$ values for transports A and C, though not entirely in close agreement with calculated values, were in the range between 0.1 and 0.4 typical of $|\varphi|/|v_e|$ calculated for both the basic and additional flight conditions of all three transports. For transport B, however, the flight $|\varphi|/|v_e|$ was consistently greater than calculated, particularly for $h_p = 32{,}160$ ft and 41,650 ft. No apparent explanation for these large discrepancies exists, except perhaps in the validity of the flight results (which had been supplied by the manufacturer) for the two high-altitude cases. For the three transports taken as a group, half of the flight conditions considered (without yaw-damper augmentation) had levels of Dutch roll damping less than that currently required of military transports for normal operation. On certain occasions, any of these civil transports may be dispatched for flight with the yaw damper out of service; or during climb, descent, or turbulence penetration, the yaw damper may become inoperative when the autopilot is turned off. In smooth air and good weather, the resulting low damping might not be highly objectionable to most airline pilots; in turbulence and during flight on instruments, however, lack of sufficient Dutch roll damping may represent a significant addition to the already heavy pilot workload.

Lateral Control Characteristics

In addition to the controls-fixed characteristics of the three jet transports, the lateral control response and closed-loop characteristics are also of interest from the standpoint of manuevering and recovery from lateral upsets due to gusts.

Coupling with the Dutch roll mode.- The range of calculated frequency ratio ω_φ/ω_d is presented for the basic flight conditions of each transport in figure 17. Values of ω_φ/ω_d for individual flight conditions are given in table IV. Values of ω_φ/ω_d less than 1.0 are associated with adverse yaw during roll maneuvers and values greater than 1.0 are associated with favorable yaw. In either case, the Dutch roll mode can be unduly excited when the pilot is controlling in roll. If ω_φ/ω_d is sufficiently less than 1.0, such excitation can result in oscillatory and severely decreased roll response; if ω_φ/ω_d is sufficiently greater than 1.0, closed-loop instability of the pilot-airplane combination may occur (see ref. 11). A value of 1.0 often is considered optimum.

The shaded area in figure 17 shows the spread of qualitative pilot opinion presented in reference 12 for a variety of flight and simulator tasks assuming vehicles with levels of Dutch roll damping comparable to those of the present jet transports. The range of ω_φ/ω_d represented by the subject transports is only a small portion of the total range discussed in reference 12 and the expected variation in pilot opinion is correspondingly small.

Transports A and B are grouped within ±0.10 of the unity value of ω_φ/ω_d. On the basis of reference 12, pilot opinions ranging from "satisfactory" to "unsatisfactory but acceptable" would be expected. For transport C, ω_φ/ω_d varied from 1.15 to 1.19 because of the favorable yaw due to roll control (resulting from asymmetrical deflection of highly effective "full-time" spoilers in addition to inboard ailerons).

It should be noted that, in most cases, the levels of pilot opinion shown by the shaded band in figure 17 applied either to control tasks involving a high order of roll maneuvering or to vehicles having large values of Dutch roll $|\varphi|/|\beta|$. However, the maneuvering requirements of the current jet transports generally are much less severe, especially outside the terminal area.

Steady rolling characteristics.- The calculated steady-state wing-tip helix angles, assuming maximum attainable roll control surface deflection, are presented for the basic flight conditions in figure 18. The boundaries indicate the minimum requirements of reference 2, assuming flight in the clean configuration, for class II airplanes in the performance range of interest.

Except for the holding and 40,000 feet cruise conditions, figure 18 shows the rolling capability of transport A (up to 300 knots) to be 30 to 50 percent less than that required of military transports. With flaps retracted, this airplane is controlled in roll by means of inboard ailerons and spoilers.

In the same speed range, transports B and C either exceed or come close to meeting the military specification. At the maximum operating Mach numbers (V_c just under 400 knots), all three jet transports exceeded the specified minimum $pb/2V$ of 0.015, according to calculations.

Roll transient response.- The rolling capabilities of airplanes have also been assessed in terms of the nature of the transient response of roll rate to aileron input, assuming single-degree-of-freedom rolling motion. The calculated roll-response parameters of the three jet transports are presented in figure 19 for the basic flight conditions. The parameters shown are maximum rolling acceleration and single-degree-of-freedom roll time constant. The boundaries are from reference 13.

Although they were derived for large transports in the landing approach condition, the boundaries in figure 19 are included on the premise that satisfactory roll response for the landing approach would be more than adequate for climb, cruise, and other conditions which usually are considered less demanding. Figure 19 shows that the roll parameters of all three subject transports, in the basic flight conditions, would fall within the satisfactory region of reference 13.

Relatively little is known about roll control requirements of airplanes disturbed by lateral gusts. From theory, reference 14 indicates that application of corrective aileron control proportional to bank angle (which might represent the action of a pilot at moderate frequencies) can decrease, more effectively in a large airplane than in a small airplane, roll excursions in continuous turbulence consisting entirely of side gusts. As airplane size and inertial parameters are increased, the problem appears to be whether the roll control power decreases more or less rapidly than the amplitude of bank in response to the turbulence. Further study is needed on this subject.

CONCLUSIONS

Several calculated and flight-measured handling-qualities factors of three subsonic jet transports have been reviewed and compared with various handling-qualities criteria. Because of inconsistencies in some of the criteria and questions regarding their relevance, no attempt was made to classify a given transport as satisfactory or unsatisfactory for scheduled passenger operation. Within these limitations, this study indicates the following:

1. On the basis of the current military specification and other published criteria, all three transports had satisfactory or acceptable predicted or flight-measured longitudinal short-period frequency and damping characteristics in the flight conditions of interest. Except for some cases of speed instability associated with disengagement of Mach trim compensation devices, acceptable longitudinal phugoid characteristics also were calculated for these transports.

2. According to several published criteria, the subject transports, without yaw dampers, exhibited lateral-directional oscillatory characteristics varying from satisfactory for normal operation to unacceptable for dampers inoperative. Unacceptably low damping, on the basis of two or more criteria, usually occurred at high altitudes or at low speeds and moderate altitudes.

3. In the climb, cruise, and holding conditions, two of the three transports had predicted roll-control characteristics that satisfied the current military specifications (or very nearly so) for steady rolling, pb/2V. At maximum speed, all three transports exceeded the specification.

4. Values of maximum roll control power and roll time constant calculated for all three transports were in a region of satisfactory response proposed by one investigator for large airplanes in the landing approach. Such characteristics probably would also be satisfactory for the flight conditions considered in this study.

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TABLE I.- MAJOR DIMENSIONS OF THE SUBJECT JET TRANSPORTS

Dimension	Transport A	Transport B	Transport C
Wing area, sq ft	2433	2758	2000
Wing span, ft	130.8	142.4	118.0
Wing mean aerodynamic chord, ft	20.16	22.17	18.94
Mean distance of engine thrust axis below fuselage reference line, ft	6.5	6.5	3.6
Incidence of engine thrust axis, deg	1.50	3.15	3.00
Distance of pilot's station ahead of center of gravity, ft	56.2	69.0	50.0

TABLE II.- PHYSICAL AND AERODYNAMIC CHARACTERISTICS. BASIC FLIGHT CONDITIONS.

		5,000-ft Climb			20,000-ft Climb			40,000-ft Cruise			35,000-ft Cruise			Maximum V_{NO}			Holding		
		Transport																	
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Altitude, ft		5,000	5,000	5,000	20,000	20,000	20,000	40,000	40,000	40,000	35,000	35,000	35,000	23,500	22,400	23,000	15,000	15,000	15,000
V_c, knots		280	280	280	285	285	285	250	216	250	295	264	295	397	376	395	240	225	240
V_e, knots		279	279	279	278	278	278	234	206	234	276	251	276	376	360	374	239	224	239
V, ft/sec		506	506	506	642	642	642	797	698	797	836	758	836	920	865	912	503	472	503
Mach number		0.46	0.46	0.46	0.62	0.62	0.62	0.82	0.72	0.82	0.86	0.78	0.86	0.90	0.844	0.89	0.48	0.45	0.48
Air density, slugs/ft^3		0.00205	0.00205	0.00205	0.00127	0.00127	0.00127	0.00058	0.00058	0.00058	0.00074	0.00074	0.00074	0.00112	0.00117	0.00114	0.00150	0.00150	0.00150
Dynamic pressure, lb/ft^2		260	260	260	260	260	260	184	142	184	257	212	257	475	435	474	191	167	191
Weight, lb		226,240	265,000	175,000	222,100	260,000	170,000	170,000	210,000	140,000	180,000	220,000	150,000	180,000	250,000	150,000	150,000	185,000	130,000
Mass, slugs		7030	8236	5440	6900	8081	5280	5280	6527	4350	5590	6838	4660	5590	7770	4660	4660	5750	4040
γ_o, deg		3.0	2.8	4.7	1.5	1.5	2.2	0	0	0	0	0	0	0	0	0	0	0	0
α_o, deg		3.39	2.65	3.17	3.07	2.22	2.88	2.47	3.80	2.10	1.70	1.86	1.08	0.57	0.12	0.16	2.71	2.85	3.04
Body axes, million slug-ft^2	I_X	3.43	5.33	2.45	3.28	5.24	2.40	2.11	4.07	1.98	2.28	4.49	2.12	2.28	5.06	2.12	1.77	3.15	1.84
	I_Y	3.59	4.08	2.23	3.59	4.07	2.19	3.41	3.98	1.97	3.44	4.02	2.03	3.44	4.06	2.03	3.45	3.89	1.91
	I_Z	7.02	9.05	4.60	6.89	8.95	4.50	5.47	7.73	3.85	5.69	8.18	4.06	5.69	8.77	4.06	5.17	6.70	3.65
	I_{XZ}	---	0.30	0.095	---	0.30	0.095	---	0.29	0.094	---	0.29	0.095	---	0.30	0.095	---	0.28	0.094
Stability axes	C_L	0.358	0.370	0.337	0.351	0.363	0.327	0.380	0.536	0.380	0.288	0.376	0.292	0.156	0.208	0.158	0.323	0.402	0.340
	C_D	0.022	0.023	0.020	0.020	0.023	0.020	0.020	0.037	0.024	0.020	0.026	0.024	0.024	0.020	0.026	0.020	0.024	0.020
	C_{L_α}	4.326	4.584	4.133	4.555	4.853	4.274	5.701	5.358	5.266	5.415	5.547	5.077	4.641	5.719	4.532	4.567	4.733	4.295
	$C_{L_{\dot{\alpha}}}$	---	1.16	---	---	1.29	---	---	1.59	---	---	1.64	---	---	1.53	---	---	1.24	---
	$C_{L_{\delta_e}}$	0.203	0.212	0.223	0.203	0.214	0.232	0.201	0.260	0.254	0.186	0.227	0.230	0.138	0.144	0.177	0.210	0.247	0.238
	C_{L_M}	-0.050	-0.108	-0.167	-0.013	0.026	0	0.077	0.313	0.099	-0.097	0.368	-0.116	-0.155	-0.198	-0.634	-0.037	-0.014	-0.157
	C_{D_α}	0.215	0.205	0.152	0.191	0.238	0.150	0.221	0.523	0.315	0.178	0.354	0.263	0.240	0.181	0.105	0.168	0.241	0.158
	$C_{D_{\delta_e}}$	-0.017	---	---	-0.016	---	---	-0.011	---	---	-0.023	---	---	-0.029	---	---	-0.017	---	---
	C_{D_M}	0	0	0	0	0.010	0	0.035	0.044	0.101	0.070	0.010	0.217	0.580	0.113	0.257	0	0	0
	C_{m_α}	-0.814	-0.756	-0.649	-0.854	-0.774	-0.655	-1.255	-0.986	-0.796	-1.209	-0.986	-0.814	-1.037	-0.945	-0.606	-0.905	-0.860	-0.716
	$C_{m_{\dot{\alpha}}}$	-4.62	-4.27	-8.98	-4.88	-4.77	-9.22	-6.19	-5.35	-10.09	-6.40	-5.80	-9.98	-6.01	-6.38	-9.36	-4.74	-4.27	-9.27
	C_{m_q}	-11.17	-10.76	-11.02	-11.53	-11.17	-11.27	-13.58	-12.62	-12.71	-13.37	-12.49	-12.44	-11.48	-11.23	-11.40	-11.64	-11.41	-11.43
	$C_{m_{\delta_e}}$	-0.66	-0.65	-0.66	-0.66	-0.65	-0.69	-0.69	-0.80	-0.76	-0.63	-0.69	-0.68	-0.43	-0.44	-0.53	-0.69	-0.76	-0.71
	C_{m_M}	0.0175	-0.016	0.120	0.0010	-0.023	0.139	0	-0.041	-0.154	-0.0525	-0.113	-0.059	-0.1400	-0.395	0.379	0.0052	0.015	0.053
	$\partial T/\partial M$	3750	3100	---	9450	9000	---	6650	9200	---	8950	9444	---	19,900	16,690	---	6200	3648	---
Body Axes	C_{Y_β}	-0.705	-0.668	-0.790	-0.722	-0.696	-0.880	-0.779	-0.741	-0.826	-0.796	-0.748	-0.849	-0.814	-0.733	-0.841	-0.705	-0.679	-0.794
	C_{Y_p}	-0.191	-0.023	---	-0.188	-0.046	---	-0.239	+0.034	---	-0.244	-0.076	---	-0.236	-0.182	---	-0.201	-0.007	---
	C_{Y_r}	0.361	0.258	---	0.378	0.270	---	0.421	0.300	---	0.435	0.297	---	0.449	0.278	---	0.363	0.268	---
	$C_{Y_{\delta_a}}$	---	---	0.027	---	---	0.026	---	---	0.021	---	---	0.020	---	---	0.018	---	---	0.027
	$C_{Y_{\delta_r}}$	0.234	0.199	0.191	0.245	0.196	0.190	0.273	0.210	0.194	0.282	0.197	0.175	0.291	0.171	0.139	0.236	0.209	0.202
	C_{l_β}	-0.176	-0.164	-0.154	-0.186	-0.159	-0.163	-0.215	-0.211	-0.192	-0.203	-0.189	-0.181	-0.169	-0.135	-0.132	-0.177	-0.168	-0.158
	C_{l_p}	-0.325	-0.356	-0.333	-0.340	-0.372	-0.342	-0.426	-0.431	-0.430	-0.389	-0.425	-0.394	-0.311	-0.395	-0.301	-0.354	-0.381	-0.360
	C_{l_r}	0.123	0.115	0.168	0.123	0.119	0.177	0.133	0.165	0.215	0.121	0.138	0.215	0.101	0.120	0.141	0.114	0.120	0.171
	$C_{l_{\delta_a}}$	-0.018	-0.042	-0.047	-0.019	-0.038	-0.050	-0.023	-0.044	-0.062	-0.017	-0.038	-0.058	-0.010	-0.025	-0.047	-0.020	-0.050	-0.051
	$C_{l_{\delta_r}}$	0.036	0.020	0.023	0.037	0.019	0.023	0.040	0.021	0.025	0.039	0.020	0.024	0.044	0.017	0.021	0.036	0.021	0.025
	C_{n_β}	0.122	0.108	0.126	0.130	0.117	0.128	0.153	0.126	0.135	0.163	0.132	0.140	0.174	0.142	0.140	0.126	0.112	0.128
	C_{n_p}	-0.012	-0.042	-0.047	-0.008	-0.039	-0.045	-0.009	-0.067	-0.052	0.013	-0.051	-0.037	0.041	-0.012	-0.018	-0.001	-0.047	-0.048
	C_{n_r}	-0.147	-0.156	-0.160	-0.154	-0.160	-0.162	-0.173	-0.171	-0.168	-0.180	-0.172	-0.170	-0.189	-0.161	-0.169	-0.149	-0.163	-0.162
	$C_{n_{\delta_a}}$	-0.0041	0.0005	-0.0230	-0.0039	0.0010	-0.0231	-0.0034	0.0004	-0.0223	-0.0026	0.0014	-0.0218	-0.0015	0.0020	-0.0209	-0.0039	0.000	-0.0231
	$C_{n_{\delta_r}}$	-0.095	-0.089	-0.083	-0.099	-0.087	-0.083	-0.110	-0.094	-0.077	-0.115	-0.088	-0.067	-0.119	-0.077	-0.051	-0.095	-0.094	-0.087

TABLE III.- PHYSICAL AND AERODYNAMIC CHARACTERISTICS. ADDITIONAL FLIGHT CONDITIONS.

		Transport											
		A				B				C			
Altitude, ft		15,000	15,000	35,000	35,000	9,300	21,000	32,160	41,650	15,000	15,000	35,000	35,000
V_c, knots		175	395	213	296	182	165	298	216	250	320	250	287
V_e, knots		174	383	211	277	180	162	280	203	247	313	239	270
V, ft/sec		370	815	623	837	350	381	805	721	525	666	723	817
Mach number		0.35	0.77	0.64	0.86	0.32	0.37	0.82	0.74	0.50	0.63	0.75	0.835
Air density, slugs/ft^3		0.00150	0.00150	0.00074	0.00074	0.00180	0.00123	0.00082	0.00054	0.00150	0.00150	0.00074	0.00074
Dynamic pressure, lb/ft^2		102	490	143	257	110	89	280	140	208	329	195	242
Weight, lb		180,000	180,000	175,000	175,000	212,500	173,400	208,100	180,400	151,700	147,200	130,000	126,000
Mass, slugs		5,590	5,590	5,440	5,440	6,600	5,385	6,465	5,595	4,715	4,575	4,040	3,915
γ_o, deg		0	0	0	0	0	0	0	0	0	0	0	0
α_o, deg		6.77	0.08	3.58	0.88	6.77	6.60	0.70	3.08	3.41	1.58	2.40	1.41
Body axes, million slug-ft^2	I_X	2.28	2.28	2.18	2.18	4.18	2.89	3.99	3.03	2.15	2.08	1.84	1.79
	I_Y	3.44	3.44	3.45	3.45	3.99	3.86	3.97	3.88	2.05	2.01	1.91	1.88
	I_Z	5.69	5.69	5.61	5.61	7.85	6.42	7.64	6.57	4.10	4.00	3.65	3.57
	I_{XZ}	---	---	---	---	0.29	0.27	0.29	0.28	0.095	0.095	0.094	0.094
Stability axes	C_L	0.725	0.151	0.503	0.280	0.702	0.705	0.270	0.467	0.365	0.224	0.333	0.260
	C_D	0.042	0.016	0.027	0.020	0.046	0.046	0.021	0.032	0.021	0.017	0.020	0.019
	C_{L_α}	4.510	4.269	4.796	5.180	4.72	4.79	5.79	5.41	4.261	4.173	4.889	5.114
	$C_{L_{\dot\alpha}}$	---	---	---	---	1.26	1.28	1.63	1.62	---	---	---	---
	$C_{L_{\delta_e}}$	0.223	0.166	0.214	0.182	0.268	0.277	0.191	0.262	0.237	0.219	0.258	0.237
	C_{L_M}	0	-0.10	-0.02	-0.097	0	0	0.365	0.356	-0.150	0	0.050	0
	C_{D_α}	0.495	0	0.256	0.178	0.688	0.685	0.311	0.430	0.168	0.073	0.172	0.161
	$C_{D_{\delta_e}}$	---	---	---	---	---	---	---	---	---	---	---	---
	C_{D_M}	0	0.025	0	0.070	0	0	0.09	0.05	0	0	0	0.066
	C_{m_α}	-0.858	-0.565	-0.878	-1.053	-0.911	-0.957	-0.997	-0.992	-0.708	-0.563	-0.714	-0.735
	$C_{m_{\dot\alpha}}$	-4.80	-5.05	-5.21	-6.39	-4.07	-4.19	-6.16	-5.52	-9.23	-9.08	-9.79	-9.92
	C_{m_q}	-12.16	-10.80	-12.58	-13.37	-11.54	-11.81	-11.53	-12.75	-11.36	-11.04	-12.22	-12.41
	$C_{m_{\delta_e}}$	-0.73	-0.54	-0.71	-0.63	-0.820	-0.848	-0.585	-0.802	-0.706	-0.652	-0.769	-0.707
	C_{m_M}	0	0	0	-0.05	-0.050	-0.055	-0.180	-0.081	+0.014	+0.022	0	-0.227
	$\partial T/\partial M$	---	---	---	---	---	---	---	---	---	---	---	---
Body axes	C_{Y_β}	-0.699	-0.762	-0.728	-0.797	-0.673	-0.679	-0.749	-0.747	-0.799	-0.794	-0.817	-0.822
	C_{Y_p}	-0.220	-0.210	-0.230	-0.248	0.188	0.186	-0.147	-0.013	---	---	---	---
	C_{Y_r}	0.391	0.467	0.422	0.522	0.269	0.274	0.294	0.303	---	---	---	---
	$C_{Y_{\delta_a}}$	---	---	---	---	---	---	---	---	0.027	0.026	0.025	0.021
	$C_{Y_{\delta_r}}$	0.235	0.250	0.245	0.282	0.215	0.218	0.186	0.209	0.199	0.179	0.198	0.182
	C_{l_β}	-0.224	-0.154	-0.214	-0.203	-0.227	-0.218	-0.144	-0.205	-0.163	-0.144	-0.177	-0.176
	C_{l_p}	-0.386	-0.281	-0.393	-0.296	-0.394	-0.405	-0.424	-0.436	-0.359	-0.316	-0.401	-0.399
	C_{l_r}	0.211	0.108	0.174	0.142	0.160	0.163	0.139	0.158	0.178	0.153	0.192	0.188
	$C_{l_{\delta_a}}$	-0.020	-0.021	-0.019	-0.017	-0.058	-0.058	-0.034	-0.047	-0.050	-0.049	-0.057	-0.059
	$C_{l_{\delta_r}}$	0.019	0.018	0.019	0.018	0.021	0.021	0.018	0.021	0.024	0.022	0.025	0.024
	C_{n_β}	0.111	0.154	0.130	0.163	0.093	0.098	0.140	0.130	0.130	0.130	0.134	0.139
	C_{n_p}	-0.168	-0.075	-0.131	-0.100	-0.099	-0.100	-0.022	-0.057	-0.051	-0.029	-0.047	-0.035
	C_{n_r}	-0.140	-0.167	-0.152	-0.186	-0.165	-0.165	-0.169	-0.174	-0.163	-0.163	-0.166	-0.169
	$C_{n_{\delta_a}}$	-0.0053	-0.0026	-0.0041	-0.0024	-0.0038	-0.0036	-0.0018	-0.0006	-0.0233	-0.0228	-0.0228	-0.0231
	$C_{n_{\delta_r}}$	-0.095	-0.109	-0.101	-0.116	-0.096	-0.097	-0.084	-0.094	-0.086	-0.077	-0.082	-0.072

TABLE IV.- COMPUTED HANDLING-QUALITIES FACTORS. BASIC FLIGHT CONDITIONS.

		5,000-ft Climb			20,000-ft Climb			40,000-ft Cruise		
		Transport								
		A	B	C	A	B	C	A	B	C
Altitude, ft		5,000	5,000	5,000	20,000	20,000	20,000	40,000	40,000	40,000
V_c, knots		280	280	280	285	285	285	250	242	250
Mach number		0.46	0.46	0.46	0.62	0.62	0.62	0.82	0.72	0.82
		Longitudinal								
Short period	$f_{n,SP}$, cps	0.300	0.306	0.303	0.297	0.299	0.296	0.303	0.244	0.282
	ζ_{SP}	0.508	0.544	0.647	0.423	0.467	0.546	0.336	0.354	0.432
	$C_{1/10}$	0.63	0.57	0.43	0.79	0.70	0.56	1.03	0.97	0.77
Phugoid	$\omega_{n,PH}$, rad/sec	0.075	0.066	0.090	0.062	0.057	0.087	0.056	0.062	---
	ζ_{PH}	0.016	0.023	0.010	0.016	0.027	0.021	0.046	0.036	---
	P_{PH}, sec	84.0	94.7	70.2	101.2	110.1	72.5	112.6	102.2	---
	$1/T_{1/2,PH}$, sec	0.00169	0.00221	0.00128	0.00143	0.00220	0.00266	0.00375	0.00317	0.0303
	$1/T_{2,PH}$, sec	---	---	---	---	---	---	---	---	0.0159
		Lateral-Directional								
Dutch roll	ω_d, rad/sec	1.33	1.20	1.42	1.36	1.22	1.42	1.39	1.05	1.30
	ζ_d	0.117	0.080	0.094	0.096	0.061	0.072	0.078	0.014	0.031
	$\omega_d\sqrt{1-\zeta_d^2}$, rad/sec	1.32	1.20	1.41	1.36	1.22	1.42	1.38	1.05	1.30
	P_d, sec	4.76	5.24	4.45	4.63	5.17	4.44	4.54	5.99	4.82
	$1/T_{1/2,d}$, 1/sec	0.224	0.138	0.191	0.189	0.108	0.146	0.156	0.021	0.058
	$2.4/T_{1/2,d}$, 1/sec	0.538	0.331	0.458	0.454	0.259	0.350	0.374	0.048	0.139
	$1/C_{1/2}$	1.07	0.72	0.85	0.88	0.56	0.65	0.71	0.12	0.28
	$\lvert\varphi\rvert/\lvert\beta\rvert$	1.98	1.69	1.58	2.18	1.72	1.80	2.62	2.22	2.12
	$\lvert\varphi\rvert/\lvert v_e\rvert$, deg/ft/sec	0.241	0.328	0.193	0.267	0.333	0.220	0.380	0.366	0.308
Spiral & roll	$1/\tau_s$, 1/sec	0.0079	0.0106	-0.0037	0.0084	0.0074	-0.0007	0.0073	0.0060	0.0004
	$1/\tau_{R_3}$, 1/sec	1.058	1.128	1.116	0.902	0.948	0.940	0.988	0.755	0.845
Roll control	$\dot{p}_{max}$, rad/sec^2	0.352	0.536	0.546	0.411	0.483	0.568	0.652	0.411	0.684
	τ_{R_1}, sec	0.977	1.032	1.018	1.138	1.238	1.238	1.026	1.659	1.425
	$(pb/2V)_{max}$, rad	0.044	0.078	0.065	0.048	0.066	0.065	0.055	0.070	0.072
	ω_φ/ω_d	1.053	0.925	1.150	1.049	0.942	1.168	1.019	0.909	1.163

TABLE IV.- COMPUTED HANDLING-QUALITIES FACTORS. BASIC FLIGHT CONDITIONS - Concluded

		35,000-ft Cruise			Maximum V_{NO}			Holding		
		Transport								
		A	B	C	A	B	C	A	B	C
Altitude, ft		35,000	35,000	35,000	23,500	22,400	23,000	15,000	15,000	15,000
V_c, knots		295	304	295	397	376	395	240	225	240
Mach number		0.86	0.78	0.86	0.90	0.844	0.89	0.48	0.45	0.48
		Longitudinal								
Short period	$f_{n,SP}$, cps	0.351	0.299	0.332	0.448	0.427	0.403	0.276	0.267	0.291
	ζ_{SP}	0.363	0.396	0.453	0.418	0.469	0.572	0.516	0.528	0.621
	$C_{1/10}$	0.94	0.85	0.72	0.80	0.69	0.53	0.61	0.59	0.46
Phugoid	$\omega_{n,PH}$, rad/sec	0.034	0.045	0.022	---	---	0.121	0.077	0.084	0.083
	ζ_{PH}	0.155	0.014	0.644	---	---	0.275	0.027	0.029	0.035
	P_{PH}, sec	185.4	139.2	368.5	---	---	54.0	81.2	75.0	76.1
	$1/T_{1/2,PH}$, sec	0.00769	0.00090	0.0208	0.204	0.160	0.0481	0.0299	0.0347	0.0420
	$1/T_{2,PH}$, sec	---	---	---	0.0317	0.136	---	---	---	---
		Lateral-Directional								
Dutch roll	ω_d, rad/sec	1.60	1.21	1.49	2.16	1.66	1.97	1.33	1.16	1.36
	ζ_d	0.100	0.032	0.046	0.147	0.082	0.089	0.137	0.076	0.086
	$\omega_d\sqrt{1-\zeta_d^2}$, rad/sec	1.59	1.21	1.49	2.14	1.66	1.96	1.32	1.16	1.36
	P_d, sec	3.94	5.20	4.23	2.94	3.79	3.20	4.77	5.44	4.63
	$1/T_{1/2,d}$, 1/sec	0.226	0.057	0.099	0.459	0.198	0.253	0.264	0.127	0.170
	$2.4/T_{1/2,d}$, 1/sec	0.542	0.137	0.238	1.102	0.475	0.607	0.634	0.305	0.408
	$1/C_{1/2}$	0.89	0.30	0.42	1.35	0.75	0.81	1.26	0.69	0.79
	$\lvert\varphi\rvert/\lvert\beta\rvert$	2.44	2.00	2.07	2.12	1.39	1.62	2.35	1.82	1.68
	$\lvert\varphi\rvert/\lvert v_e\rvert$, deg/ft/sec	0.300	0.272	0.256	0.192	0.131	0.147	0.334	0.276	0.242
Spiral & roll	$1/\tau_s$, 1/sec	0.0085	0.0070	-0.0003	0.0096	0.0028	0.0018	0.0119	0.0132	0.0009
	$1/\tau_{R_3}$, 1/sec	1.075	0.898	0.943	1.362	1.208	1.158	1.555	1.357	1.164
Roll control	$\dot{p}_{max}$, rad/sec^2	0.491	0.469	0.695	0.384	0.476	0.733	0.776	0.706	0.662
	τ_{R_1}, sec	0.915	1.354	1.256	0.682	0.908	0.972	0.638	0.836	0.974
	$(pb/2V)_{max}$, rad	0.035	0.060	0.062	0.019	0.035	0.046	0.064	0.089	0.075
	ω_φ/ω_d	1.047	0.939	1.184	1.070	0.970	1.187	1.041	0.914	1.147

TABLE V.- COMPUTED HANDLING-QUALITIES FACTORS. ADDITIONAL FLIGHT CONDITIONS.

		Transport											
		A				B				C			
Altitude, ft		15,000	15,000	35,000	35,000	9,300	21,000	32,160	41,650	15,000	15,000	35,000	35,000
V_c, knots		175	395	213	296	182	165	298	216	250	320	250	287
Mach number		0.35	0.77	0.64	0.86	0.32	0.37	0.82	0.74	0.50	0.63	0.75	0.835
		Longitudinal											
Short period	$f_{n,SP}$, cps	0.196	0.359	0.224	0.329	0.221	0.203	0.342	0.247	0.287	0.335	0.281	0.327
	ζ_{SP}	0.499	0.560	0.383	0.384	0.530	0.487	0.424	0.368	0.590	0.643	0.494	0.505
	$C_{1/10}$	0.64	0.54	0.89	0.88	0.59	0.66	0.79	0.93	0.50	0.44	0.64	0.63
Phugoid	$\omega_{n,PH}$, rad/sec	0.106	0.035	0.065	0.031	0.107	0.099	---	0.054	0.074	0.065	0.058	---
	ζ_{PH}	0.014	0.193	0.029	0.203	0.0094	0.0088	---	0.053	0.038	0.051	0.036	---
	P_{PH}, sec	59.2	183.0	96.3	207.6	58.9	63.6	---	115.7	85.0	97.1	109.6	---
	$1/T_{1/2,PH}$, sec	0.00211	0.00971	0.00276	0.00909	0.00144	0.00126	0.0395	0.00419	0.00405	0.00476	0.00302	0.1050
	$1/T_{2,PH}$, sec	---	---	---	---	---	---	0.0247	---	---	---	---	0.0885
		Lateral-Directional											
Dutch roll	ω_d, rad/sec	1.13	2.20	1.25	1.68	0.95	0.96	1.40	1.13	1.35	1.66	1.37	1.55
	ζ_d	0.024	0.062	0.0007	0.008	0.032	0.032	0.065	0.019	0.078	0.093	0.049	0.056
	$\omega_d\sqrt{1-\zeta_d^2}$, rad/sec	1.13	2.20	1.25	1.68	0.95	0.96	1.40	1.13	1.35	1.66	1.37	1.55
	P_d, sec	5.54	2.86	5.03	3.74	6.59	6.54	4.50	5.56	4.65	3.80	4.60	4.06
	$1/T_{1/2,d}$, 1/sec	0.040	0.198	0.001	0.021	0.043	0.044	0.131	0.031	0.153	0.224	0.096	0.125
	$2.4/T_{1/2,d}$, 1/sec	0.095	0.475	0.003	0.051	0.104	0.107	0.314	0.075	0.367	0.538	0.231	0.300
	$1/C_{1/2}$	0.22	0.57	0.007	0.08	0.285	0.291	0.590	0.174	0.71	0.85	0.44	0.51
	$\lvert\varphi\rvert/\lvert\beta\rvert$	1.95	1.86	2.36	2.42	1.95	2.07	1.57	2.35	1.56	1.70	2.01	2.04
	$\lvert\varphi\rvert/\lvert v_e\rvert$, deg/ft/sec	0.381	0.165	0.379	0.297	0.368	0.434	0.191	0.393	0.215	0.184	0.285	0.256
Spiral & roll	$1/\tau_s$, 1/sec	-0.0014	0.0061	0.0028	0.0069	0.0180	0.0135	0.0024	0.0064	0.00014	0.0023	0.00067	0.0012
	$1/\tau_{R_3}$, 1/sec	1.156	1.858	1.062	1.158	1.034	1.094	1.104	0.945	1.047	1.190	0.944	1.076
Roll control	$\dot{p}_{max}$, rad/sec^2	---	---	---	---	---	---	---	---	---	---	---	---
	τ_{R_1}, sec	1.018	0.640	1.160	1.149	1.194	1.086	1.016	1.277	1.094	0.949	1.238	1.072
	$(pb/2V)_{max}$, rad	---	---	---	---	---	---	---	---	---	---	---	---
	ω_φ/ω_d	0.878	1.005	0.960	1.001	0.824	0.820	0.970	0.920	1.152	1.185	1.163	1.181

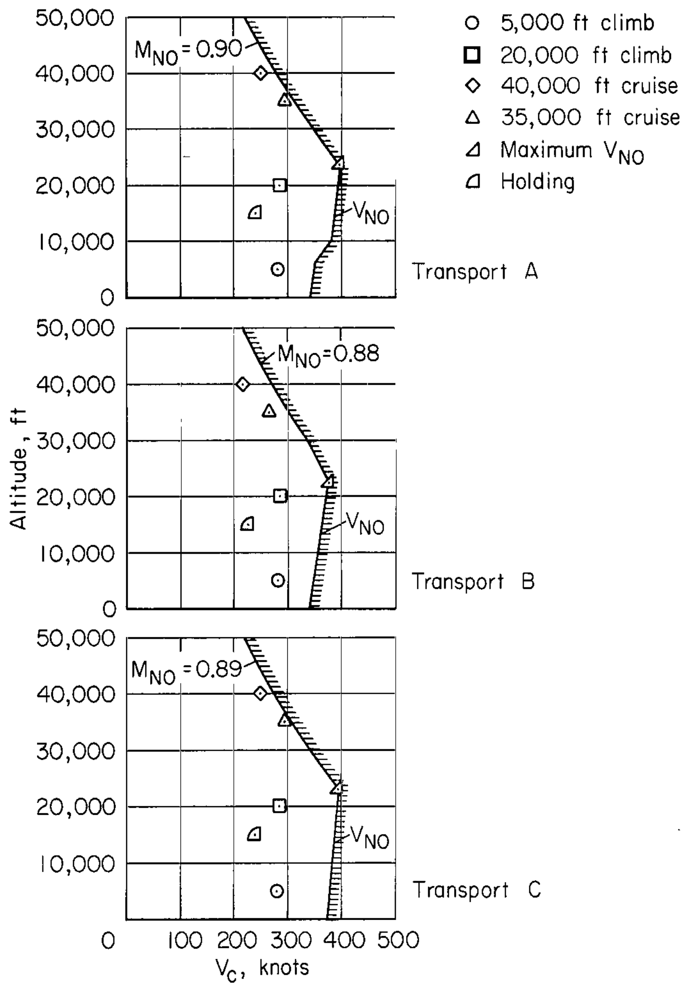

Figure 1.- Basic flight conditions compared with operating speed limitations.

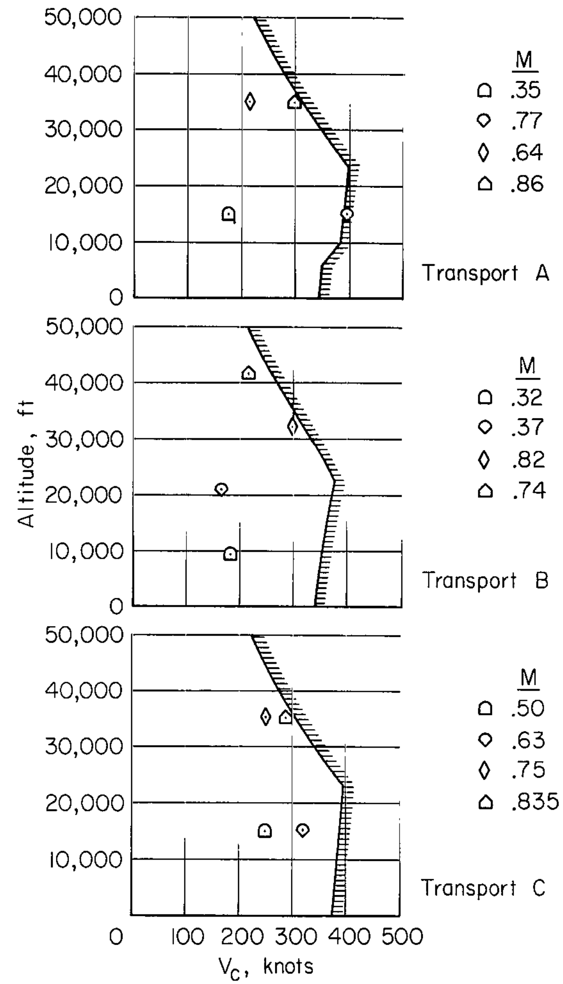

Figure 2.- Additional flight conditions compared with operating speed limitations.

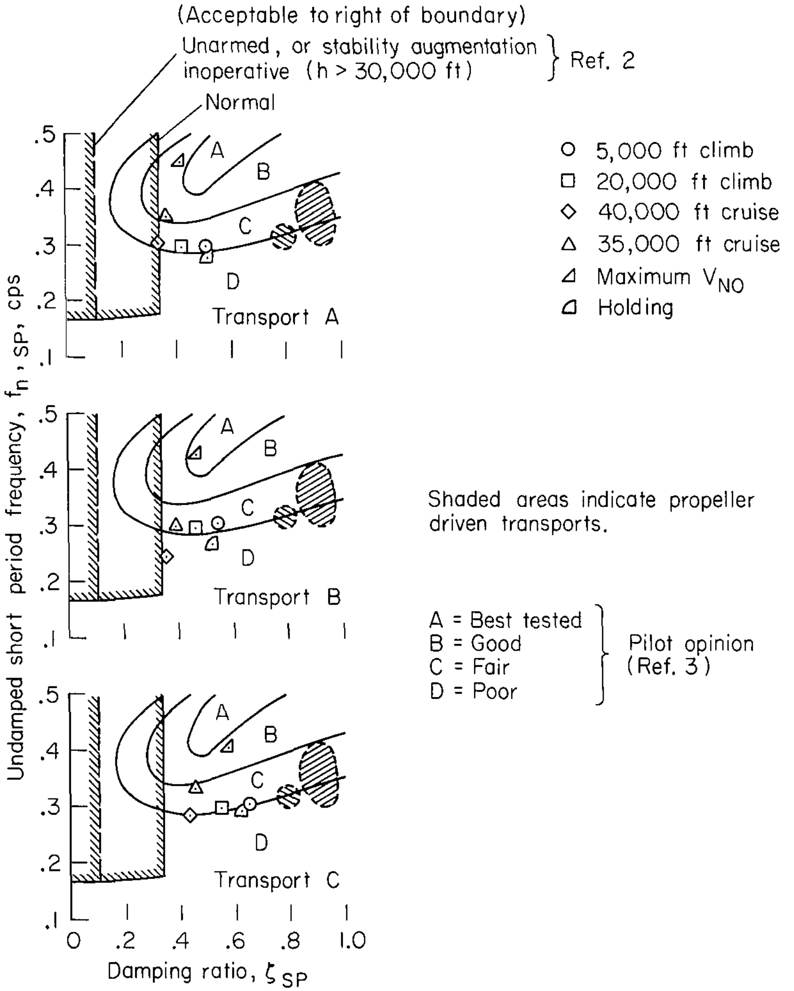

Figure 3.- Longitudinal short-period natural frequency and damping ratio compared with boundaries of references 2 and 3. Basic flight conditions.

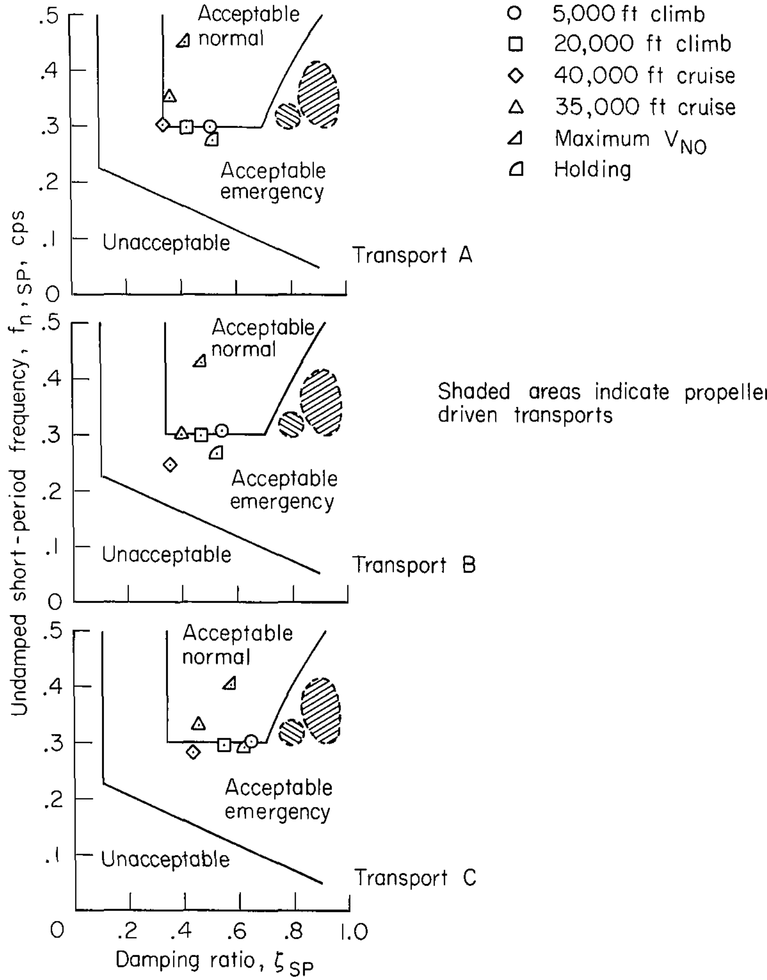

Figure 4.- Longitudinal short-period natural frequency and damping ratio compared with suggested boundaries of reference 6. Basic flight conditions.

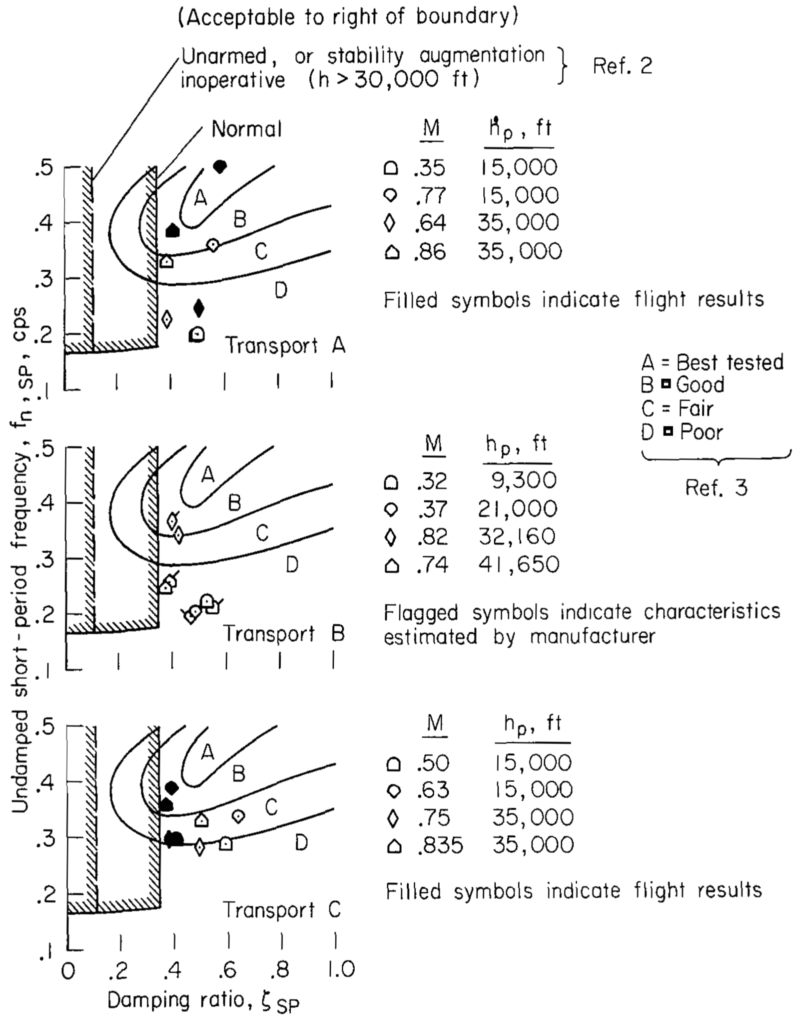

Figure 5.- Longitudinal short-period natural frequency and damping ratio compared with pilot opinion boundaries of references 2 and 3. Additional flight conditions.

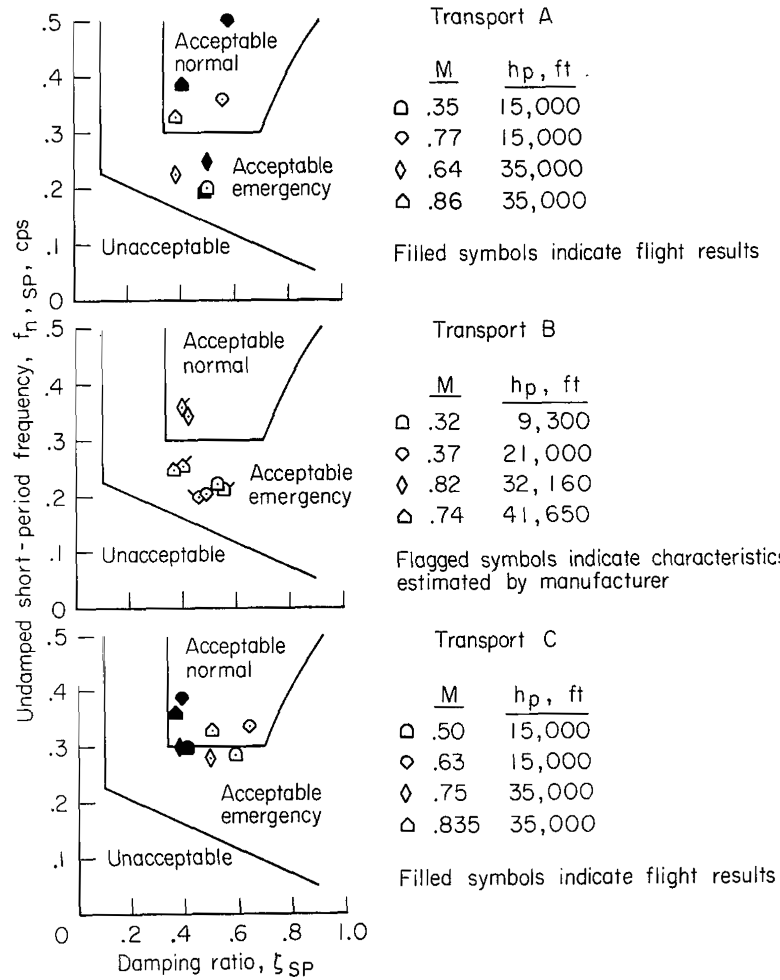

Figure 6.- Longitudinal short-period frequency and damping ratio compared with proposed boundaries of reference 6. Additional flight conditions.

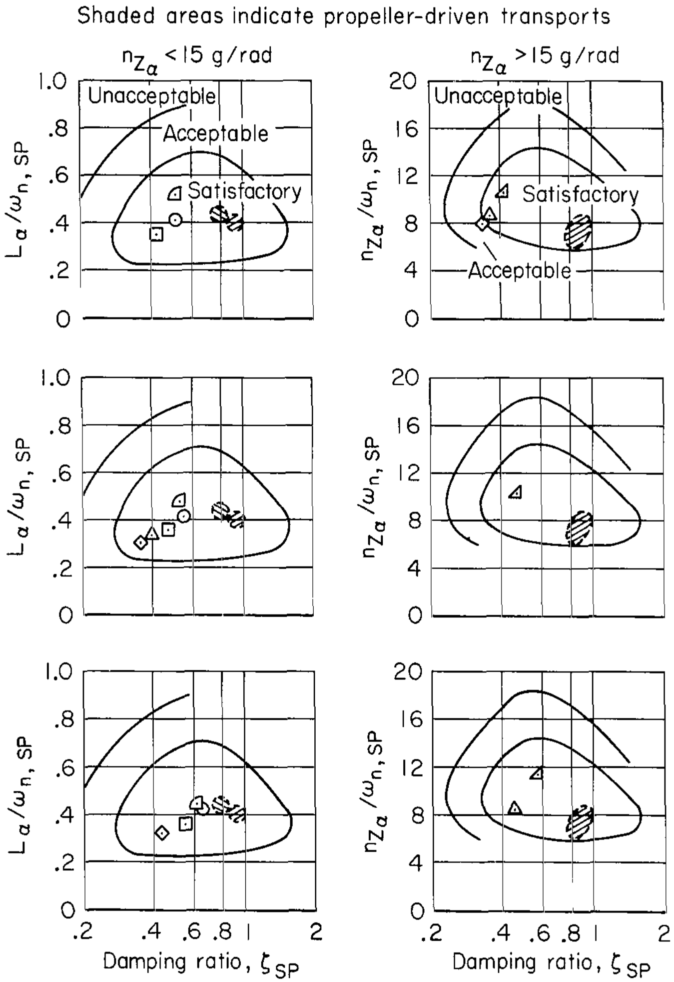

Figure 7.- Longitudinal short-period characteristics compared with boundaries of reference 7. Basic flight conditions.

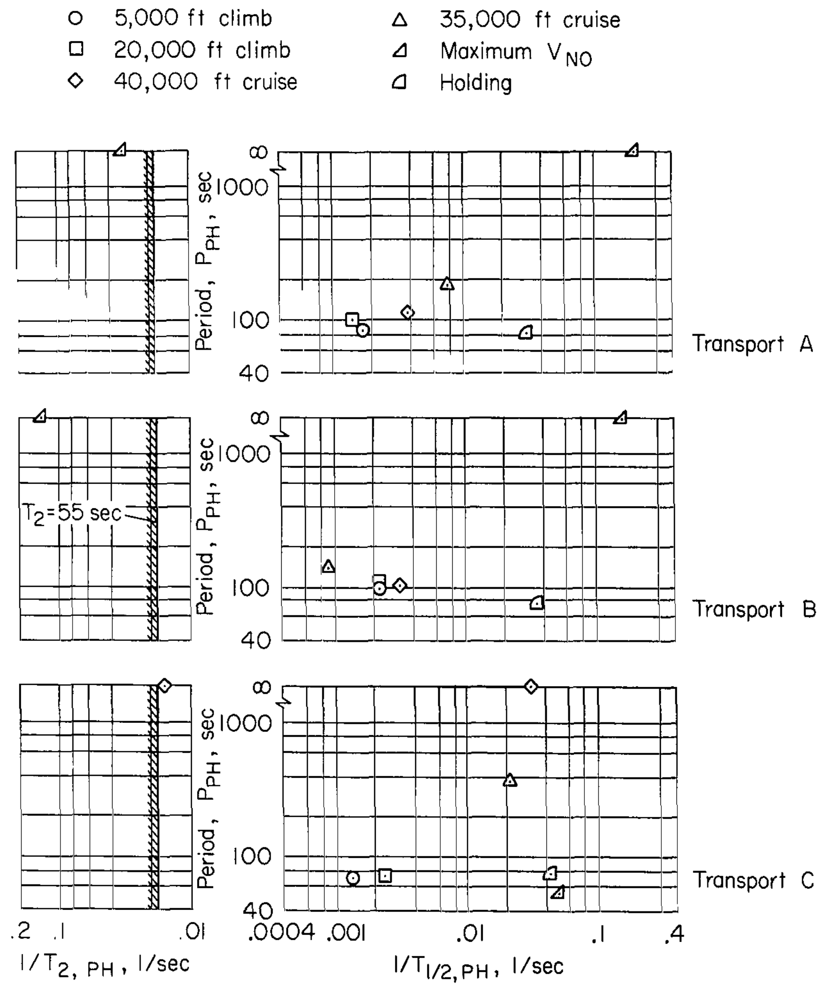

Figure 8.- Phugoid period and damping. Basic flight conditions.

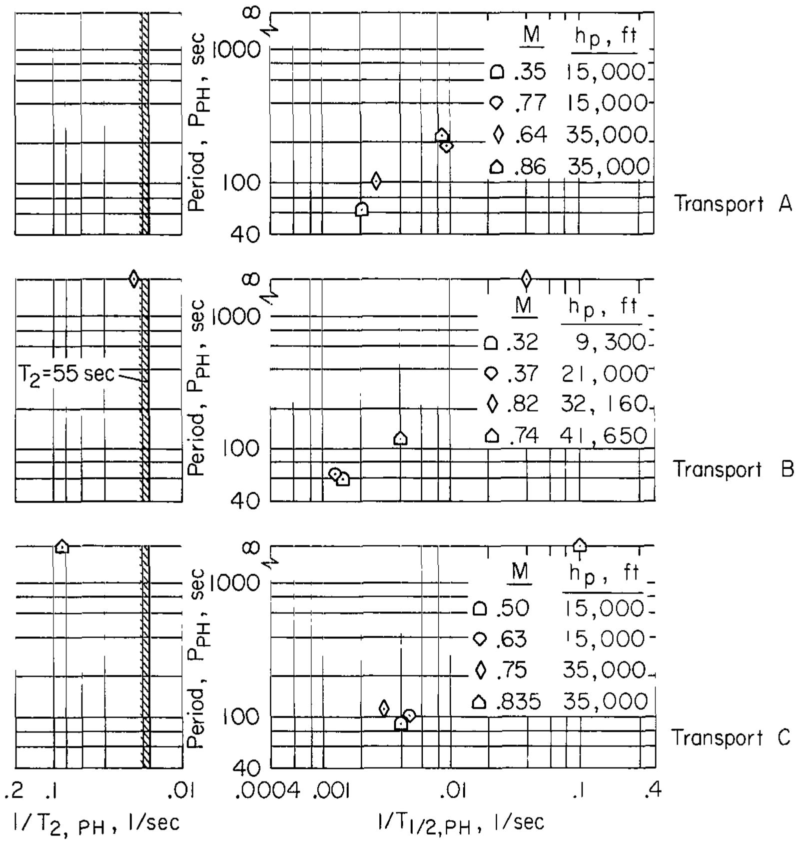

Figure 9.- Phugoid period and damping. Additional flight conditions.

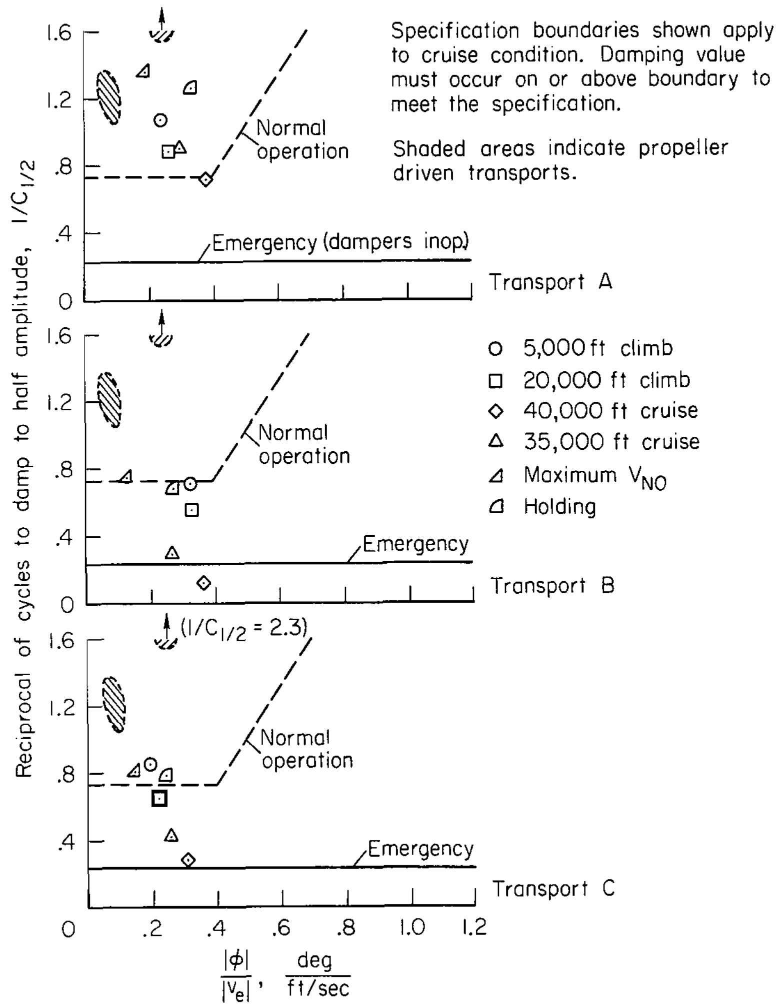

Figure 10.- Lateral oscillatory (Dutch roll) characteristics compared with current military specification (ref. 2). Basic flight conditions.

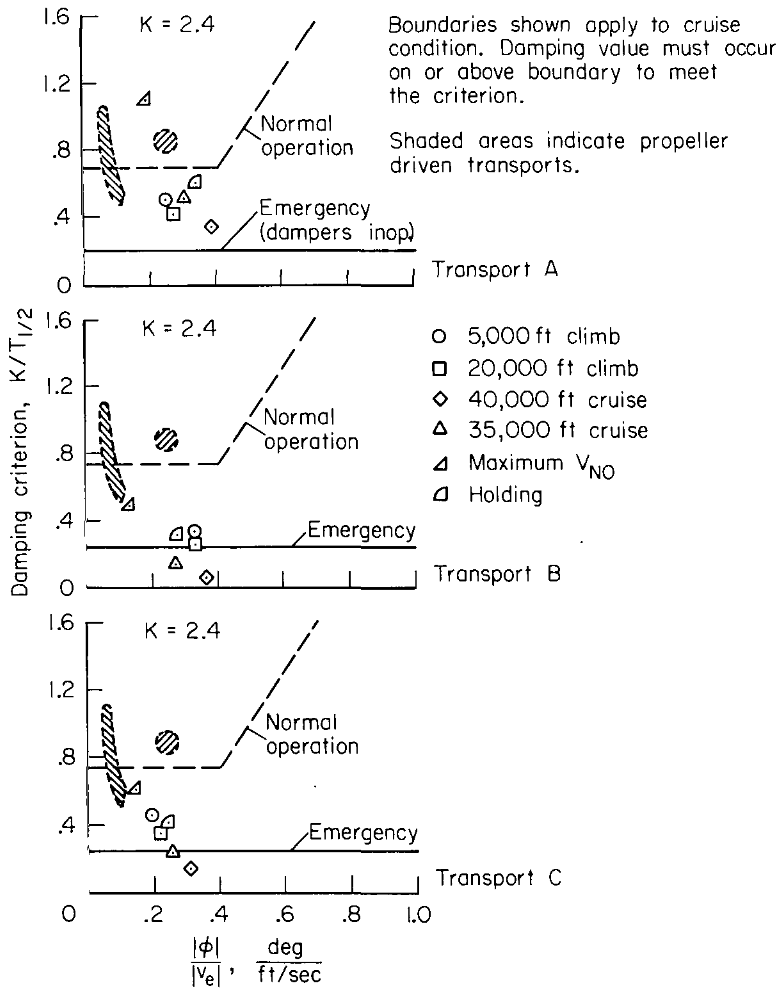

Figure 11.- Lateral oscillatory (Dutch roll) characteristics compared with criterion of reference 9. Basic flight conditions.

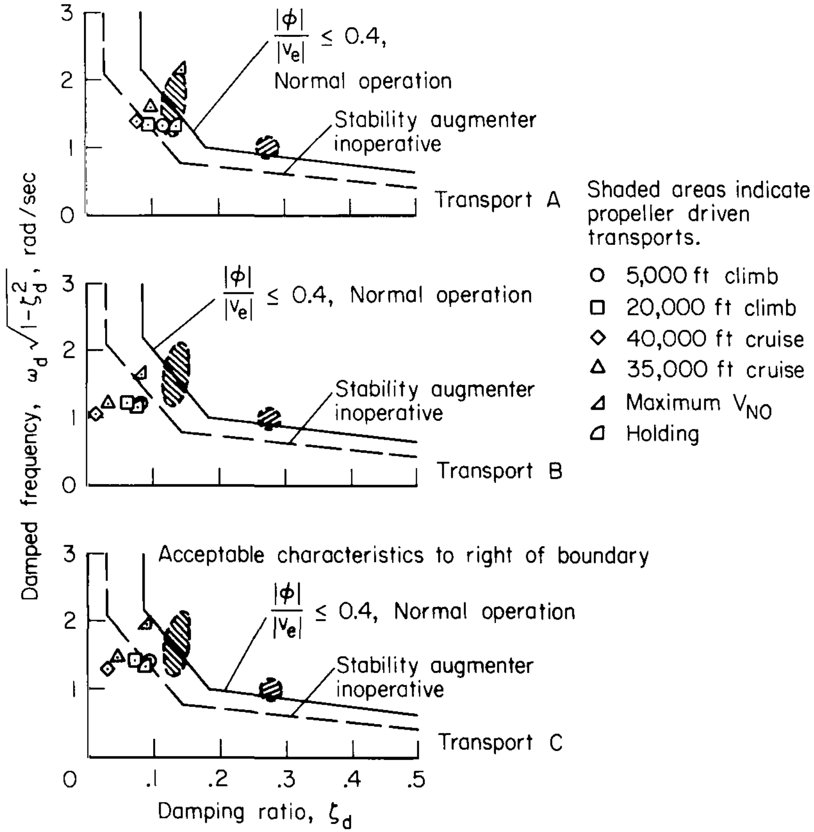

Figure 12.- Lateral oscillatory (Dutch roll) characteristics compared with criterion of reference 6. Basic flight conditions.

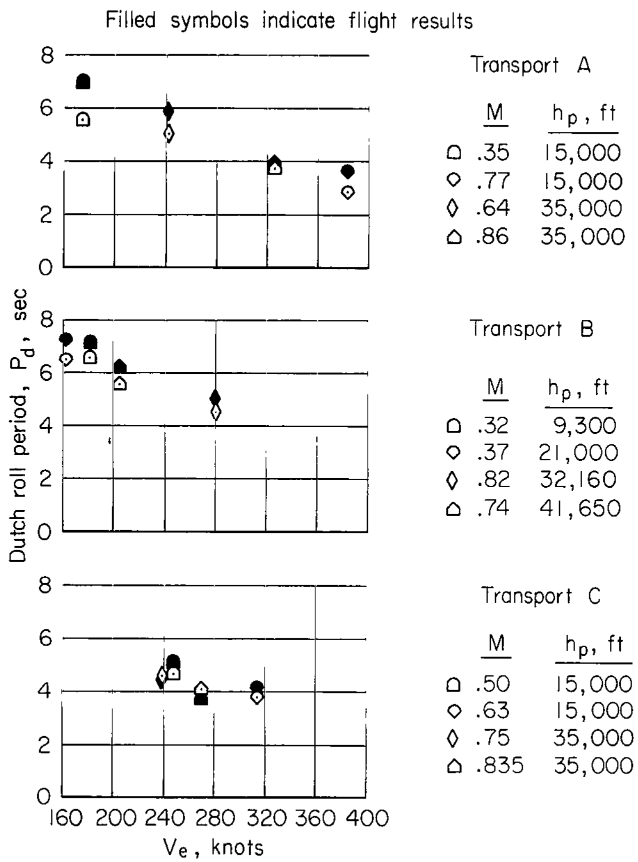

Figure 13.- Variation of Dutch roll oscillation period with equivalent airspeed. Additional flight conditions.

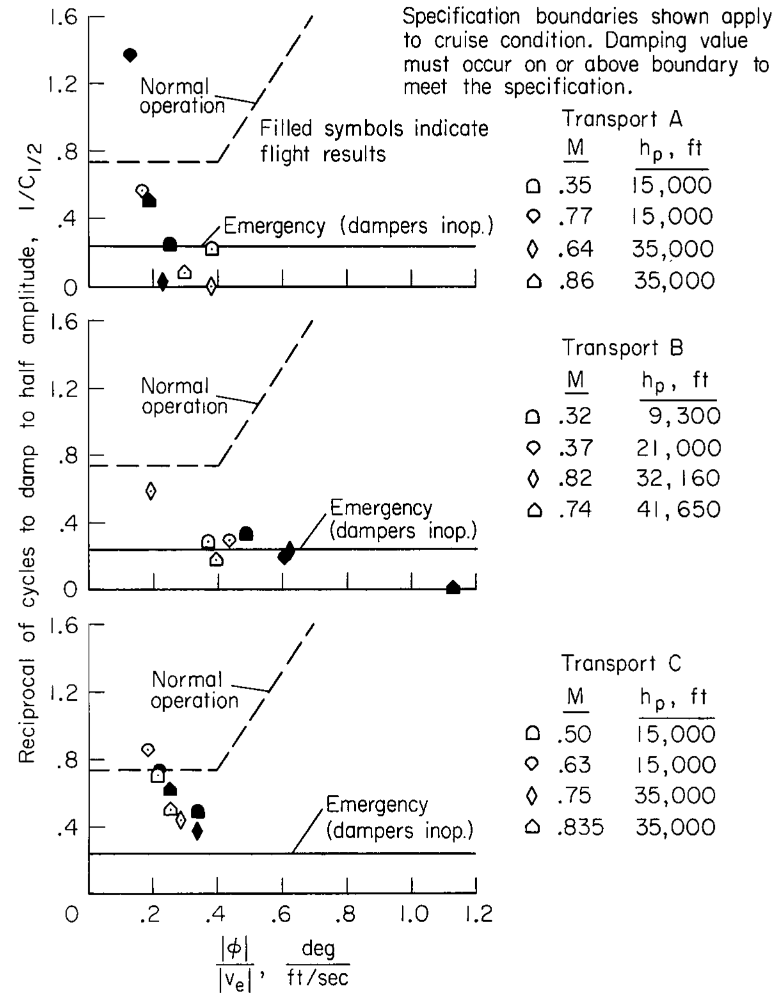

Figure 14.- Lateral oscillatory characteristics of the additional flight conditions compared with current military specification (ref. 2).

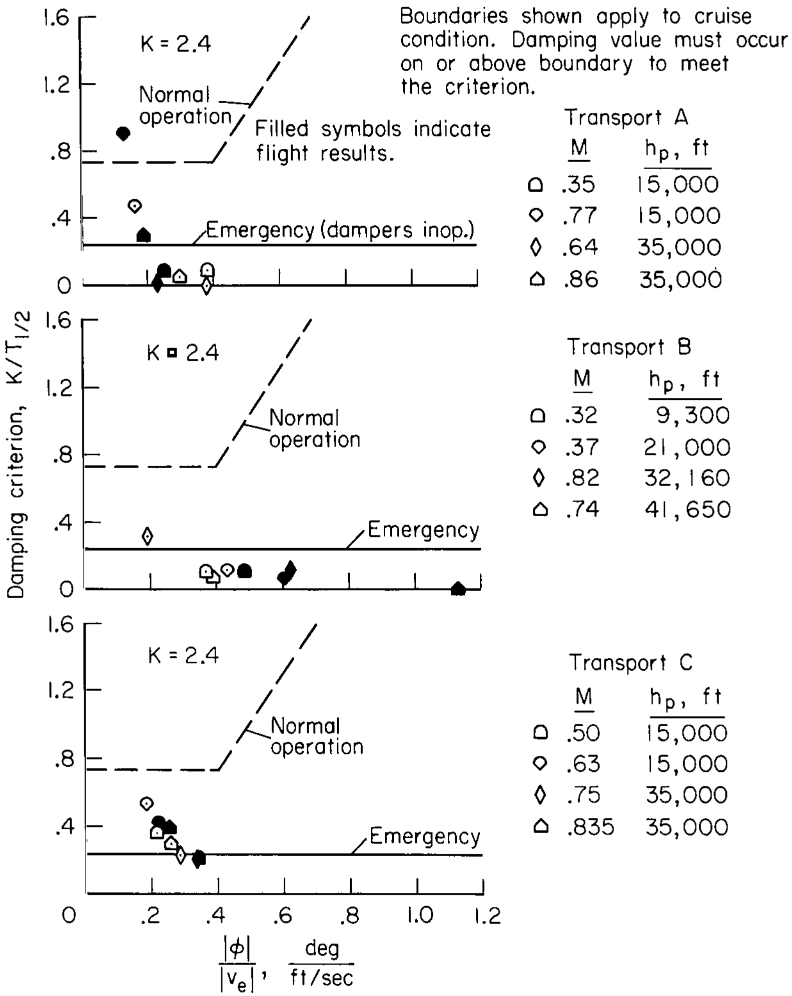

Figure 15.- Lateral oscillatory characteristics of the additional flight conditions compared with the criterion of reference 9.

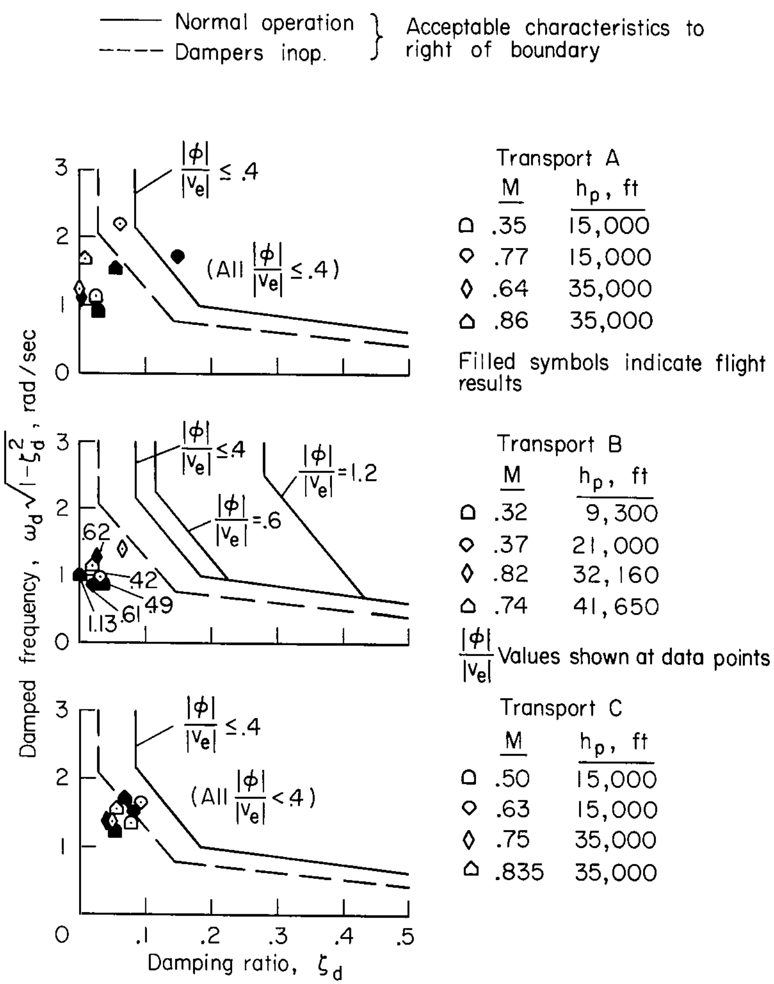

Figure 16.- Lateral oscillatory characteristics of the additional flight conditions compared with the proposed requirements of reference 6.

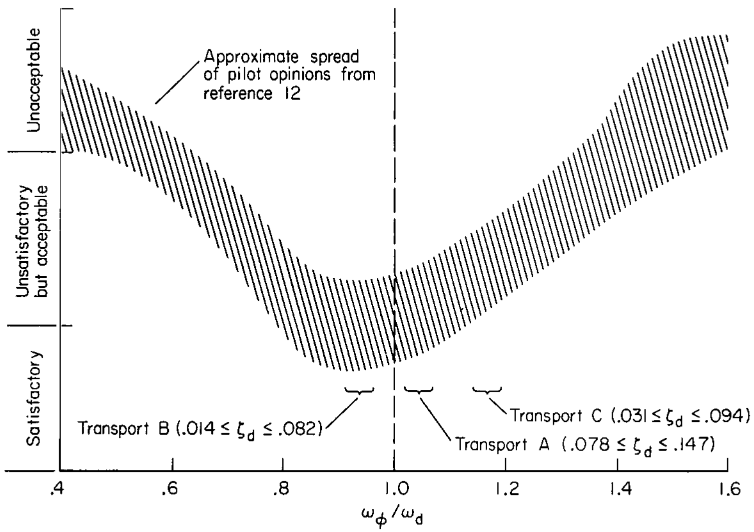

Figure 17.- Ranges of ratio of ω_φ to ω_d for the subject jet transports. Basic flight conditions.

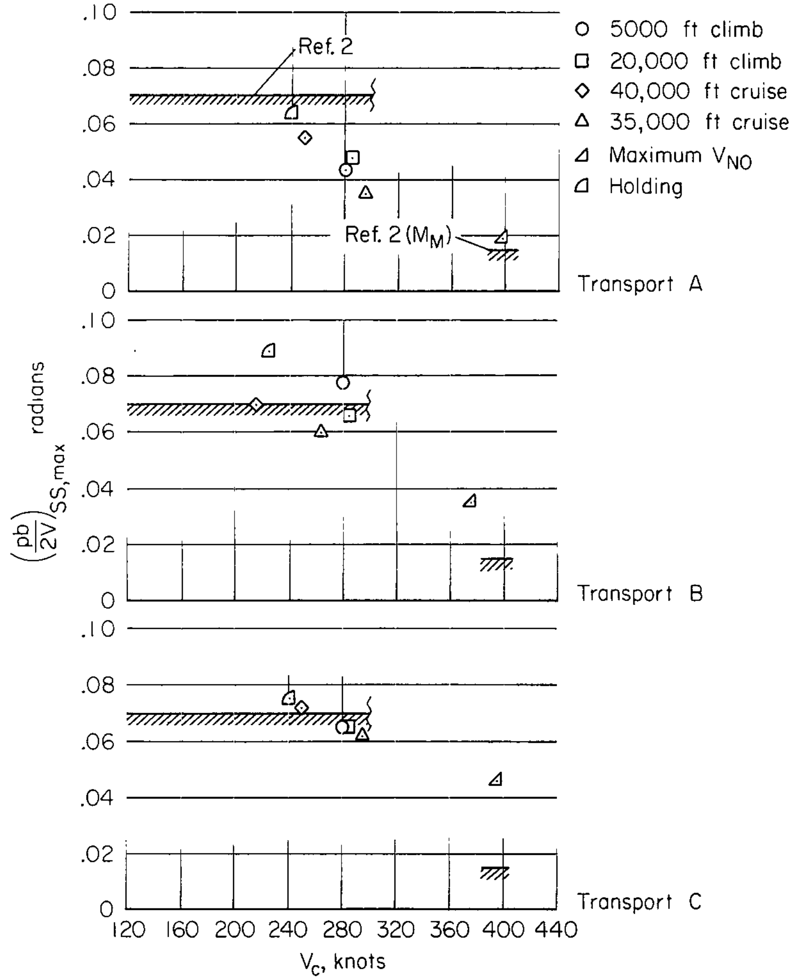

Figure 18.- Maximum steady-state wing-tip helix angle, $(pb/2V)_{ss,max}$, compared with current military specifications, reference 2. Basic flight conditions.

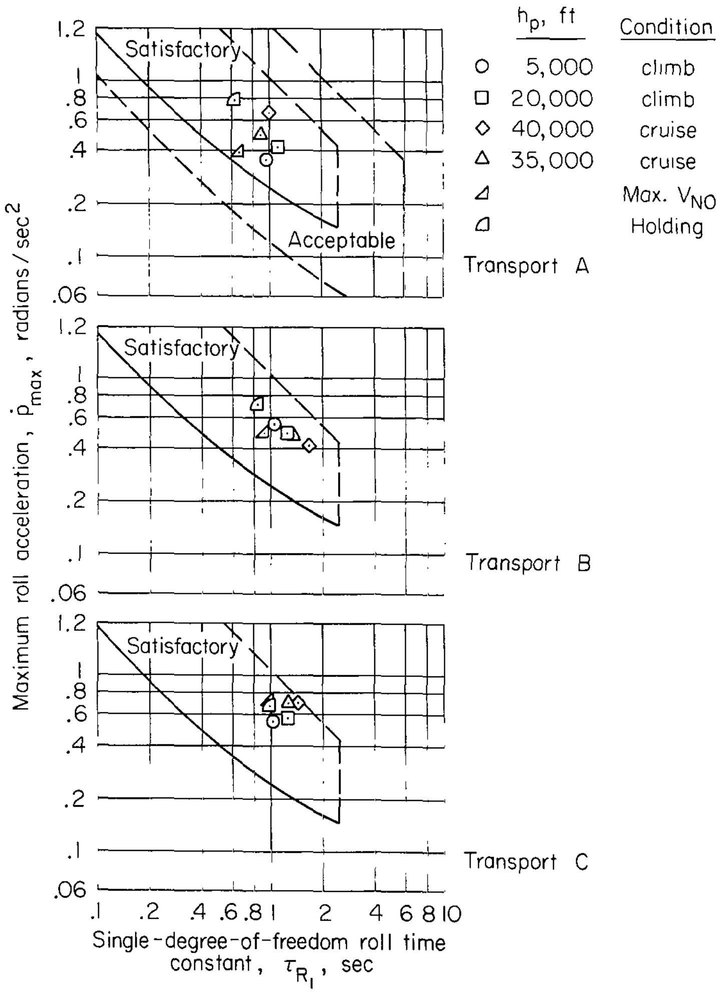

Figure 19.- Maximum roll acceleration and single-degree-of-freedom roll time constant compared with criterion of reference 13. Basic flight conditions.

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