LONGITUDINAL MANEUVERING CONTROL CHARACTERISTICS OF A CANARD-WING FIGHTER CONFIGURATION

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Analyses are made of a canard-wing fighter configuration, each surface having a trailing edge flap, to determine the maneuvering and tracking capability. Variations in the relationship between the canard and wing flap deflection allow longitudinal control concepts to range from a pure pitch control (pure pitching moment change) to a pure direct lift control (pure lift change at constant angle of attack). Results from a piloted tracking simulation are given and compare direct lift control for maneuvering and tracking to pitch control concepts and to an aft tail configurations. A reduction in tracking error is shown for the direct lift control mode. Evaluations of the direct lift control mode are made with reference to MIL-F-8785B, Military Specification - Flying Qualities of Piloted Airplanes. The specification problems encountered in assessing the direct lift control mode are discussed.

NOMENCLATURE

$C_{L_{\delta_c}}$	Canard lift with δ_c
$C_{L_{\delta_w}}$	Wing lift with δ_w
C_{L_δ}'	Total control lift
$C_{M_{\delta_c}}$	Canard pitching moment with δ_c
$C_{M_{\delta_w}}$	Wing pitching moment with δ_w
C_{M_δ}'	Total control moment
C_{L_α}	Airplane lift curve slope
$(C_L)_{1g}$	$W/\bar{q}s$
g	Acceleration of gravity
m	Airplane mass
M_δ'	Total control pitching moment derivative
M_w	Airplane pitching moment derivative due to w
M_α	$M_w V$
M_q	Pitch damping derivative due to q
$M_{\dot{w}}$	Pitch damping derivative due to $\dot{w}$
$M_{\dot{\alpha}}$	$M_{\dot{w}} V$
N_z	Normal acceleration in g units
q	Pitch rate
$\bar{q}$	Dynamic pressure
s	Reference area (wing)
V	Total velocity
w	Vertical velocity
Z_δ'	Total control normal force derivative
Z_w	Normal force derivative due to w
α	Angle of attack
δ_c	Canard flap deflection
δ_w	Wing flap deflection
δ'	Reference deflection (same as δ_c)
$\omega_{N_{SP}}$	Short period frequency
ζ_{SP}	Short period damping factor
$\ddot{\theta}$	Pitch acceleration
τ_{θ_2}	Lead factor in θ/δ transfer function

Special Subscripts

$t=0^+$	Evaluated with initial value theorem
ss	Evaluated with final value theorem

INTRODUCTION

The altering of aircraft flight paths by direct force as opposed to angle of attack change through pitching has come into increased interest. It has been investigated in the past in some studies in the form of jet thrust and wing flap deflection for increased combat normal and transverse g capability and also for flight path control in the approach to landing (reference 1 to 4). Reference 5 and 6 analytically examined direct lift control for a wide range of applications. Past investigations of direct lift control applications have generally been for wing-tail configurations.

The interesting aspect of direct lift control, as produced by a flapped surfaces, is the immediate acceleration force available limited only by the rate of flap deflection and the aerodynamic circulation lift build-up. Still another interesting aspect is the capability to produce flight path changes without the need to rotate the entire aircraft to increase angle of attack to obtain the accelerative lift. Some studies such as reference 7 have used a form of direct lift control to point an aircraft while essentially at constant lift.

A canard-wing aircraft configuration lends itself well to a study of aircraft pitch control and direct lift control. With effective trailing edge flaps on both the canard surface and the wing surface, a range of control relationships from a powerful pitching moment control to a direct lift control can be investigated. In this study a pitching moment control system is defined as one in which deflection of the canard and wing flap deflections are opposite to produce summing moments and opposing lifts. A direct lift control is defined as one in which the canard and wing surfaces deflect in the same direction to produce opposing moments but summing lifts.

It is possible to produce a pure pitching moment control in which the net lift due to the canard and wing flap deflections is zero. Conversely, a <u>pure</u> direct lift control is one in which deflection of the canard and wing flaps produce zero pitching moment change. A <u>perfect</u> direct lift control is defined as one in which the steady state angle of attack change with normal acceleration is zero.

The specification MIL-F-8785B, Flying Qualities of Piloted Airplanes, however, has developed over the years based on experience, analysis and studies of conventionally controlled (generally wing-tail) airplanes in pitch, i.e., flight path changes accomplished with angle of attack change through rotation in pitch. While the current specification acknowledges the concept of direct lift control, quantification and definition of assessment parameters is clearly lacking. Therefore, by use of the variability offered by a canard-wing configuration, various degrees of direct lift control are examined as to capability and the relationship to MIL-F-8785B, Flying Qualities of Piloted Airplanes. The study is exploratory to examine what can be accomplished with direct lift control and what kinds of problems might be encountered.

CANARD-WING CONFIGURATION DESCRIPTION

The configuration examined is shown in Figure 1 along with the important geometric constraints. This configuration offers some unique aerodynamic features. One feature is the excellent pitch damping resulting from the fact that both the wing and canard centers of lift due to angle of attack are located a good distance from the aircraft center of gravity. As a result the basic airframe short period damping is excellent as will be shown later.

The pitch and/or direct-lift control is obtained from the canard surface trailing edge flap and the wing surface trailing edge flap which in the latter also serves as the roll control. Either the canard or wing flap can produce large pitching moments due to the relatively large distance from the c.g. of their centers of pressure due to deflection.

The wing deflection is linearly related to the canard deflection by

$$\delta_w = \frac{\delta_w}{\delta_c} \delta_c + \delta_{w_o} \tag{1}$$

The effective values of the total airplane lift and moment pitch control effectiveness are obtained as follows:

$$C_{L_\delta}' = C_{L_{\delta_c}} + C_{L_{\delta_w}} \frac{\delta_w}{\delta_c} \tag{2}$$

$$C_{M_\delta}' = C_{M_{\delta_c}} + C_{M_{\delta_w}} \frac{\delta_w}{\delta_c} \tag{3}$$

Variation of the linear gearing, (δ_w/δ_c), and both positive and negative values allows a large range of effective values of C_{L_δ}' and C_{M_δ}' to be achieved. The deflection δ' is referenced to the canard flap deflection in equations (2) and (3), above. Figure 2 illustrates the above control effectiveness values for the three specific Mach numbers considered. The value of δ_{w_o} (equation 1) is used to bias the wing deflection to place the canard and wing surface deflection range at reasonable values with respect to the maximum and minimum deflections.

Maneuvering Characteristics

The typical maneuvering characteristics are illustrated for a transonic combat flight range at 20,000 ft for a gross weight of 18,500 lbs at a nominal center-of-gravity. The basic airframe dynamic characteristics are presented in Figure 3 and are, of course, independent of the control relationships. Figure 4 illustrates the variations in M_δ' and Z_δ' as a function of canard-wing gearing.

The steady state normal acceleration values available as a function of the canard-wing gearing are shown in Figure 5. The positive values of the obscissa in Figure 4 represent direct lift control gearings while the negative values are pitch control values. As can be seen in Figure 5, the normal acceleration per unit deflection decreases as the canard-wing gearings tend toward direct lift controls. The incremental values of the canard deflection to maneuver to the assumed maximum normal acceleration are shown in Figure 6. It is evident in Figure 6 that large deflections are required for high levels of direct lift control which can limit the maneuvering envelope. This can be alleviated to some degree by biasing the wing deflection at neutral control to shift the range of canard deflections but possibly at the expense of the opposite end of the envelope at some flight conditions and center-of-gravities.

The reciprocal of the normal acceleration sensitivity is presented in Figure 7. Very little change can be seen in Figure 7 for the normal acceleration sensitivity for a relatively wide range of wing to canard deflection ratios. For values of $\alpha/N_z = 0$, the quickening of normal acceleration response due to control input should be at its maximum since no steady state angle of attack change is necessary. It is noted that at the low Mach number of .6, achieving low values of α/N_z with δ_w/δ_c gearings of about .6 is not feasible since, as Figure 5 indicates, little normal acceleration can be produced.

Tracking Simulation Description

The most useful application for direct lift control would appear to be in target tracking. It is in this flight task that the most demanding requirements for pitch control response exists. A five degree-of-freedom piloted simulation was conducted to determine the effect of the type of longitudinal control system on the air-to-air tracking task. The pitch control configuration consisted of an aft tail pitch control and various combinations of canard-wing pitching moment control and direct lift control as discussed earlier. The simulation evaluations were performed at Mach = .6, .9 and 1.3. The altitude range was 10,000 feet to 35,000 and each run was initiated at 20,000 feet.

The simulation was conducted on the Rockwell International Corp., Columbus Aircraft Division's Dynamic Flight Simulator which utilizes a moving base cockpit and a projected television visual display for the out-of-cockpit view. A fixed reticle sight mounted at the wind screen was used to sight and track the target aircraft. The target was a scale aircraft model mounted on an angular table system which was driven by the computer. The target motions were obtained by fighter pilots flying the cockpit of the Dynamic Flight Simulator in mock evasive maneuvers using the cockpit instrument panel. The target Euler angles and spacial coordinates were recorded during the evasive maneuvering flights for subsequent playback during the evaluation phase.

The five degrees-of-freedom aircraft equations of motion were programmed on hybrid computing equipment with Mach number held constant during a run. The taped Euler angles and spacial coordinates of the target aircraft were played back and similar real time computed data for the pursuing aircraft were used to present a pictorial image on the visual display to the pilot. The pilot then tracked the target by flying the cockpit to keep the gun sight pipper on the target. The range to the target was held constant. Since relatively long term accelerations were involved, cockpit motions could not be utilized. However, cockpit buffet was simulated to warn of approaching stall was produced as a function of normal acceleration and altitude at each Mach number. Pilot cues other than buffet were provided by the visual presentation of the target airplane, the cockpit instruments and the cockpit control forces.

Good lateral-directional aircraft characteristics were employed with appropriate stability augmentation so that the emphasis could be put on the longitudinal control. Excellent roll response was available at all speeds. No longitudinal stability augmentation was employed. The basic airframe longitudinal short period frequency and damping which were considered satisfactory for the evaluation is shown in Figure 3 for the mid-altitude of 20,000 ft.

The longitudinal control configurations evaluated consisted of four canard-wing relationships. In addition, a wing tail configuration was evaluated. Table I shows the wing to canard ratios and the wing-tail configuration elevator characteristics evaluated.

Table I.

δ_w/δ_c	M	N/α g/RAD	N/δ g/RAD	Configuration
-.35	.6	17.37	92.27	Canard-Wing
	.9	44.73	77.49	"
	1.3	82.07	75.35	"
.2	.6	17.4	39.24	"
	.9	45.5	38.96	"
	1.3	84.0	36.95	"
.48	.6	25.02	12.39	"
	.9	70.03	19.48	"
	1.3	171.67	17.42	"
.6	.9	163.3	11.09	"
	1.3	-546.2	9.05	"
-	.6	17.37	18.16	Wing-Tail
-	.9	44.73	69.84	"
-	1.3	82.07	69.73	"

The wing-tail configuration was evaluated using the same wing as the canard-wing configuration.

The stick force per g values were maintained within a range of 4.5 to 6 lbs/g for 20,000 ft as shown in Figure 8. The range of stick force per g values were considered optimum for the tracking evaluations. Stick deflection sensitivity was maintained at reasonable values for all control configurations.

Tracking Simulation Results

The simulator tracking evaluations were flown by 5 combat rated fighter pilots. The various configurations were flown by them in a random order. Each pilot also rated each control configuration.

The step response for each control configuration is shown in Figure 9 and were obtained from the simulation. For .6 Mach number in Figure 9, note that the highest wing-to-canard deflection ratio evaluated was δ_W/δ_C = .48 due to the high deflections required for values of δ_W/δ_C greater than .48 at that flight condition. Examination of the N_Z and α traces shows that for δ_W/δ_C = .48 only a small reduction in angle of attack and small improvement in normal acceleration response can be noticed. Significant improvement for the values of δ_W/δ_C = .48 and .6 can be seen for the .9 and 1.3 Mach number responses in Figure 9. The normal initial N_Z reversal for the wing-tail configurations at all Mach numbers can be seen in Figure 9. This, of course, is due to the downward direct normal force from the horizontal tail which is used to pitch the aircraft up. It does, however, result in a delay in N_Z increase for approximately .1 to .2 seconds for the step responses of Figure 9. No delay occurs for the canard-wing cases with δ_W/δ_C = -.35 and -.2 and in immediate increase in N_Z is apparent for δ_W/δ_C = .48 and .6 as illustrated in Figure 9.

The target sighting errors which were averaged for all pilots for each control configuration are shown in Figure 10. No improvement in sighting error is apparent for the .6 Mach number case as δ_W/δ_C values become negative. The .9 and 1.3 Mach number show reductions in sighting error as direct lift control values of δ_W/δ_C are approached in Figure 10. It is significant that the greatest reduction in sighting error was obtained at the highest Mach number evaluated.

A typical distribution in tracking error is shown for 1.3 Mach number in Figure 11 and clearly shows the improvement in error as the control tends to greater degrees of direct lift control.

The tracking error was also separated into lateral and vertical errors as the evaluation were flown. Generally, the lateral errors were about the same order of magnitude as the vertical errors. However, for the control configuration values of δ_W/δ_C = .48 and .6 for 1.3 Mach number, the vertical errors were about 15% less than the lateral errors.

The averaged pilot ratings were presented in Figure 12 and show approximately the same trends as the sighting error performance. The low range of the pilot ratings is due to several overall factors in the simulation the pilots disliked. These factors being the lack of a horizon reference in the outside visual view, the narrow field of view and the lack of additional "G" cues other than stick force and buffet near stall. However, the important feature to be shown with the pilot ratings is that as the mode of longitudinal control changed from pitch control to direct lift control and its rapid response, no degradation in pilot ratings occurred. Even at the Mach number of 1.3 for the direct lift control with the steady state $\alpha/N_z = 0$ the pilot ratings were relatively good.

It was concluded, like previous analytical studies conducted at the Columbus Aircraft Division of Rockwell International Corporation had shown, direct lift control could improve longitudinal maneuvering characteristics. It is not clear yet just how direct lift control should be implemented. In view of the large flap deflections and possible drag penalties incurred, the best form of application must be further studied. Perhaps direct lift control used for short term precision maneuvering or a form that utilizes the initial response characteristic which then washes out might be the best use. In any event, forms of direct lift control will most likely find usage in future military aircraft.

MIL-F-8785B CONSIDERATIONS

As is known the present requirements in regard to longitudinal control in the specification MIL-F-8785B are based on the wealth of data and analyses available for wing-tail configurations. Use of MIL-F-8785B as guidance for design of direct lift control systems was, of course, not intended and the current specification acknowledges this. Use of the parameter N_z/α is the fundamental problem. One such use of the parameter N_z/α is in the MIL-F-8785B requirement for $\omega_{N_{SP}}$. Surprisingly, many of the direct lift control configurations evaluated in the simulation fall in the level one region as seen in Figure 13. However, the case of 1.3 Mach number with $\delta_W/\delta_C = .6$ cannot be plotted in Figure 13 since N_z/α is a large negative number (small α/N_z).

The maneuvering stick force gradient specification requirement is also in terms of N_z/α in MIL-F-8785B. It presents less of a problem applied to direct lift control systems since at high values of N_z/α the stick force maximum and minimum gradients are specified as a constant. Figure 14 shows the force gradients used in the simulation compared to MIL-F-8785B boundaries. Values cannot be shown for 1.3 Mach number since the value of N_z/α is a large negative number as for the $\omega_{N_{SP}}$ comparison.

The analytical expression for N_z/α can be examined as follows:

$$\frac{N_z}{\alpha} = \frac{V}{g}\left[\frac{Z_\delta{}'\,M_w - M_\delta{}'\,Z_w}{M_\delta{}' - \frac{Z_\delta{}'\,M_q}{V}}\right] \qquad (4)$$

For conventional wing-tail configurations or whenever the prodominate terms in equation (4) are $M_\delta' Z_w$ (numerator) and $Z_\delta' M_q/V$ (denominator) then equation (4) reduces to

$$\frac{N_z}{\alpha} = \frac{V}{g}\frac{(-M_\delta' Z_w)}{M_\delta} = \frac{V}{g} Z_w = \frac{C_{L\alpha}\,\bar{q}s}{m\,g} = \frac{C_{L\alpha}}{(C_L)_{1g}} \tag{5}$$

which is a function of the lift curve slope and flight condition embodied in $(C_L)_{1g}$. For the pure direct lift control case ($M_\delta' = 0$) the normal acceleration sensitivity is then given by

$$\frac{N_z}{\alpha} = \frac{-V^2}{g}\frac{M_w}{M_q} = \frac{-V}{g}\frac{M_\alpha}{M_q} \tag{6}$$

which is a function of the aircraft longitudinal stability and pitch damping. It is noted that the case of $M_\delta' = 0$ is not of primary interest.

If a perfect direct lift control system is assumed, i.e., $\alpha/N_z = 0$, (or $N_z/\alpha = \infty$) then

$$\frac{\alpha}{N_z} = 0 = M_\delta' - \frac{Z'_\delta M_q}{V} \tag{7}$$

or

$$M_\delta' = \frac{Z_\delta' M_q}{V} \tag{8}$$

In the case of the canard-wing configuration, δ_w/δ_c can be chosen to satisfy equation (8). In this case, as expected, N_z/α is no longer a function of $C_{L\alpha}$.

Intuitively, it would be expected that for $\alpha/N_z = 0$, N_z/δ would be a function only of Z'_δ. This can be shown as follows. For the steady state

$$\frac{N_z}{\delta} = \frac{V}{g}\frac{(Z_\delta' M_w - M_\delta' Z_w)}{\omega^2_{N_{SP}}} \tag{9}$$

Replacing M_δ' with equation (8)

$$\frac{N_z}{\delta} = \frac{-Z_\delta'}{g}\frac{(Z_w M_q - M_m V)}{\omega^2_{N_{SP}}} \tag{10}$$

and since

$$\omega^2_{N_{SP}} = Z_w M_q - M_w V \tag{11}$$

then

$$\frac{N_z}{\delta} = \frac{-Z_\delta{}'}{g} \tag{12}$$

It is also of interest to examine the development of the current MIL-F-8785B boundary $\omega^2_{N_{SP}}/N/\alpha$. One approach was the ratio of the initial pitch acceleration response to the steady state normal acceleration response. The expression for the above ratio, from reference 8, is written for constant speed equations of motion by applying the initial value theorem to the $\ddot{\theta}/\delta$ transfer function and the final value theorem to the N/δ transfer function.

$$\frac{\left.\frac{\ddot{\theta}}{\delta}\right|_{t=0^+}}{\left.\frac{N}{\delta}\right|_{ss}} = \frac{\omega^2_{N_{SP}}}{\frac{V}{g}\,\frac{1}{\tau_{\theta_2}}} \tag{13}$$

where the lead factor

$$\frac{1}{\tau_{\theta_2}} = \frac{Z_\delta\, M_w - M_\delta\, Z_w}{M_\delta + Z_\delta\, M_{\dot{w}}} \tag{14}$$

Applying the expression for a perfect direct lift control (equation 8) the lead factor reduces to

$$\frac{1}{\tau_{\theta_2}} = \frac{\omega^2_{N_{SP}}}{-M_q - M_{\dot{\alpha}}} \tag{15}$$

Thus, for a perfect direct lift control the response ratio is

$$\frac{\left.\frac{\ddot{\theta}}{\delta}\right|_{t=0^+}}{\left.\frac{N}{\delta}\right|_{ss}} = \frac{(-M_q - M_{\dot{\alpha}})}{V/g} \tag{16}$$

Reference 8 shows that for conventional wing-tail airplanes with pitch control systems

$$\frac{\left.\frac{\theta}{\delta}\right|_{t=0^+}}{\left.\frac{N}{\delta}\right|_{ss}} \approx \frac{\omega_{N_{SP}}^2}{N/\alpha} \tag{17}$$

and it is the ratio $\omega_{N_{SP}}^2/(N/\alpha)$ which forms the boundaries currently in MIL-F-8785B for the $\omega_{N_{SP}}$ requirement. If equation (17) is erroneously used for a perfect direct lift control, it would yield a value of zero. However, as equation (16) shows, a value does exist as it intuitively should since there is a small pitch transient even for a perfect direct lift control. This implies that the lower boundaries for the $\omega_{N_{SP}}$ vs N/α requirement in MIL-F-8785B cannot be met especially for direct lift control systems where α/N_z approaches 0. Indeed, the current MIL-F-8785B specification allows the boundary on $\omega_{N_{SP}}$ and N/α to be relaxed, with the approval of the procuring activity, if a suitable type of direct-lift control is provided.

In essence, the above discussion has aimed at illustrating that the background of pitch control systems understandably so prevalent in the MIL-F-8785B specification of longitudinal maneuvering requirements is inappropriate for direct lift control systems. The current requirements may be satisfactory in some cases for direct lift control systems that are a combination of pitch control and direct lift. However, for direct lift control approaching values of $\alpha/N = 0$, new parameters need to be developed to adequately specify desirable flying qualities. Perhaps maneuvering control force gradients would be better specified in terms of N/δ for direct lift control, being somewhat analagous to N/α. Continued interest and flight testing of direct lift control applications should provide the needed data for further development.

Conclusions

A canard-wing aircraft configuration with a canard flap and a wing flap provides a wide range of longitudinal maneuvering control concepts. The relationship between the canard flap and wing flap deflections with cockpit control deflection was evaluated in a fighter target tracking simulation. Target tracking error showed continuous reduction at .9 and 1.3 Mach number as greater degrees of direct lift control were provided. At .6 Mach number sufficient levels of direct lift control could not be achieved due to the large flap deflections required at the altitude evaluated. Pilot ratings were as good for direct lift control that utilized little to no angle of attack (steady state) change even though the $\omega_{N_{SP}}$ vs N/α specification boundary was not satisfied.

The present MIL-F-8785B specification parameter, N/α, used for longitudinal maneuvering control, is not applicable to direct lift control concepts that approach a perfect direct lift control (α/N = 0). Control force gradients might be better specified in terms of N/δ instead of N/α for perfect direct lift control concepts.

The form of the application of direct lift control for maneuvering is not clear yet. It may be better utilized for small normal acceleration changes or in a control system that washes out the direct lift control used in conjunction with a pitch control.

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Wing Area = 293 ft^2

Reference Chord (Wing = 12.5 ft

Wing Span = 24.8 ft

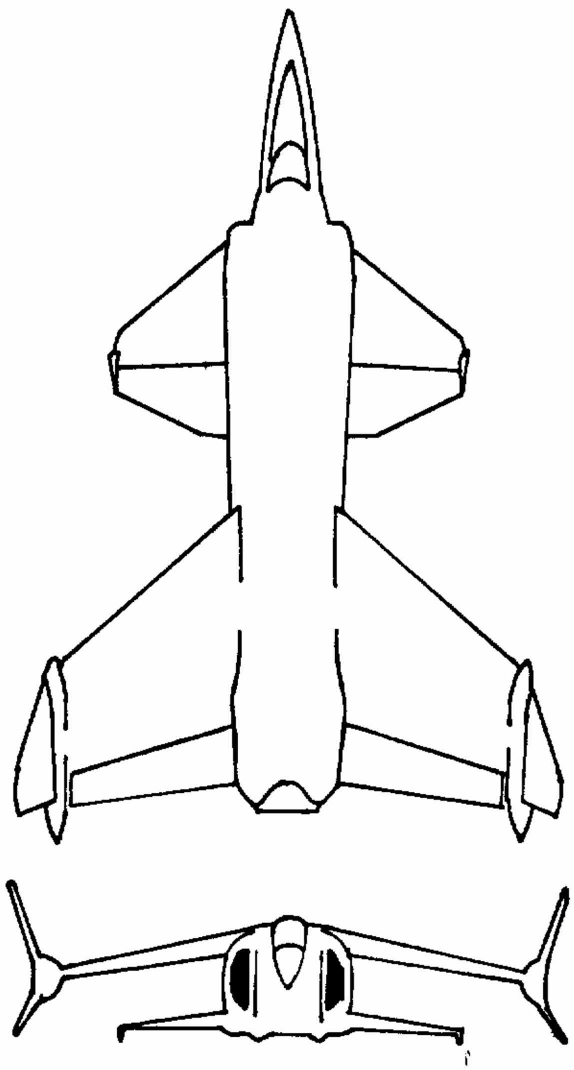

Figure 1. Canard-Wing Configuration

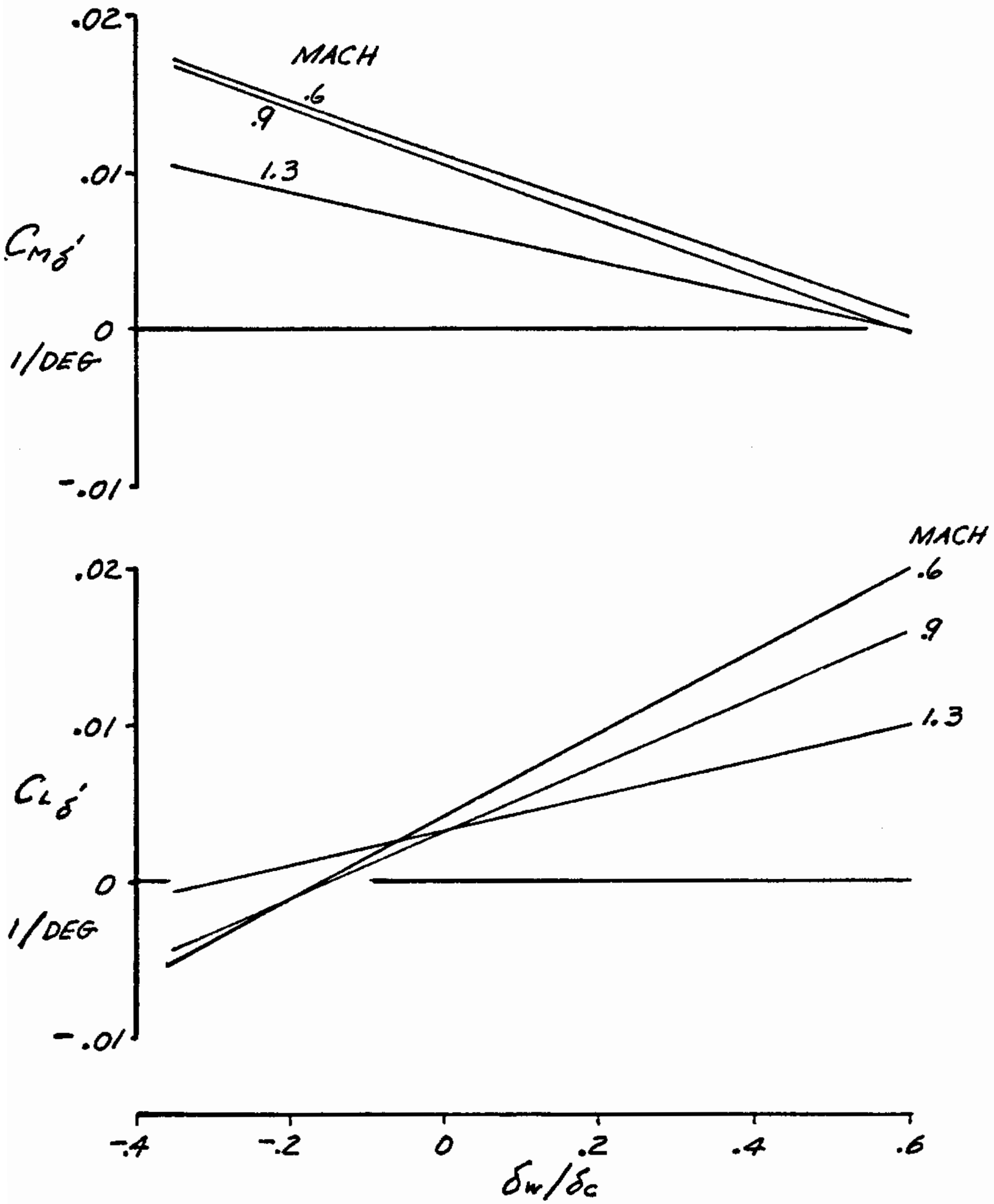

Figure 2. Control Coefficients

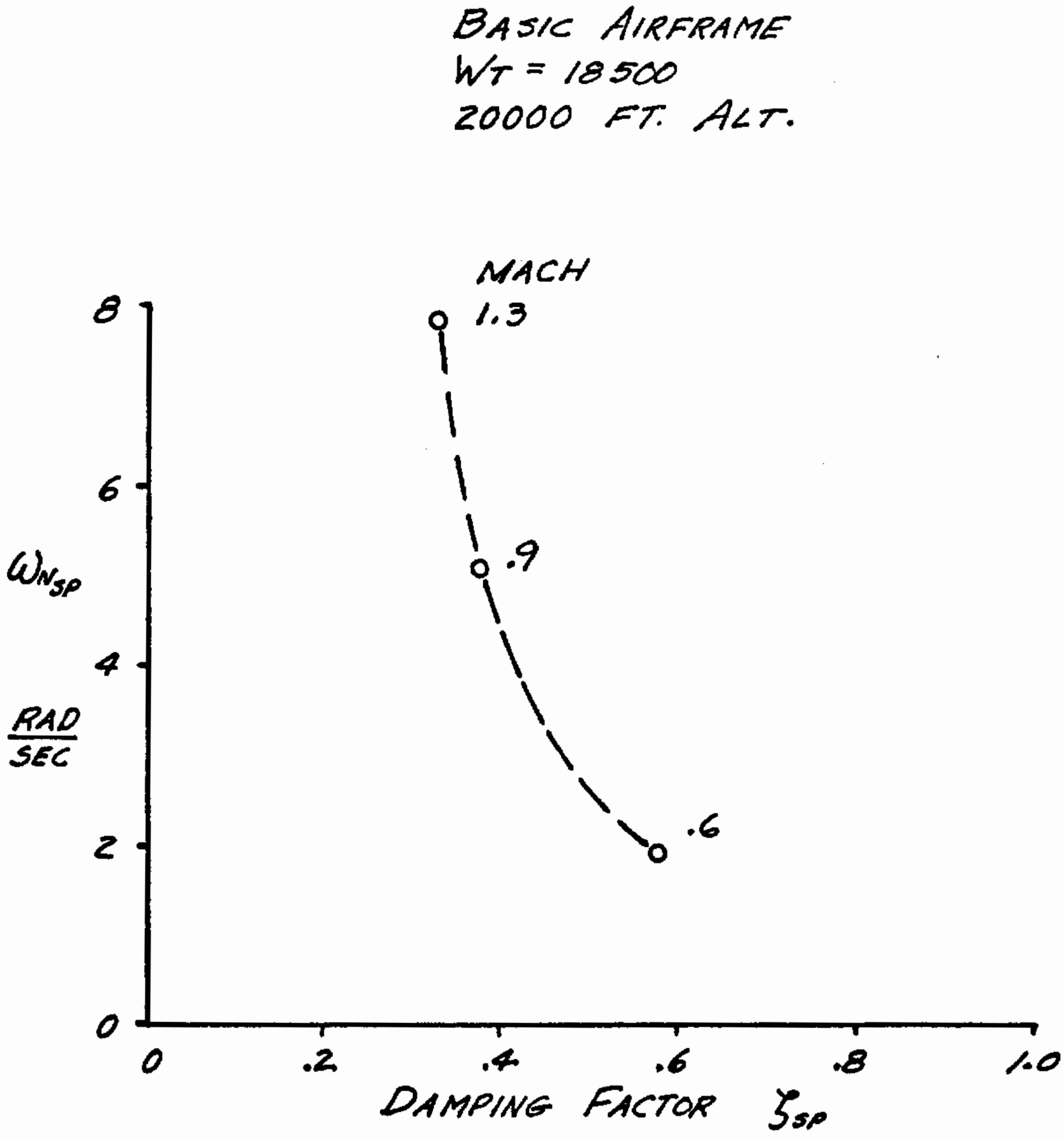

Figure 3. Longitudinal Short Period Frequency and Damping

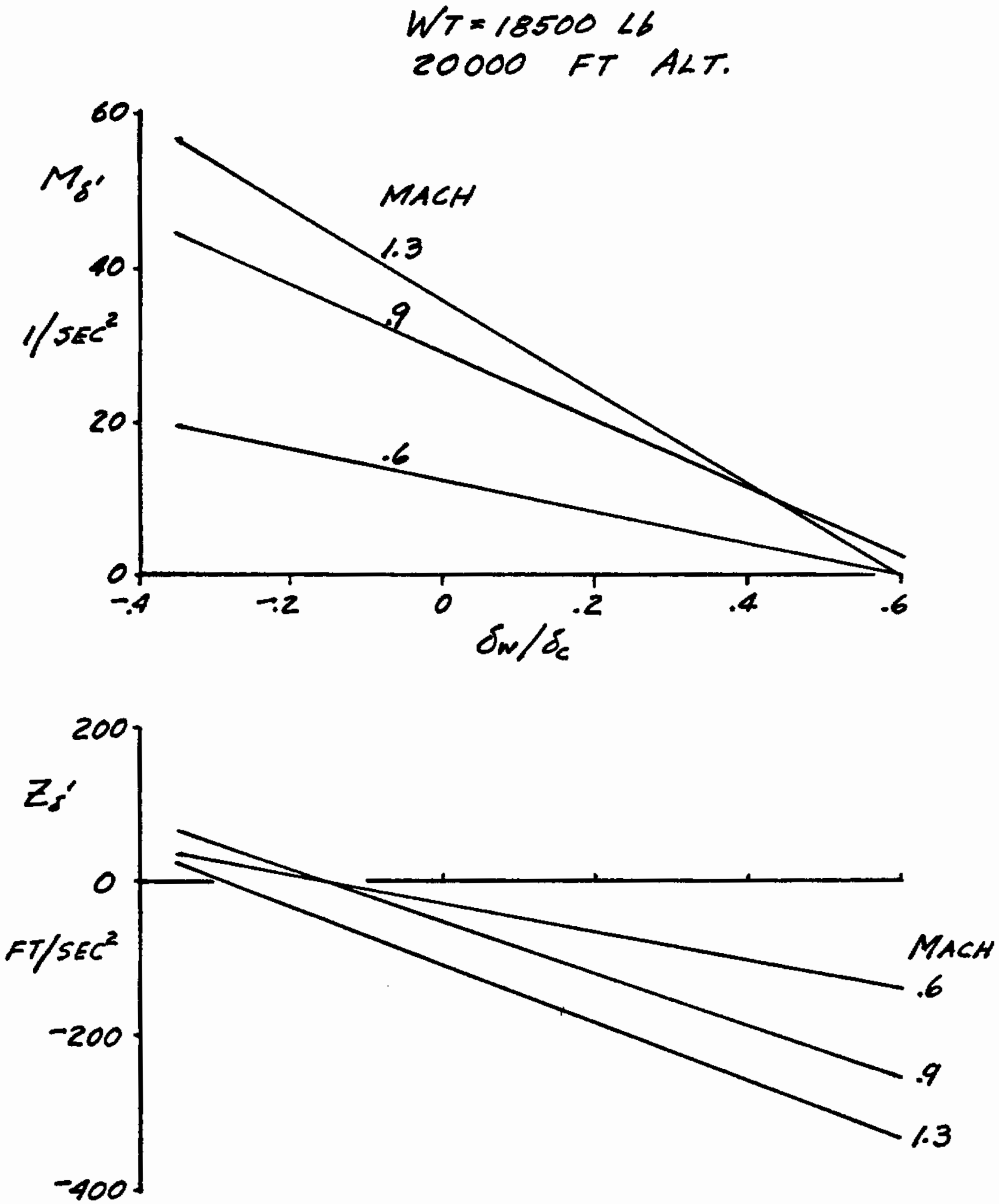

Figure 4. Control Dimensional Derivatives

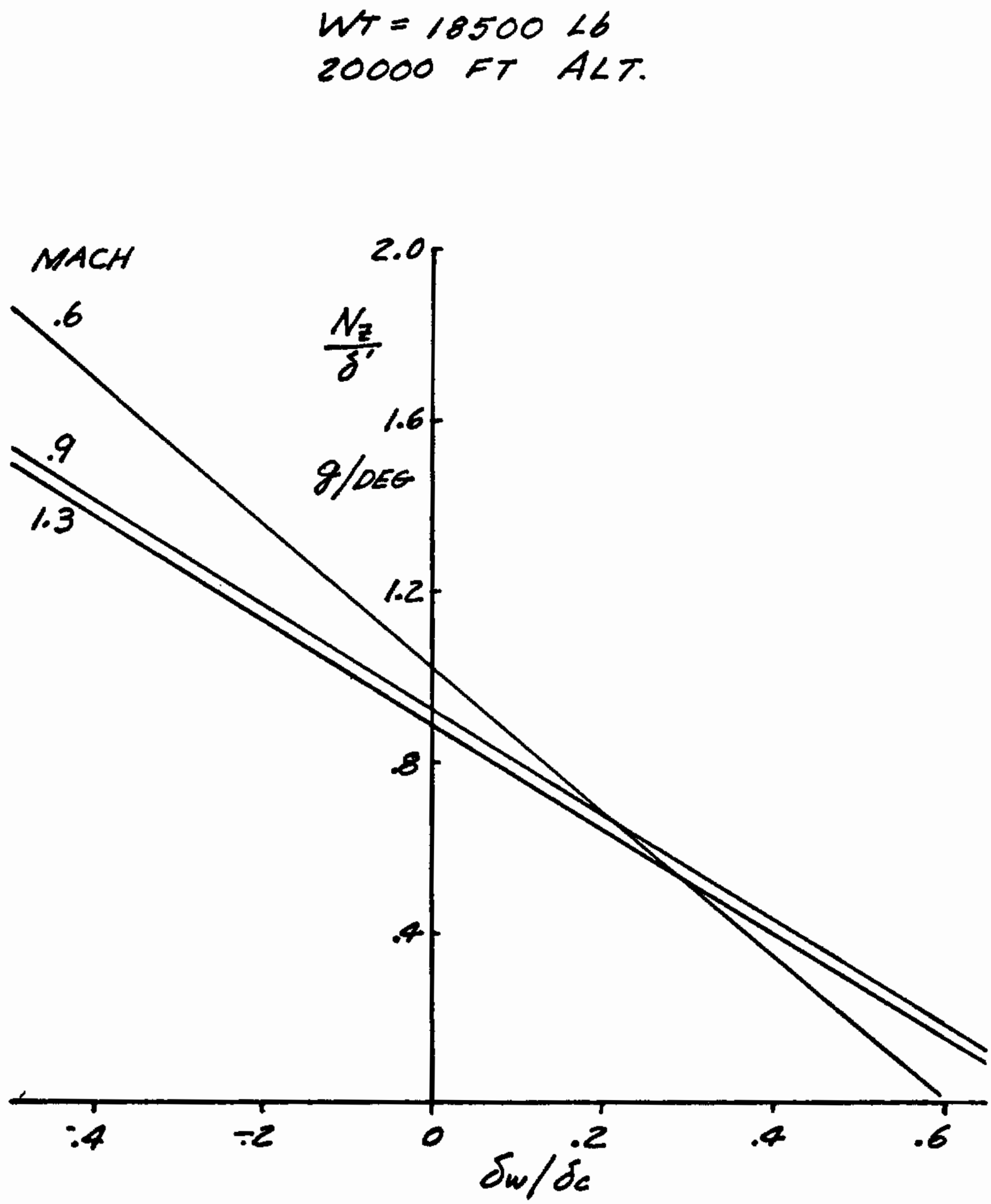

Figure 5. Normal Acceleration due to Control Deflection

WT = 18500 Lb
20000 FT ALT

M	N_z
.6	3.86
.9	6.5
1.3	6.5

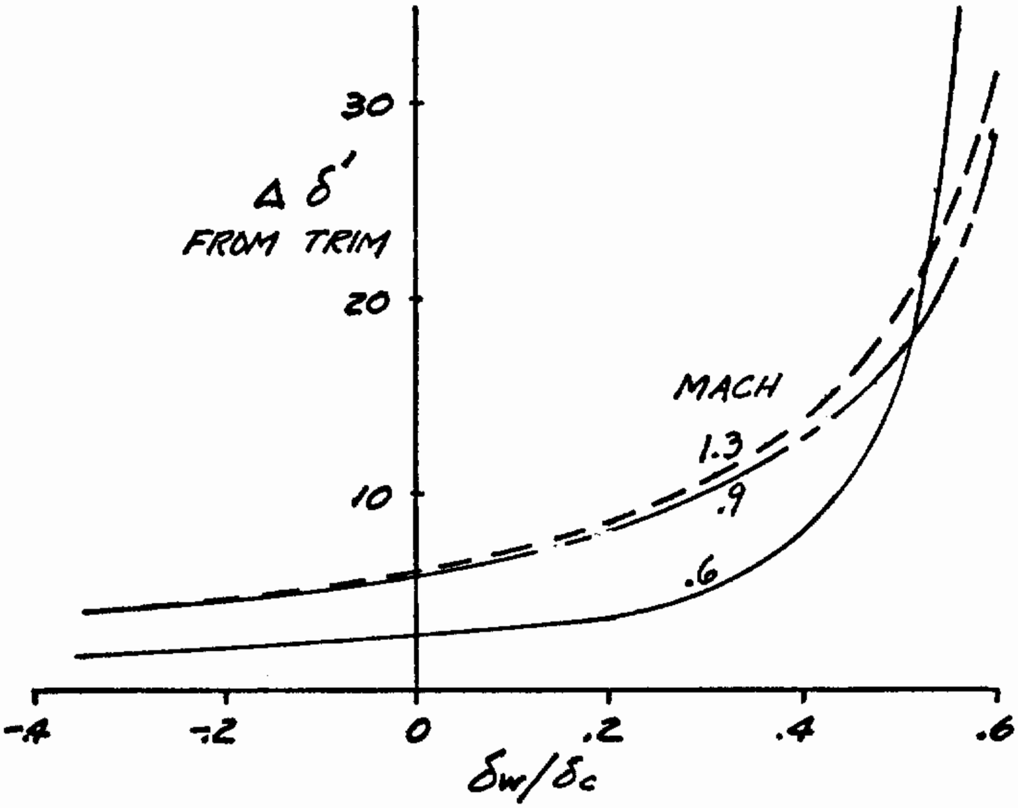

Figure 6. Control Incremental Deflection to Maneuver to Maximum N_z

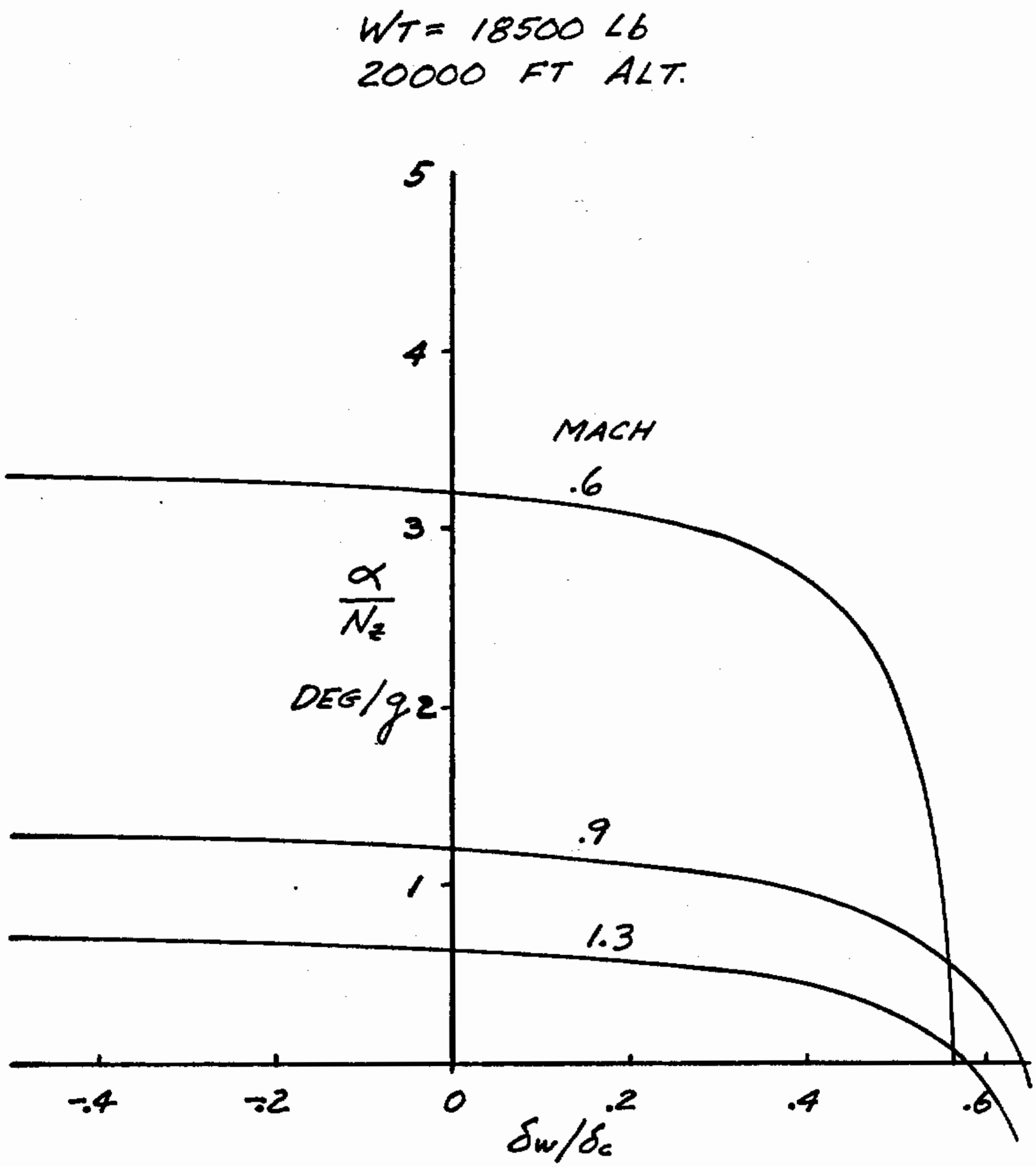

Figure 7. Normal Acceleration Sensitivity Reciprocal

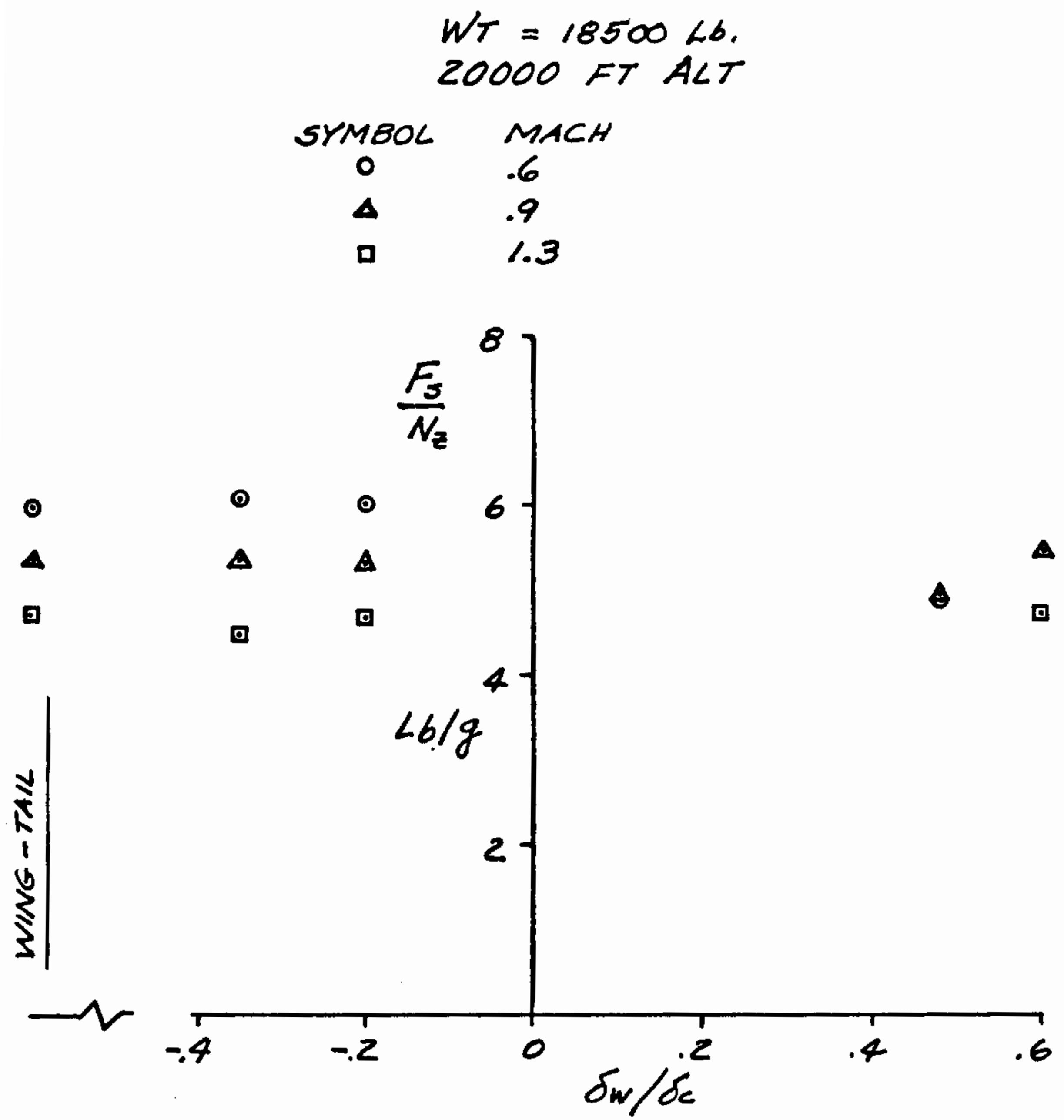

Figure 8. Maneuvering Force Gradients for Tracking Simulation

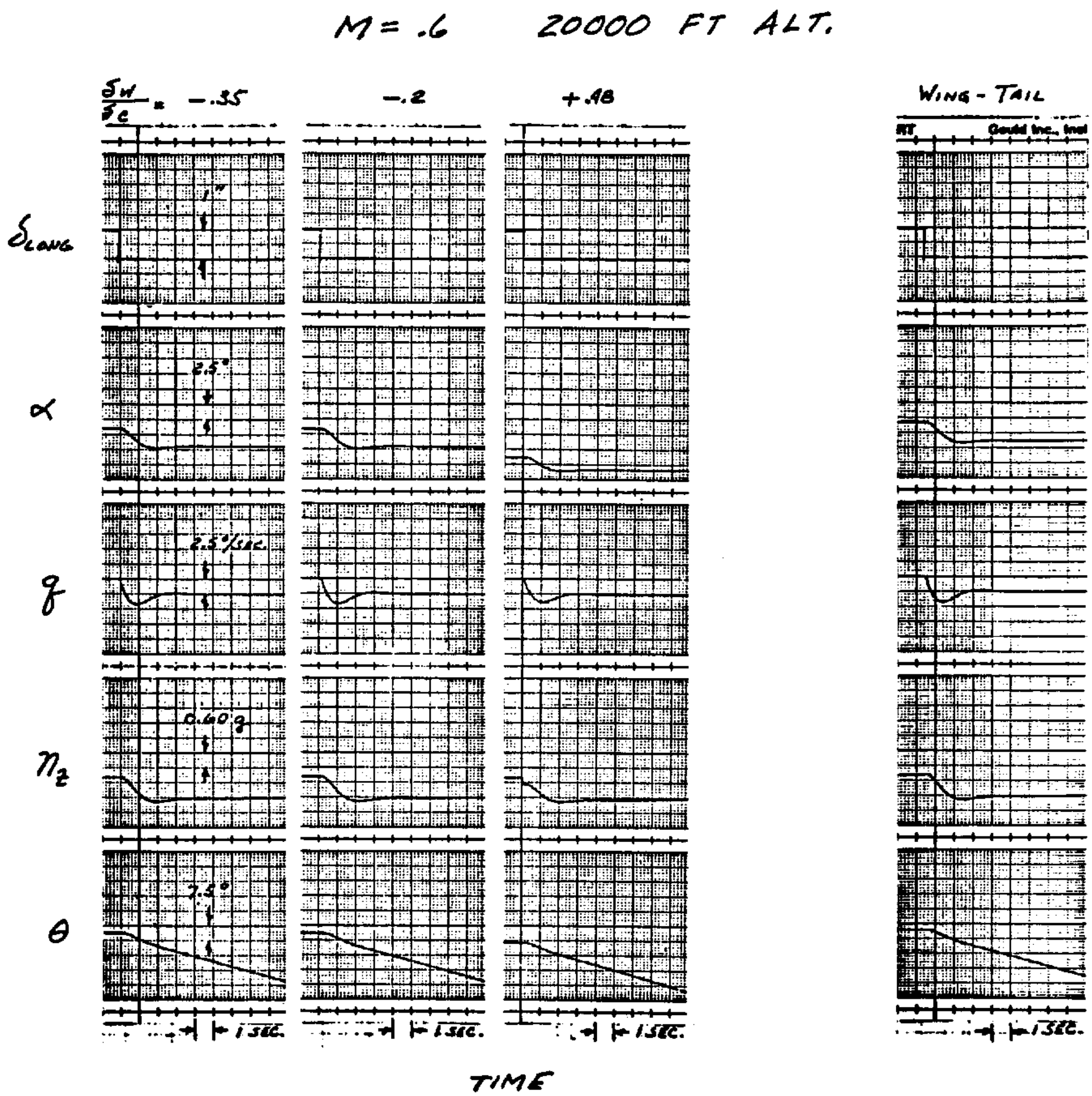

Figure 9a. Time Histories of Response to a Unit Step Stick Input

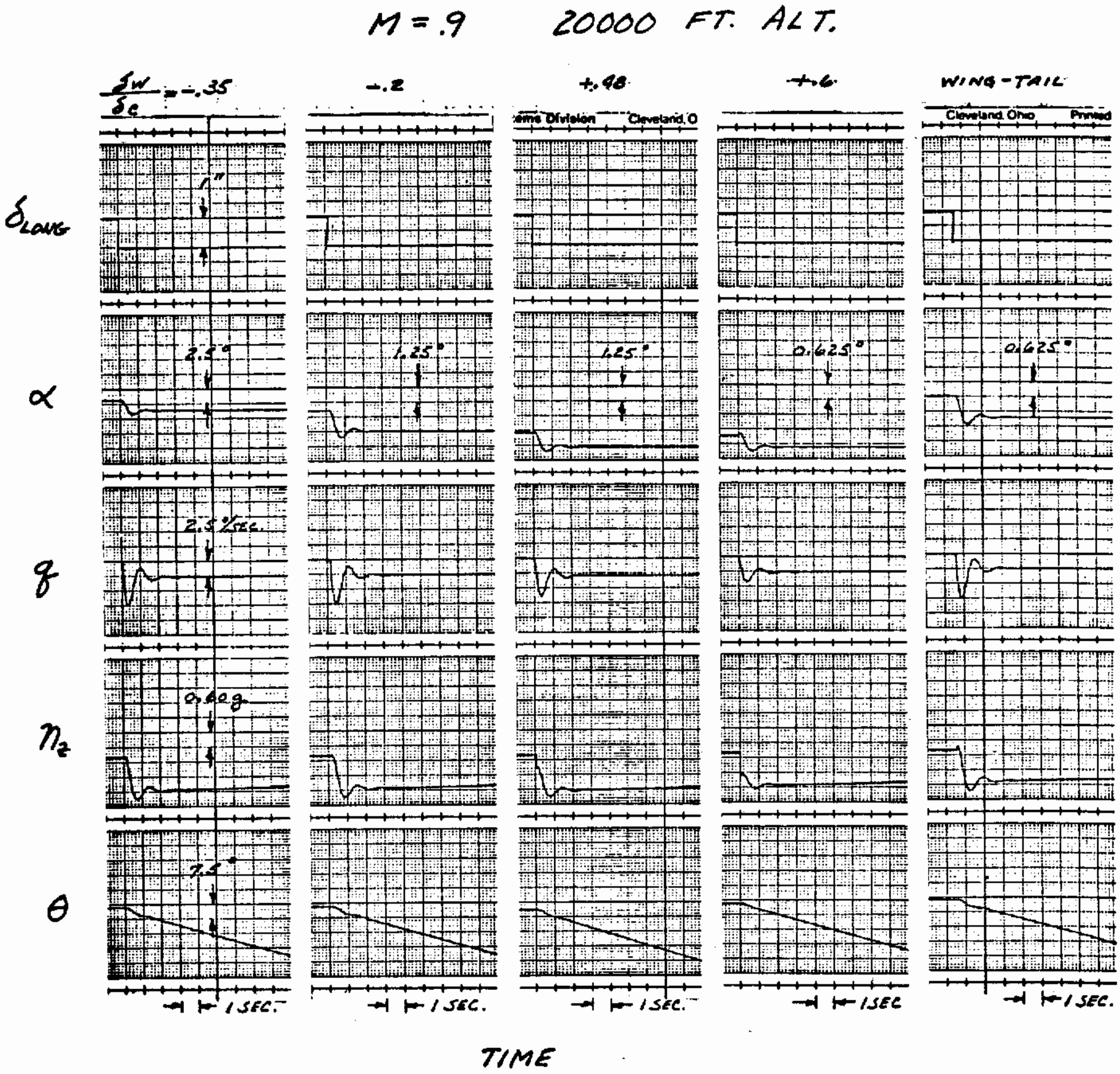

Figure 9b. Time Histories of Response to a Unit Step Stick Input

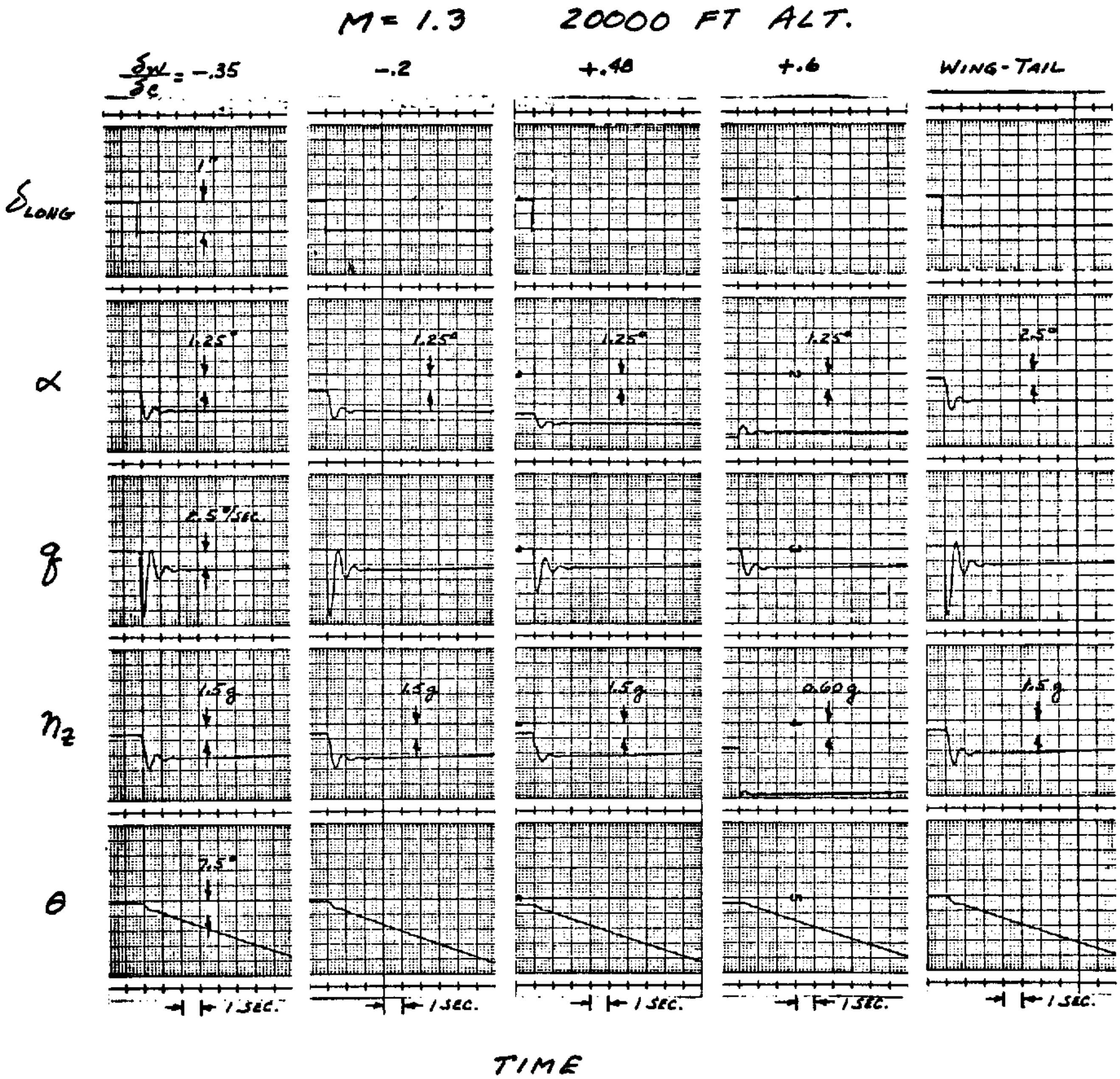

Figure 9c. Time Histories of Response to a Unit Step Stick Input

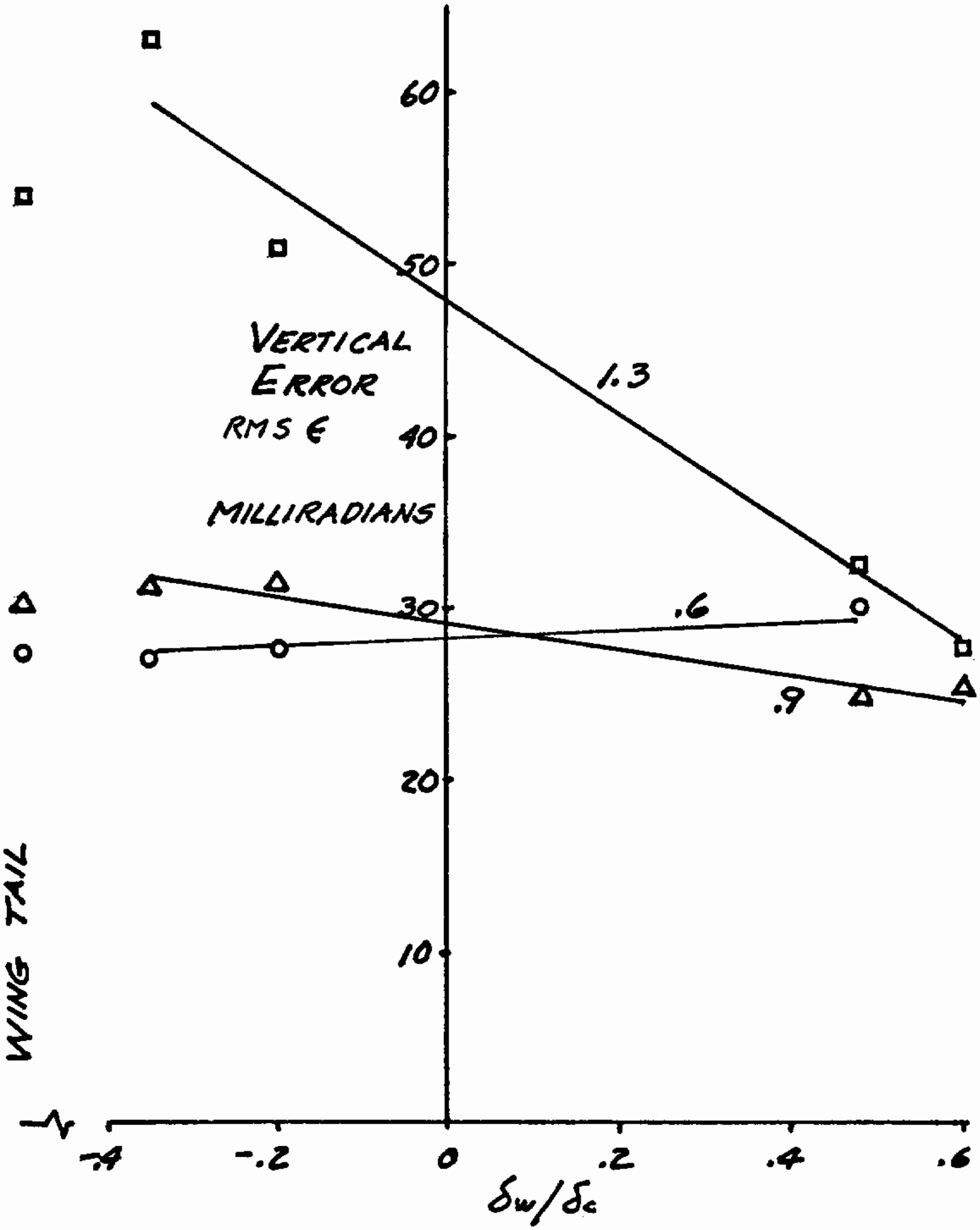

Figure 10. Vertical Tracking Error Results from Simulation

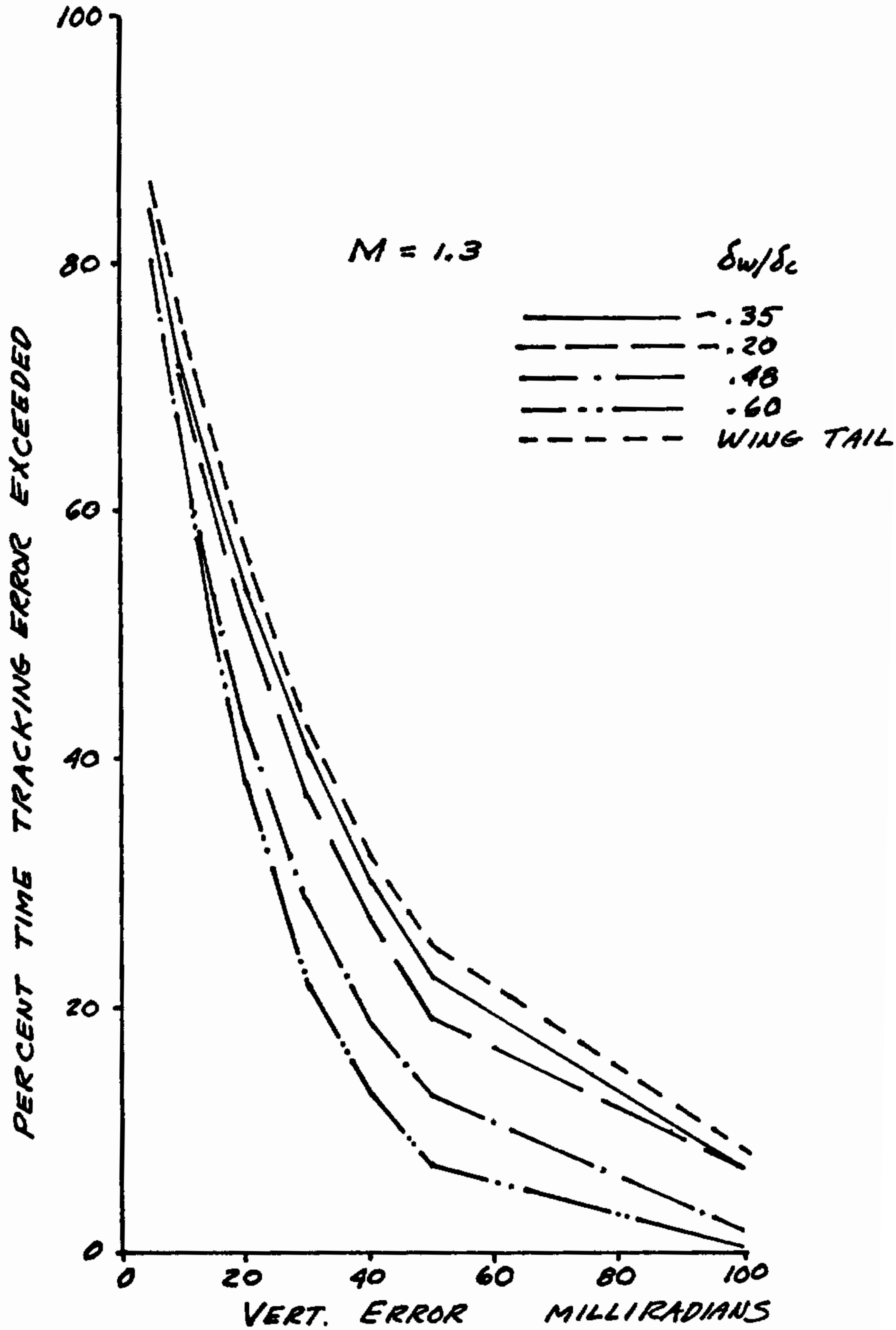

Figure 11. Typical Tracking Error Distributions

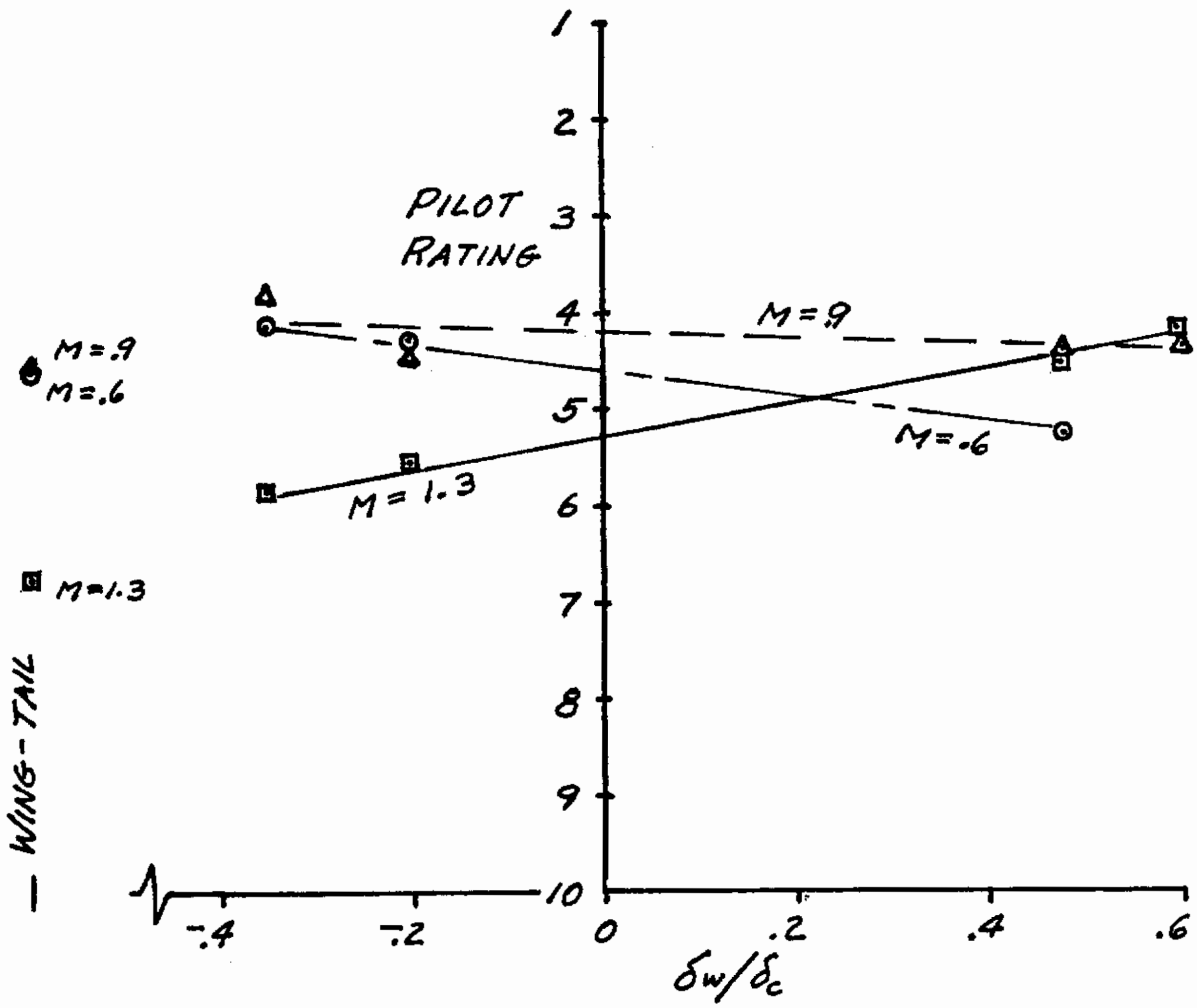

Figure 12. Pilot Ratings for Control Relationships

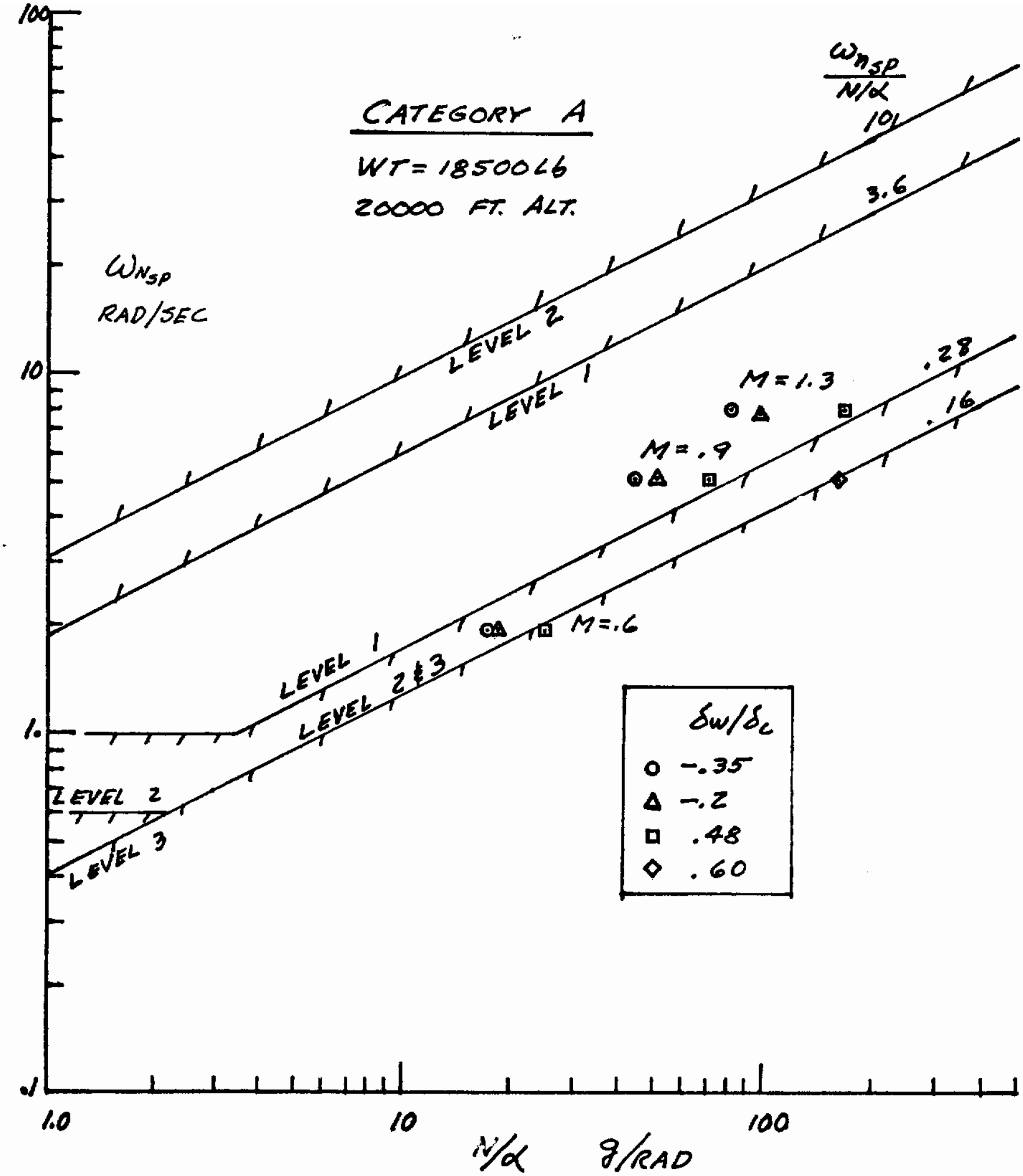

Figure 13. Short Period Frequency Requirements Comparison

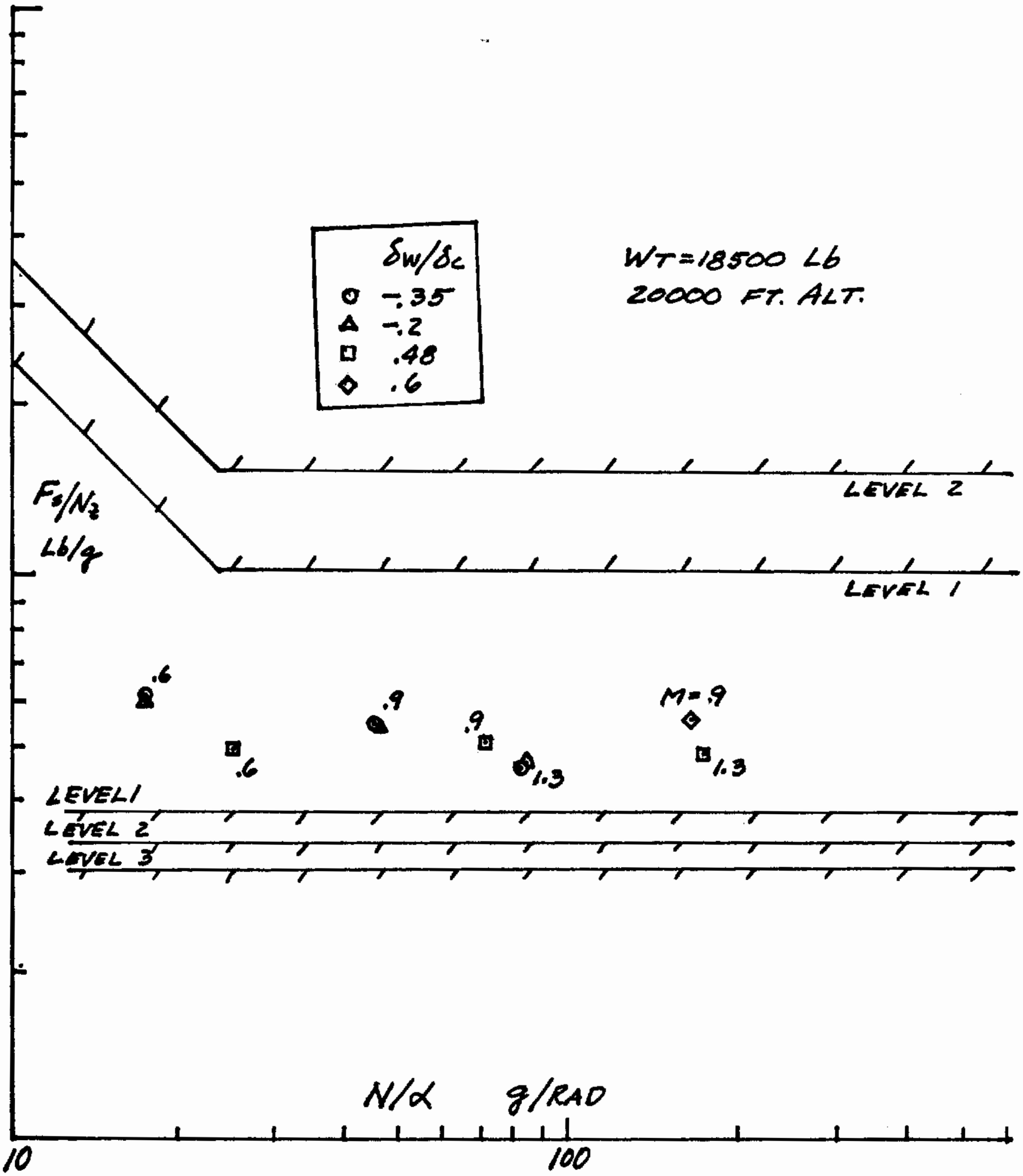

Figure 14. Maneuvering Force Gradient Requirements Comparison

Tom Twisdale, AFFTC: What maneuvers were used for tracking?
Answer: Large amplitude roll and pitching maneuvers. Rolls were about $\pm 100°$ and pitch maneuvers were a maximum of about +5, -1 g's. Abrupt motions were included also.

Jerry Lockenour, Northrop: The ω_n^2 vs n_z criterion of MIL-F-8785B has its origin in the CAP parameter ($\ddot{\theta}_{t=0} / n_{z_{ss}}$) which has required minimum and maximum levels. This is approximately a ratio of initial g's at the pilots station to steady state g's. Had we originally stated the requirement in this more fundamental form there would be no problem in analyzing higher order system and might be satisfactory even for direct lift control modes.
Answer: I'm not criticizing the parameter n_z/α. I think it's a fine parameter for evaluating typical airplanes. I'm just saying for direct lift control systems (longitudinal maneuvering) it's inappropriate and we need another kind of parameter to assess direct lift controls.