AN APPROACH TO SIMPLIFY THE SPECIFICATION OF LOW SPEED MANEUVERING PITCH CONTROL FORCE

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It is shown that for an irreversible pitch control system at low speeds, the use of the pitch control force gradient parameter F_S/N is inappropriate. The pitch control force gradient variation with speed at low Mach numbers is discussed along with the maximum load factor variation with speed. Typical maneuvering control force characteristics with load factor are given for several aircraft to illustrate the point. Recommendations are put forth for the specification of low speed maneuvering pitch control forces.

The emphasis of maneuvering characteristics has generally been in the mid or high speed range for most aircraft. In many cases the low speed or high angle of attack range is important also. However, the criterion for maneuvering characteristics developed for the higher speeds cannot be applied to the low speed range due to some fundamental differences.

The variation of the maneuvering force gradients is developed below for an irreversible control system. From the linearized longitudinal lift and moment equations, assuming constant coefficient data, the elevator control deflection for steady maneuvering is given by

$$\delta_e = \frac{C_{M_\alpha}\left[-\left(C_L\right)_{\alpha=0} + \frac{2W}{\rho V_T^2}\frac{N_z}{S_w}\right] + C_{L_\alpha}\left[\left(C_M\right)_{\alpha=0} + C_{M_q}\frac{qc}{2V_T}\right]}{C_{M_\alpha} C_{L_{\delta_e}} - C_{L_\alpha} C_{M_{\delta_e}}} \tag{1}$$

and

$$\frac{\partial \delta_e}{\partial \delta N} = \frac{C_{M_\alpha}\frac{2W}{\rho V_T^2 S_w} + C_{L_\alpha} C_{M_q}\frac{\bar{c}}{2V_T}\frac{\partial q}{\partial N}}{C_{M_\alpha} C_{L_{\delta_e}} - C_{L_\alpha} C_{M_{\delta_e}}} \tag{2}$$

Assuming turning flight is more representative of low speed maneuvering, pitch rate is given by,

$$q = \frac{g}{V_T}\left(N - \frac{1}{N}\right) \tag{3}$$

$$\frac{\partial q}{\partial N} = \frac{g}{V_T}\left(1 + \frac{1}{N^2}\right) \tag{4}$$

Then,

$$\frac{\partial \delta_e}{\partial N} = \frac{C_{M_\alpha}\frac{2W}{\rho V_T^2 S_w} + C_{L_\alpha} C_{M_q}\frac{\bar{c}g}{V_T^2}\left(1 + \frac{1}{N^2}\right)}{C_{M_\alpha} C_{L_{\delta_e}} - C_{L_\alpha} C_{M_{\delta_e}}} = f\left(\frac{1}{V_T^2}\right) \tag{5}$$

The control force gradient is given by

$$\frac{\partial F_s}{\partial \delta N} = \left(\frac{dF_s}{d\delta_e}\right)_{\substack{\text{feel}\\\text{spring}}} \cdot F\left(\frac{1}{V_T^2}\right) \tag{6}$$

which indicates that control force gradients increase as speed is decreased as shown in Figure 1. For a pure manual control system with linear aerodynamic characteristics, it can be shown that

$$\frac{\partial F_s}{\partial N} = \frac{1}{\partial} \rho V_T{}^2 S_e C_e G_e \left[C_{n\delta_e} \frac{\partial \delta_e}{\partial N} + C_{n\alpha_H} \frac{\partial \alpha_H}{\partial N} \right] \tag{7}$$

where

$$\frac{\partial \alpha_H}{\partial N} = \frac{\partial \alpha}{\partial N} \left(1 - \frac{\partial \epsilon}{\partial \alpha}\right) + \frac{g \ell_t}{V_T{}^2} \left(1 + \frac{1}{N^2}\right) \tag{8}$$

and

$$\frac{\partial \alpha}{\partial N} = \frac{-C_{L\delta_e} \frac{\partial \delta_e}{\partial N} + \frac{2\,W}{\rho V_T{}^2\, S_w}}{C_{L\alpha}} = f\left(\frac{1}{V_T{}^2}\right) \tag{9}$$

The partial derivative $\partial\delta_e/\partial N$ is the same expression developed above (equation 5). Again, in terms of functions of true airspeed, the force gradient is

$$\frac{\delta F_s}{\partial N} = f(V_T{}^2) \cdot f\left(\frac{1}{V_T{}^2}\right) = \text{constant with } V_T \tag{10}$$

For a spring tab system the expression for the maneuvering gradient contains an additional term which contains the spring constant as follows

$$\frac{\partial F_s}{\partial N} = f(V_T{}^2) \cdot \left[f_1\left(\frac{1}{V_T{}^2}\right) + f_2\left(\frac{1}{V_T{}^2 + K_s}\right)\right] \tag{10a}$$

Depending on the spring constant value, a non-linear variation of the force gradient occurs with speed. The gradient variation is small though for typical spring constants employed. In the practical case, non-linearities of aerodynamic characteristics with angle of attack and surface deflections usually further increase the force gradients as speed is decreased.

Except for aircraft with minimum speeds limited by control surface deflection or heavy buffet, any additional force at stall speed produces no further g increase and, thus, the maneuvering gradient is infinite. The g capability, however, is decreasing with decrease in speed as shown in Figure 2.

The maximum g available at low speeds is given by

$$N_{MAX} = \left(\frac{C_{L_{MAX}}\ S\ 1/2\rho}{W}\right)\ V_T^2 \tag{11}$$

Of course, at constant altitude $C_{L_{MAX}}$ may vary slightly with Mach number at low speeds but the major variation in g is controlled by V_T^2. For the ideal case (linear characteristics) the control force is constant at maximum lift since

$$F_s = \frac{F_s}{N}\ (N_{MAX} - 1) = f\left(\frac{1}{V_T^2}\right) \cdot f(V_T^2) = \text{constant} \tag{12}$$

Again, in many cases, non-linear aerodynamic characteristics produce non-linear forces with g, generally increasing non-linear force. In some airplanes this is desirable as an indicator of stall or stall buffet.

Use of the parameter force gradient, F_s/N, becomes less useful in the speed range where an aircraft is lift limited. The intent of the parameter, F_s/N for the maximum gradient is to insure that the maximum control force at N_L, the design limit load factor, is within the pilot's strength capability, as given by

$$F_{s_{MAX}} = \frac{F}{N}\ (N_L - 1) \tag{13}$$

Earlier specifications as well as the current version of MIL-F-8785B (at high values of N/α) use for the maximum allowable stick force gradient

$$\frac{F_s}{N} = \frac{56}{N_L - 1} \qquad \text{(center stick controllers)} \tag{14}$$

where the value of 56, in equation (14), represents a maximum one arm pilot effort in pounds. During the period of time, the OV-10A aircraft was in the flight test stage, it was proposed in reference (a) that at low speeds the specification of the maximum force gradient in MIL-F-8785 be revised. The applicable requirement and the reference (a) proposed limits are shown in Figure 3.

The current MIL-F-8785B specification for the level 1 maximum gradient, requires not more than 28 pounds per g or $240/(N/\alpha)$ lbs/g for center stick controllers and 120 lbs/g or $500/(N/\alpha)$ for wheel controllers. Reference

(b) incorporated the basic idea of allowing force gradient increase at low speeds or low values of N/α, but without supporting data set a maximum value of 28 lbs/g for center stick controllers (level 1) and 120 lbs/g for wheel controllers.

Figure 4 illustrates the control force maneuvering gradient for the OV-10A airplane, which employs a reversible manual control system. A misleading and incomplete picture of the low speed maneuvering forces is obtained from the force gradient variation in Figure 4. However, as shown in Figure 4, as speed is reduced less maximum load factor, N, is available as the force gradients are increasing. In actuality, the peak control force at the accelerated stall is reduced also with speed reduction as shown in Figure 5.

Similar results occur for irreversible control systems as shown in Figure 6 for the XFV-12A aircraft which are based on estimated data. Again, the force gradient shows a misleading picture while the maximum force at the lift limited speed shows nearly a constant force level.

Since combat maneuvering in current and future fighter aircraft is expected to occur also at high angle of attack near stall in combat and tactical maneuvers, this flight regime should be adequately covered in the specification. The control sensitivity is currently handled by the minimum force gradient which is applicable at all speeds.

Therefore, it is recommended that at low values of N/α, the current requirements for maximum force gradient defined as $X/(N/\alpha)$ for level 1 and 2 continue to apply at lower values of N/α as shown in Figure 7. The level 3 maximum force gradient should terminate where it intersects the level 2 boundary. In addition, at all conditions where the operational flight envelope is set by other than the limit load factor, the maximum allowable pitch control force should be as shown below for the load factors specified in para. 3.2.3.2.

Center Stick Controllers

Level	Max Force at $N_O(+)$
1	56
2	85
3	85

Wheel Controllers

Level	Max Force at $N_O(+)$
1	120
2	182
3	182

If sustained maneuvering is required in turning flight, the procuring agency should specify a different value for the maximum stick forces than those recommended above or allow the use of trim to reduce pitch control forces during the sustained maneuver. At the limits of the permissible flight envelope, pitch control forces should be allowed to increase to any pull force.

References

(a) Chalk, C. R., et al, Recommendations for Revision of MIL-F-8785(ASG), "Military Specification - Flying Qualities of Piloted Airplanes," draft dated 20 March, Revised 26 May 1967, Cornell Aeronautical Laboratory, Inc.

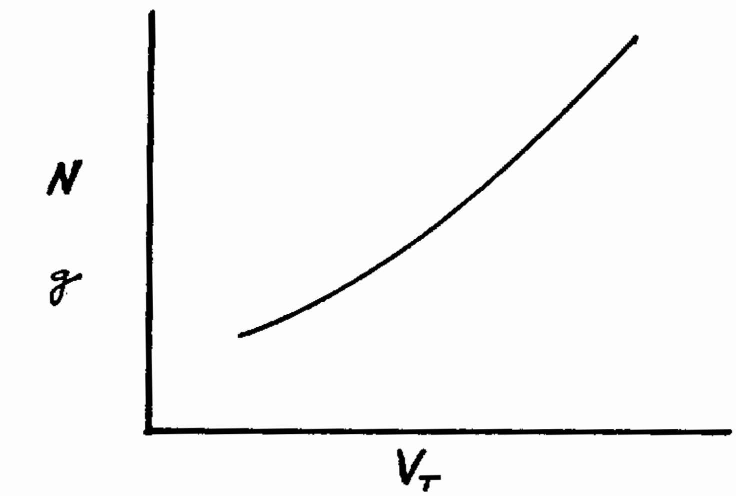

FIG. 2

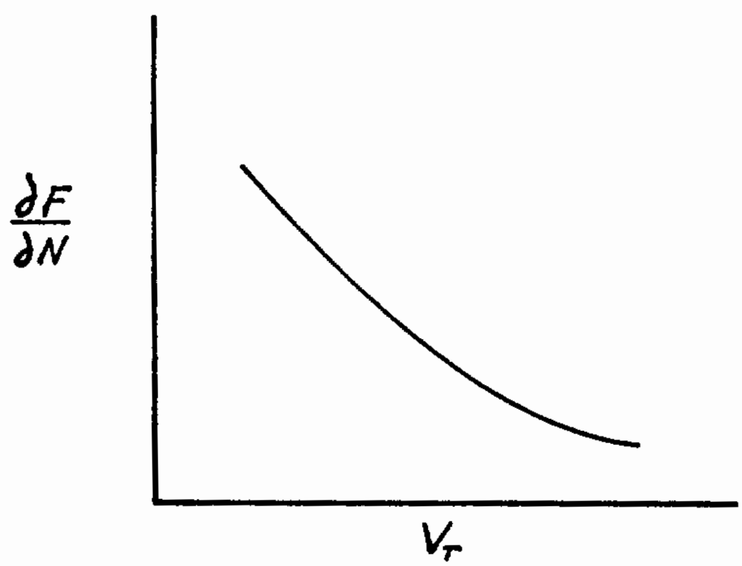

FIG. 1

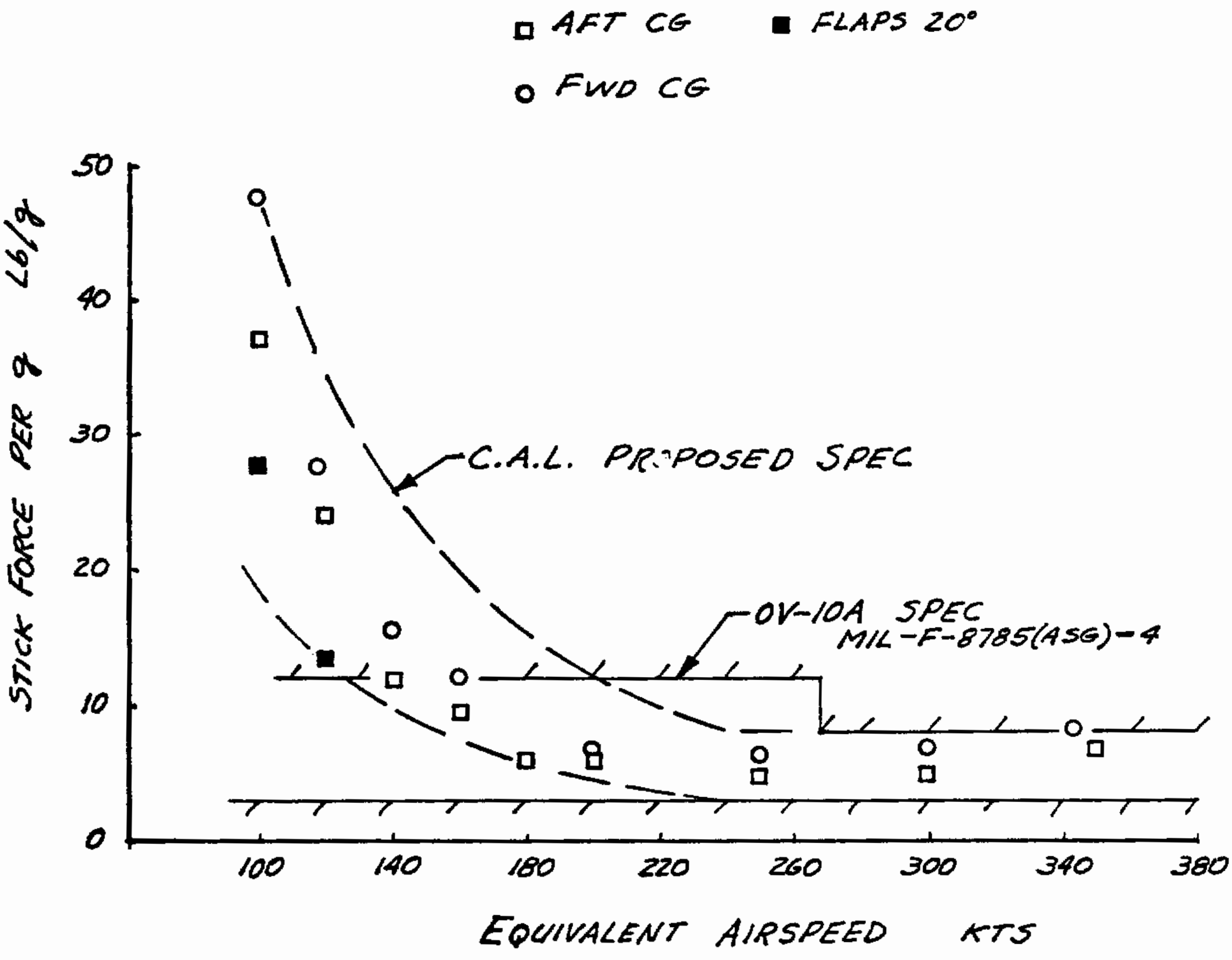

FIG. 3 OV-10A STICK FORCE PER G

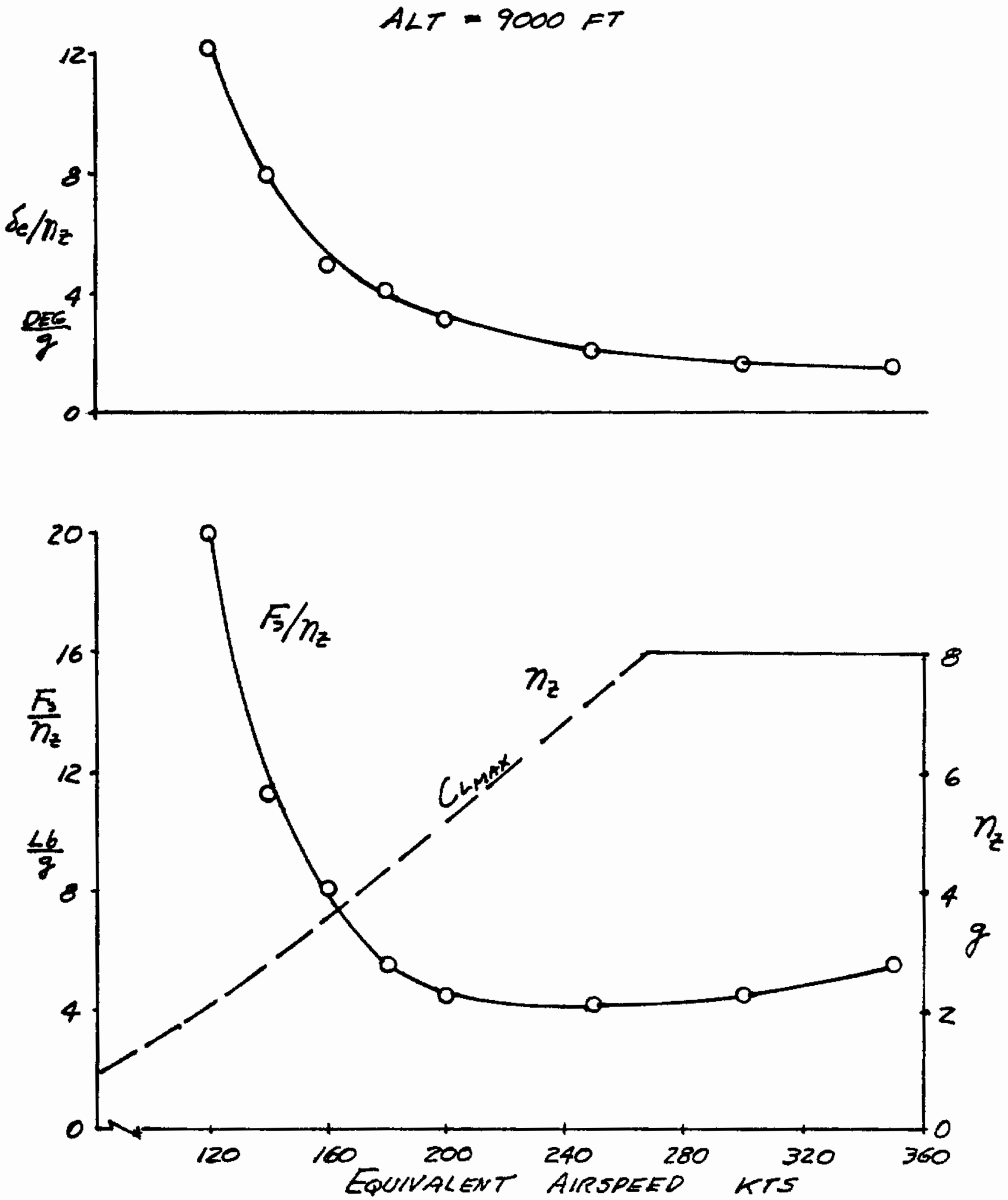

FIG. 4 OV-10A MANEUVERING CONTROL

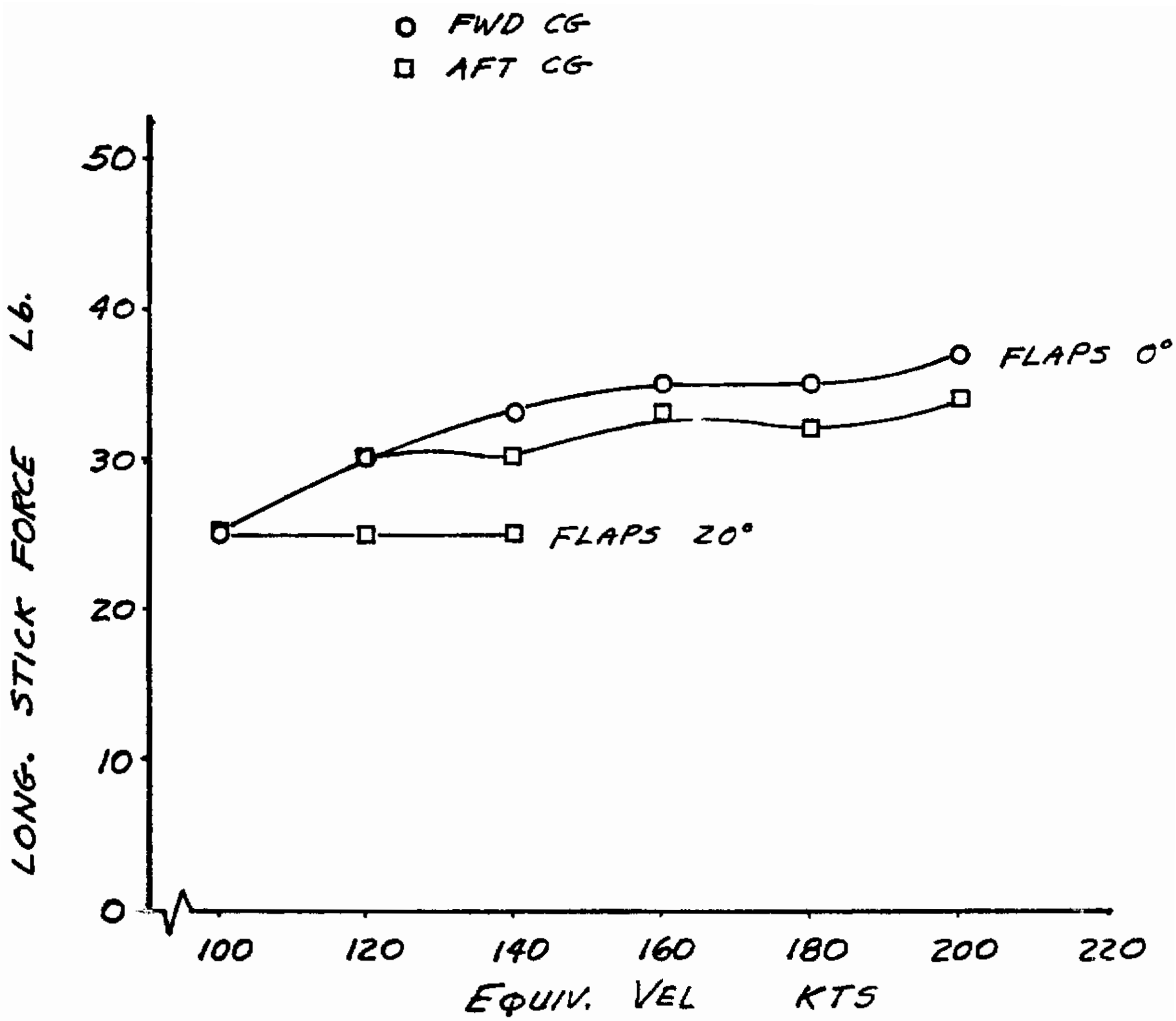

FIG. 5 LONG. STICK FORCE AT STALL

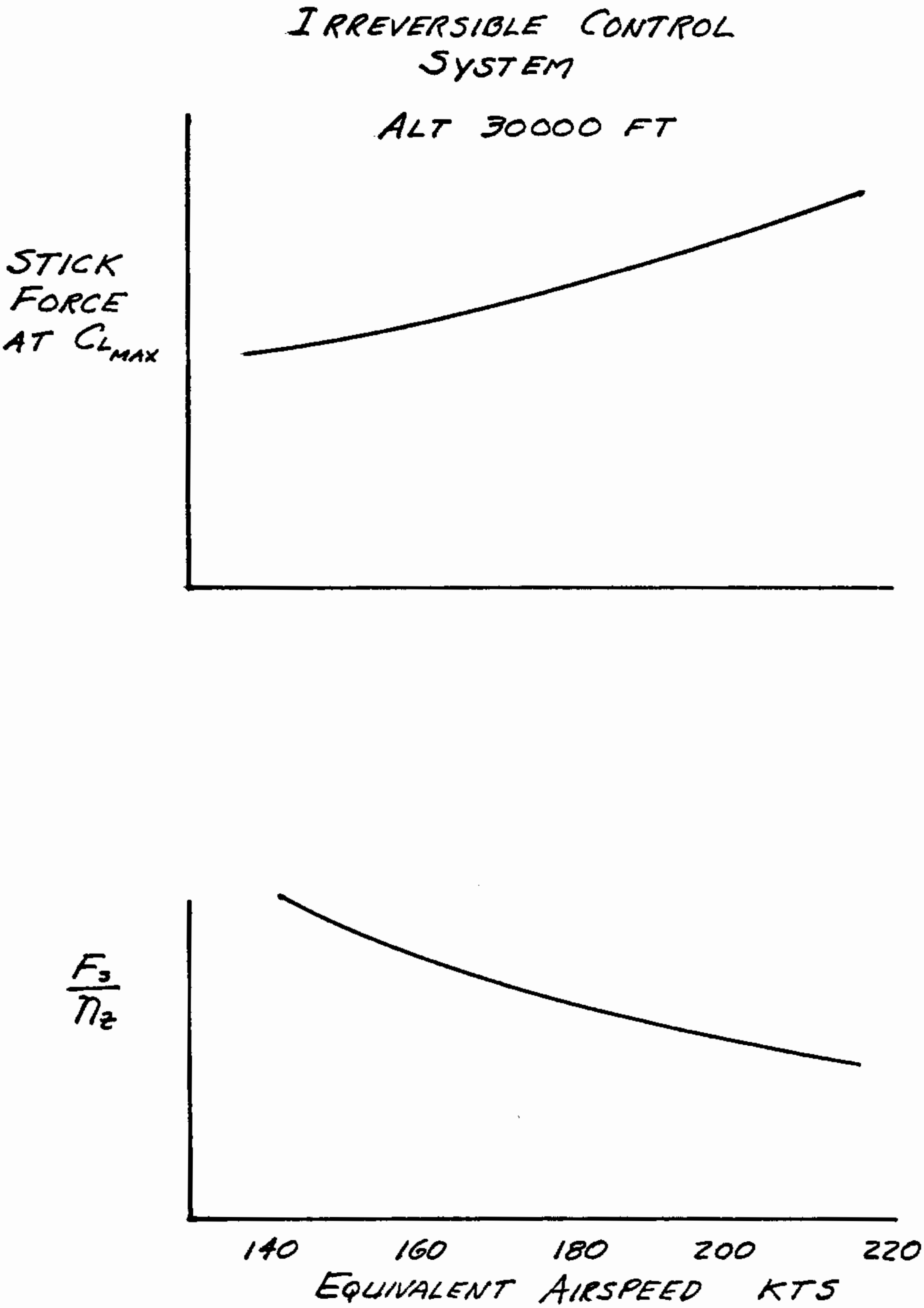

FIG. 6 IRREVERIBLE CONTROL FORCE

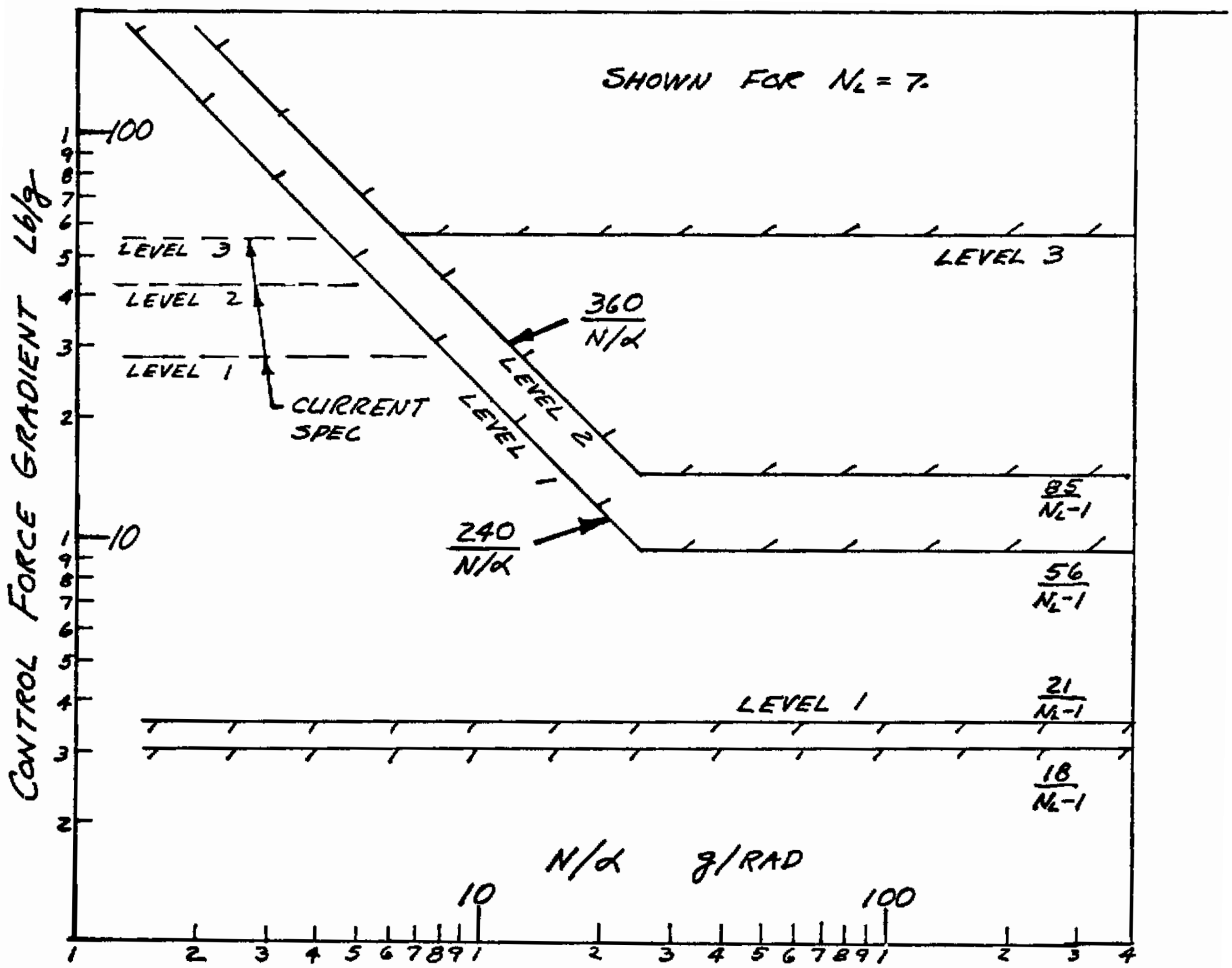

FIG. 7 FORCE GRADIENT REQUIREMENTS

Dwight Schaeffer, Boeing: Do you feel force at limit load factor (or max load factor) is all that is important? Are you also concerned with forces to exceed n_z being too light?
Answer: The minimum force gradients specified in the spec should still apply at low speeds as well. I think the max stick force at limit lift is more important than the max force gradient at low speeds.