Analysis and Design of Sidestick Controller Systems for General Aviation Aircraft

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A method to design sidestick controllers for general aviation aircraft with reversible flight controls is proposed. The use of a sidestick in this type of flight vehicle generally increases the stick forces required for maneuvering; this is due to a reduction in the moment arm of application of the force. In the present study, the reduction of stick forces is achieved by incorporating geared tabs in the control-surface design. A complete analysis using the rigid-body aircraft longitudinal equations of motion and stick-force equation in coupled form is carried out. Lateral stick forces are predicted by solving the single-degree-of-freedom roll approximation and aileron stick-force equations. Data are presented for configurations with various tab areas and a wide range of gearing ratios. The results indicate that the method can be used successfully for geared-tab design and stick-force prediction. It is shown that gearing-ratio selection is critical but that tab area does not have a significant impact on the magnitude of stick forces and stick force to stick deflection gradients.

Introduction

THE increasing use of sidestick controllers in military and commercial aircraft (F-16, Airbus A-320) has renewed interest in the potential applications of these devices to general aviation. Since research was begun on sidestick controllers in the mid 1950's, many of their advantages over conventional controllers have been verified. Replacement of a standard wheel/yoke type of controller by a sidestick generally yields the following benefits:[1–4]

1) Additional space is made available on the instrument panel for modern instrument systems such as cathode ray tube displays.
2) Better visibility of all flight instruments is made possible.
3) Pilot fatigue is reduced in maneuvering flight or instrument flight rules (IFR) operations.
4) An improvement in trajectory control is observed.
5) The vehicle's crashworthiness is enhanced by the removal of a forward obstruction.

Most current technology production sidesticks (except in the case of home-built aircraft) are operated in conjunction with fly-by-wire control systems. A typical installation consists of a displacement stick with an artificial constant force gradient. However, in most general aviation aircraft, the flight controls are not powered: the stick or yoke is directly connected to the control surface. Because of the reduced moment arm of the sidestick as compared to conventional controllers, the pilot must exert a greater force to overcome the aerodynamic loads about the control surface hinge line. As determined in previous studies,[5] the problem may be solved by installing a geared tab driven by the main control-surface deflection. This concept has been investigated further and applied to the present study. The stick-force analysis is performed for a high-wing single-engine general aviation aircraft.

Design Criteria

The method used here consists of calculating the stick force required and computing the stick force to stick angular deflection ratio $\Delta F_s/\Delta\delta_s$ for a given maneuver. Since the sidestick deflection is related to the control-surface deflection through the gearing ratio, the parameter $\Delta F_s/\Delta\delta_s$ is an indication of the rate of increase in required stick force per unit aerodynamic surface deflection. The selection of a design range for $\Delta F_s/\Delta\delta_s$ was straightforward, since the recommended values of Refs. 1–5 were generally of the same magnitude. The selected upper bounds for required stick force are based on anthropology studies. For a sidestick operated with the right hand with a pilot sitting upright, the limits were taken from the fifth percentile data.[6] The design objectives for lateral and longitudinal stick deflections are listed in Table 1.

Maneuvers described in the Federal Aviation Regulations (FAR) were used to produce the required stick-force data. The FAR's specify that the airplane be trimmed at a given speed and then maneuvered to a different flight condition without retrimming[7] (usually at power and flap settings which differ from the initial flight condition). In an airplane with reversible flight controls, this generally results in a nonlinear variation of F_s with elevator deflection and hence a varying $\Delta F_s/\Delta\delta_s$ gradient. However, in the studies from which the design criteria were derived, the gradients $\Delta F_s/\Delta\delta_s$ were applied to the test sidesticks using artificial feel systems and held constant over a given stick-deflection range. Standards were then established from pilot ratings based on handling qualities. Therefore, the different conditions under which the design guidelines and analytical data of the present study were produced pose a first limitation. Also, the solution of the steady-state equations of motion along with the stick-force equation[8] does not account for dynamic effects that might occur during the prescribed maneuvers.

Therefore, in the analyses that follow, only the stick forces and elevator deflections in the initial and final steady-state

Table 1 Selected design criteria for a general aviation sidestick controller

Force/deflection gradients (lb/deg)	
longitudinal	$0.5 \le \Delta F_s/\Delta\delta_s \le 2.0$
lateral	$0.15 \le \Delta F_A/\Delta\delta_s \le 1.28$
Required stick force	
longitudinal	
not to exceed 43 lb, stick forward	
not to exceed 49 lb, stick aft	
lateral	
not to exceed 22 lb, stick left	
not to exceed 16 lb, stick right	

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flight conditions are considered. Thus, the values of ΔF_s and $\Delta\delta_E$ used to obtain the ratios $\Delta F_s/\Delta\delta_s$ in this study yield only a mean slope computed for the maneuver. It is therefore assumed that the dynamic effects associated with the rate of change of power and flap settings are of short duration. These assumptions do not apply to the analysis of lateral stick forces.

Mathematical Model

Prediction of Longitudinal Stick Forces

In this study, the aircraft steady-state equations of motion are solved in coupled form with the stick-force equation.[8] These equations are based on a rigid-aircraft assumption and are developed in stability axes. The left-hand sides of the lift, drag, and pitching-moment equation contain the mass, inertia, and acceleration terms. The aerodynamic and other applied forces are found on the right-hand sides. The force and moment coefficients are written as Taylor-series expansions of the following independent variables: α (angle of attack), i_H (stabilizer incidence angle), δ_E (elevator deflection), and δ_t (trim tab deflection). The stick-force equation also may be written in similar form, as follows:

$$F_S = G_E\eta_H S_E c_E \bar{q}(C_{h_0} + C_{h_\alpha}[\alpha(1 - \mathrm{d}\varepsilon/\mathrm{d}\alpha) - \varepsilon_0 + i_H + Q_1\ell_H/U_1] + C_{h_{\delta_E}}\delta_E + C_{h_{\delta_t}}\delta_t) \tag{1}$$

where C_h is the hinge moment coefficient and $C_{h_\alpha} = \partial C_h/\partial\alpha$, etc. η_H is the dynamic pressure ratio at the horizontal tail $\bar{q}/q_H$, while ε is the average downwash angle. The last term in the tail angle-of-attack expression is due to steady-state pitch rate Q_1, if any.

The elevator gearing ratio is given by $G_E = -\delta_E/\Delta s$, in ft^{-1}. This gearing ratio is determined at the outset from stick length and throw selections for the design.[9] The stability derivatives are estimated using standard empirical methods.[10-14] In matrix form, the system of equations is rewritten as follows:

$$[A][X] = [B] \tag{2}$$

where the unknown vector is given by

$$[X] = [\alpha,\gamma,i_H,\delta_E,\delta_t,F_s] \tag{3}$$

The variable γ represents the flight-path angle. The first solution is obtained for the trimmed steady-state flight condition, so the variables F_s ($=0$) and i_H are prespecified. For the second solution, i_H is known (the stabilizer is fixed), and the computed value of δ_t is carried over as the second prespecified variable. The second solution thus yields the stick force F_s required to maintain the final flight condition. The stick deflection $\Delta\delta_s$ is obtained from the relation $\Delta s = -\Delta\delta_E/G_E = \ell_s \sin\Delta\delta_s$. Since sidesticks usually allow small linear deflections only ($\Delta s = 1$–2 in.) to make control inputs, then the relationship $G_E = -\delta_E/\Delta s$ clearly indicates that G_E will be larger for a given elevator deflection compared to a conventional controller. The stick force will thus increase in magnitude, as shown by Eq. (1).

The reduction of hinge moment due to the geared tab is accounted for by adding an extra term to the Taylor-series expansion of the hinge moment coefficient as follows:

$$C_h = C_{h_0} + C_{h_\alpha}\alpha + C_{h_{\delta_E}}\delta_E + (C_{h_{\delta_t}}\delta_t)_{\substack{\text{geared}\\\text{tab}}} + (C_{h_{\delta_t}}\delta_t)_{\substack{\text{trim}\\\text{tab}}} \tag{4}$$

Since the geared tab is installed on the elevator, a new value of $C_{h_{\delta_E}}$ may be defined by combining the third and fourth terms in Eq. (4). The expression for $(C_{h_{\delta_E}})_{GT}$ as altered by the geared tab may thus be written

$$(C_{h_{\delta_E}})_{GT} = (C_{h_{\delta_E}})_{\text{basic}}\left(1 + \frac{(C_{h_{\delta_t}})_{\substack{\text{geared}\\\text{tab}}}}{(C_{h_{\delta_E}})_{\text{basic}}}G_T\right) \tag{5}$$

The tab-gearing ratio is defined as $G_T = \delta_t/\delta_E$. For this particular case, since the forces are to be reduced, δ_t and δ_E will be of opposite sign and $G_T < 0$. $(C_{h_{\delta_E}})_{GT}$ will be reduced in magnitude compared to the basic value, thus reducing F_s. In a similar fashion, the expressions for variation of lift, drag, and pitching-moment coefficients with respect to elevator deflection ($C_{L_{\delta_E}}$, $C_{D_{\delta_E}}$, $C_{m_{\delta_E}}$) are also altered due to the addition of a geared tab.[9] Thus, if $G_T < 0$, the elevator lift effectiveness $C_{L_{\delta_E}}$ and elevator control power $C_{m_{\delta_E}}$ are reduced.

Prediction of Lateral Stick Forces

The maneuvers described in two low-speed FAR's were used to generate data in the analysis of lateral stick forces. Both of these [FAR's 23.157(a) and (c)][7] require that the aircraft be rolled 60 deg, from a steady turn with 30 deg of bank, so as to reverse the direction of the turn in a specified length of time. Also, to verify the magnitude of F_A and $\Delta F_A/\Delta\delta_s$ at cruise speeds, some data were produced to satisfy the standards of Ref. 15.

To compute the lateral stick forces, the aileron deflection δ_A necessary to perform the required maneuver is obtained by solving the single-degree-of-freedom rolling approximation equation.[8] The stick force is then calculated from

$$F_A = G_A q_A S_A c_A(C_{h_{\delta_A}}\delta_A + C_{h_{\alpha_A}}\Delta\alpha) \tag{6}$$

The parameter $\Delta\alpha$ is obtained from the steady-state roll rate, and as in the longitudinal case, the derivative $C_{h_{\delta_A}}$ is reduced by the aileron geared tab. Similarly, the aileron control power of the aircraft ($C_{\ell_{\delta_A}}$), which appears in the roll-approximation equation, is also reduced by the addition of a geared tab. Each selected value of G_{T_A} yields a different aileron deflection, thereby establishing the relationship between stick force and stick deflection. The aileron gearing ratio G_A is calculated in the same manner as G_E, from sidestick geometry and maximum aileron authority.

Results

Longitudinal Stick Force and Gradients

The analysis is carried out for the most aft center-of-gravity position, for which stick forces are typically the highest. For a given configuration, the stick forces and variations in elevator deflection are computed for $0 \geq G_T \geq -1.6$ for a series of 10 maneuvers as dictated by the FAR's for longitudinal control. The limited availability of empirical data to calculate $(C_{h_{\delta_t}})_{\substack{\text{geared}\\\text{tab}}}$ precluded a study of the independent effect of tab chord c_t or span b_t on F_s. Therefore, geared-tab area was used as the secondary design variable. Table 2 lists the

Table 2 Elevator geared-tab characteristics

Configuration	c_t, in.	b_t, in.	% of Elevator area	$(C_{h_{\delta_t}})_{\substack{\text{geared}\\\text{tab}}}$ rad^{-1}
1	6.5	41.9	22.8	−0.322
2	5.75	56.0	26.9	−0.461
3	5.0	29.1	12.2	−0.293

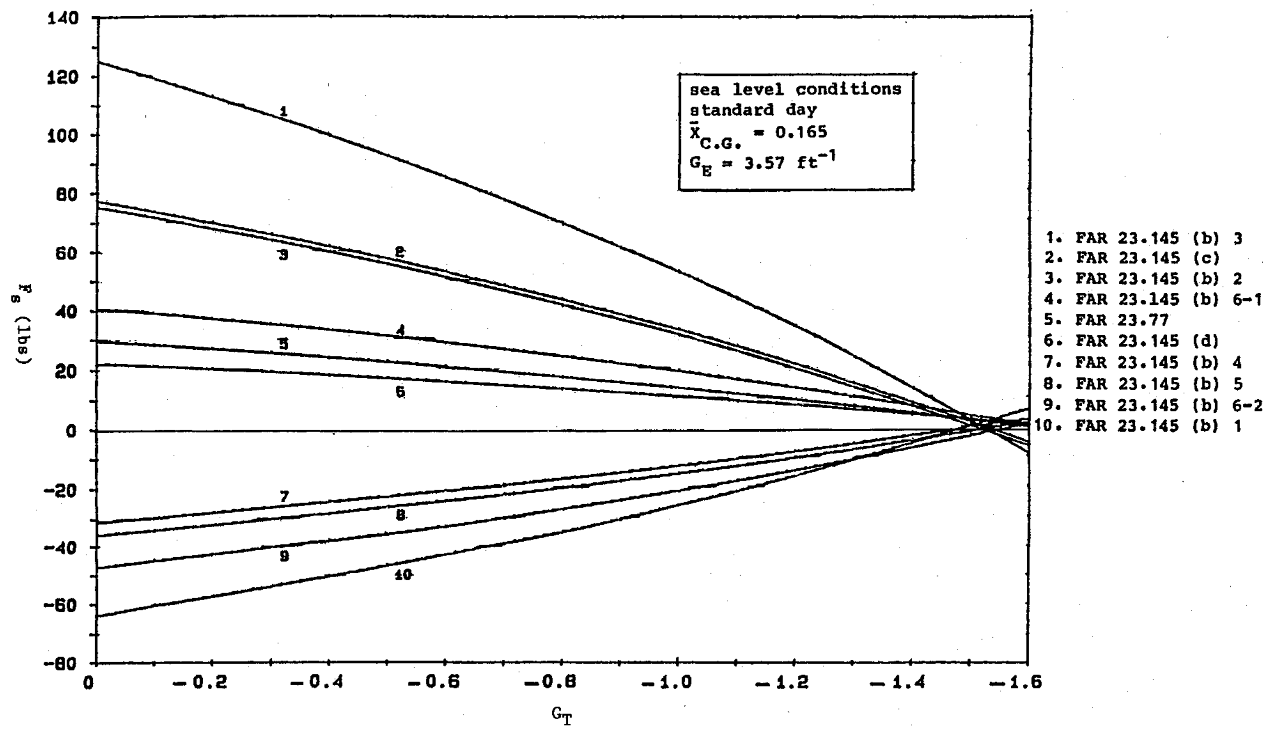

Fig. 1 Variation of stick force with tab gearing ratio for configuration 1.

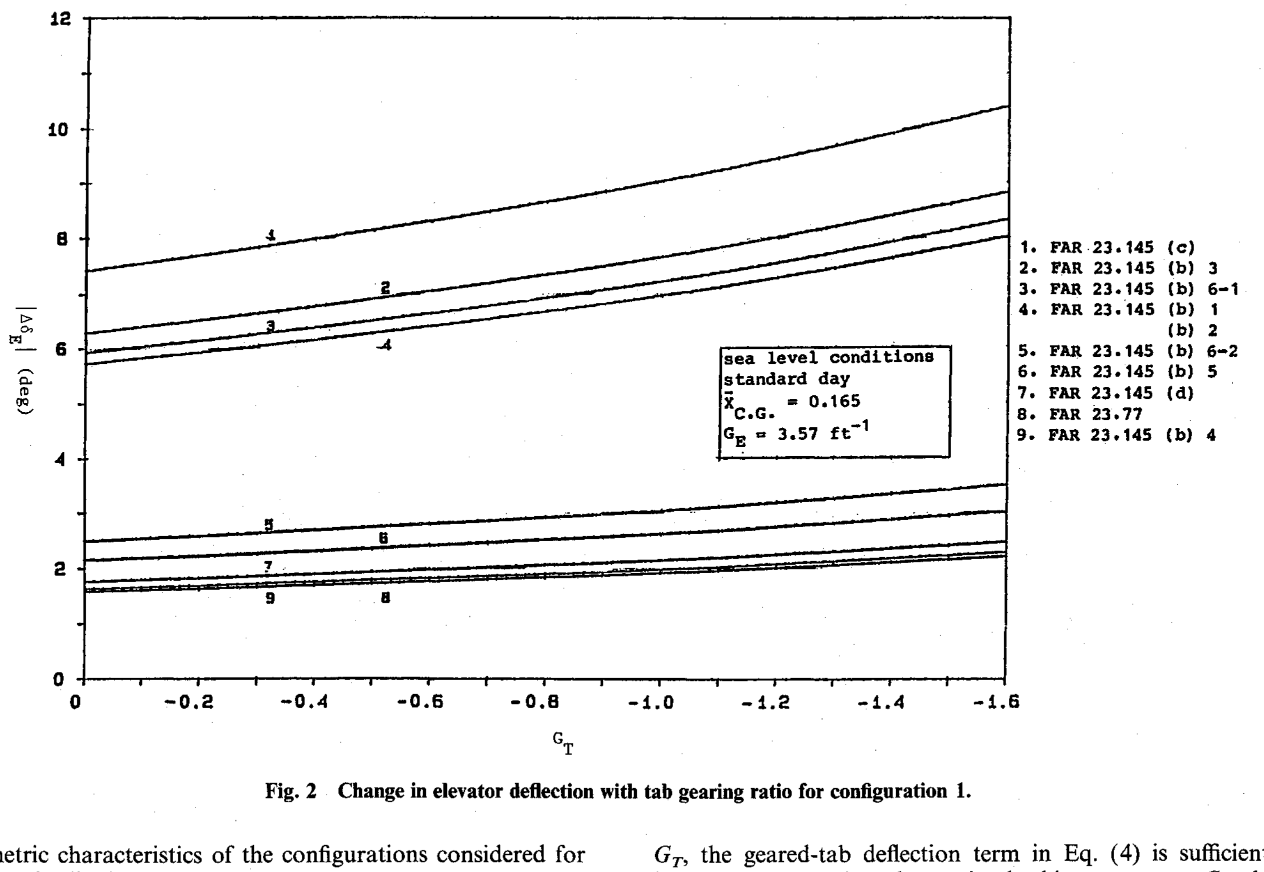

Fig. 2 Change in elevator deflection with tab gearing ratio for configuration 1.

geometric characteristics of the configurations considered for the longitudinal case.

The first configuration consists of a geared tab that has the same dimensions as the trim tab. Figure 1 illustrates the variation of the stick force required to maintain the flight condition in the second phase of the maneuver. As expected, the forces decrease in magnitude as the tab gearing ratio increases. Also, the curves converge towards one value of gearing ratio for which the forces change sign and begin to increase in magnitude again $[(G_T)_{crit}]$. For high magnitudes of G_T, the geared-tab deflection term in Eq. (4) is sufficiently large to cause a sign change in the hinge moment C_h, thus requiring a stick force of opposite sign to maintain the aircraft's final attitude. The selected design value of tab gearing ratio must lie to the left of this point to avoid stick-force reversal during the maneuver. Therefore, for all of geared-tab designs considered in the present study, the selected value of G_T for which F_s and $\Delta F_s/\Delta\delta_s$ are compared to the design criteria of Table 1 will be 90% of $(G_T)_{crit}$. The 10% safety margin is intended to yield relatively low stick forces

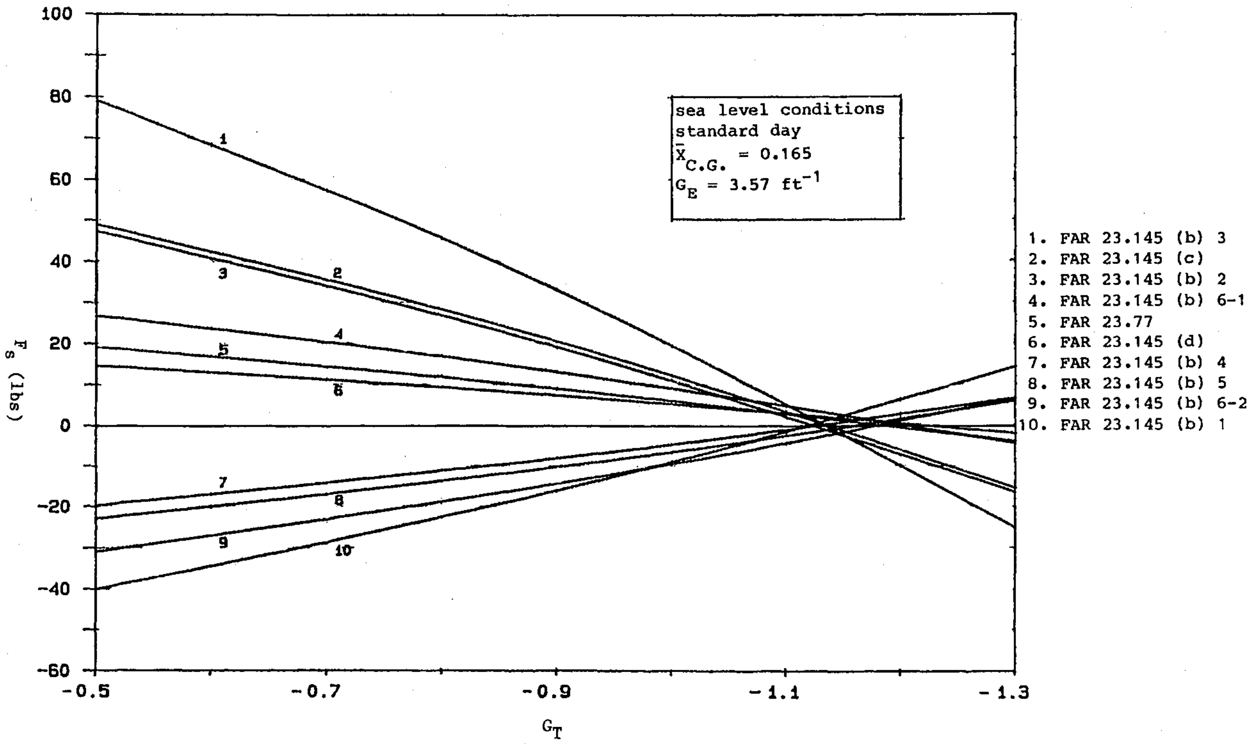

Fig. 3 Variation of stick force with tab gearing ratio for configuration 2.

while maintaining an acceptable safety factor away from $(G_T)_{crit}$. Figure 2 shows the computed variations in elevator deflection (from the trimmed flight condition to the final flight condition) as a function of geared-tab gearing ratio. Larger elevator deflections are required at higher magnitudes of G_T due to the reduction in elevator control power $C_{m_{\delta_E}}$. For each FAR, the magnitude of $|\Delta\delta_E|$ is read off the curves at 90% of $(G_T)_{crit}$; the corresponding sidestick deflection is then calculated as explained earlier.

For configuration 2, the tab chord is reduced but its span is increased. The slightly larger surface results in a higher value of $(C_{h_{\delta_t}})_{\substack{\text{geared}\\ \text{tab}}}$ and thus reduces the coefficient $C_{h_{\delta_E}}$ of the elevator by a larger amount for a given geared-tab gearing ratio. Figure 3 shows the variation of stick force for $-0.5 \geq G_T \geq -1.3$. For a given value of G_T, the forces obtained from Fig. 3 are lower in magnitude than those of Fig. 1. However, the crossover point has moved to the left and in this case, $(G_T)_{crit} = -1.12$. With the 10% safety factor applied here also, the forces and force/deflection gradients are calculated at $G_T = -1.01$. For configuration 3, the critical point moved to the right (due to lower $C_{h_{\delta_t}}$) and it was determined that $(G_T)_{crit} = 1.65$.

Figure 4 shows a comparison of forces and force/deflection gradients for the three configurations. The stick forces have been reduced to well below the maximum permissible, but the desired range for $|\Delta F_s/\Delta\delta_s|$ is achieved only for four maneuvers. Despite a substantial decrease in tab area for configuration 3, these data show that the variations in $\Delta F_s/\Delta\delta_s$ from one configuration to the other are insignificant. The reason for this is quite clear. Higher magnitudes of G_T yield larger reduction in stick forces. However, since the 10% safety margin increases as $(G_T)_{crit}$ increases, the reduction of stick forces is limited at the design point. The combined effect of slight variations in F_s and $\Delta\delta_E$ also result in a relatively constant force/deflection ratio from one configuration to the other.

One other important consideration must be accounted for in the design process. With a higher tab gearing ratio, the actual tab deflection relative to the elevator might exceed 13–15 deg, where nonlinear aerodynamic effects cannot be neglected. In the nonlinear range, the derivative $(C_{h_{\delta_t}})_{\substack{\text{geared}\\ \text{tab}}}$ is difficult to estimate and the predicted stick forces could be considerably in error. Although not used as design parameters, the stick force to speed $\Delta F_s/\Delta V$ and stick force per unit load factor $\Delta F_s/\Delta n$ gradients were computed for configuration 1. The latter varied from 16–25 lb/g for the maneuvers considered. As expected, the reduction in $C_{h_{\delta_E}}$ yielded values of $\Delta F_s/\Delta V$ that were negative but below the minimums for conventional controllers.[8]

Lateral Stick Forces and Gradients

The lateral stick forces F_A were also calculated for three different configurations. These consisted of a geared tab on each aileron and were studied in ascending order of effective area (10, 19, and 22% of the area of one aileron, respectively). The limiting factor in this particular phase of the analysis was the onset of nonlinear aerodynamic effects as the geared-tab gearing ratio was increased. Therefore, for any of the three configurations studied, the stick forces were not computed beyond geared-tab deflection angles of ≈ 15 deg. The computed stick forces represent the highest in magnitude encountered during the roll maneuver since $\Delta\alpha$ in Eq. (6) is obtained from the steady-state roll rate.[8] Table 3 lists the stick forces obtained from the highest possible gearing ratio for each tab configuration.

The results show that as the geared-tab area increases, the value of G_{T_A} at which nonlinear effects are encountered is seen to decrease. This is due to the decrease in roll control power $C_{l_{\delta_A}}$, which leads to larger aileron deflections to meet the dynamic roll-rate requirements [FAR's 23.157(a) and (c)].[7] Hence, larger aileron deflections cause higher geared-tab deflections and the 15 deg linearity limit is attained at a lower value of G_{T_A}.

For configuration 1, the lateral stick forces meet the design objective of Table 1, while the predicted value of $|\Delta F_A/\Delta\delta_s|$ for FAR 23.157(c) is only slightly above the required value. This satisfies the initial goal. However, since the requirements of FAR's 23.157(a) and (c) were satisfied at low speed (1.2 V_{stall} and 1.3 V_{stall}), it can be shown that the high-speed force gradients for configuration 1 (requirements of MIL-

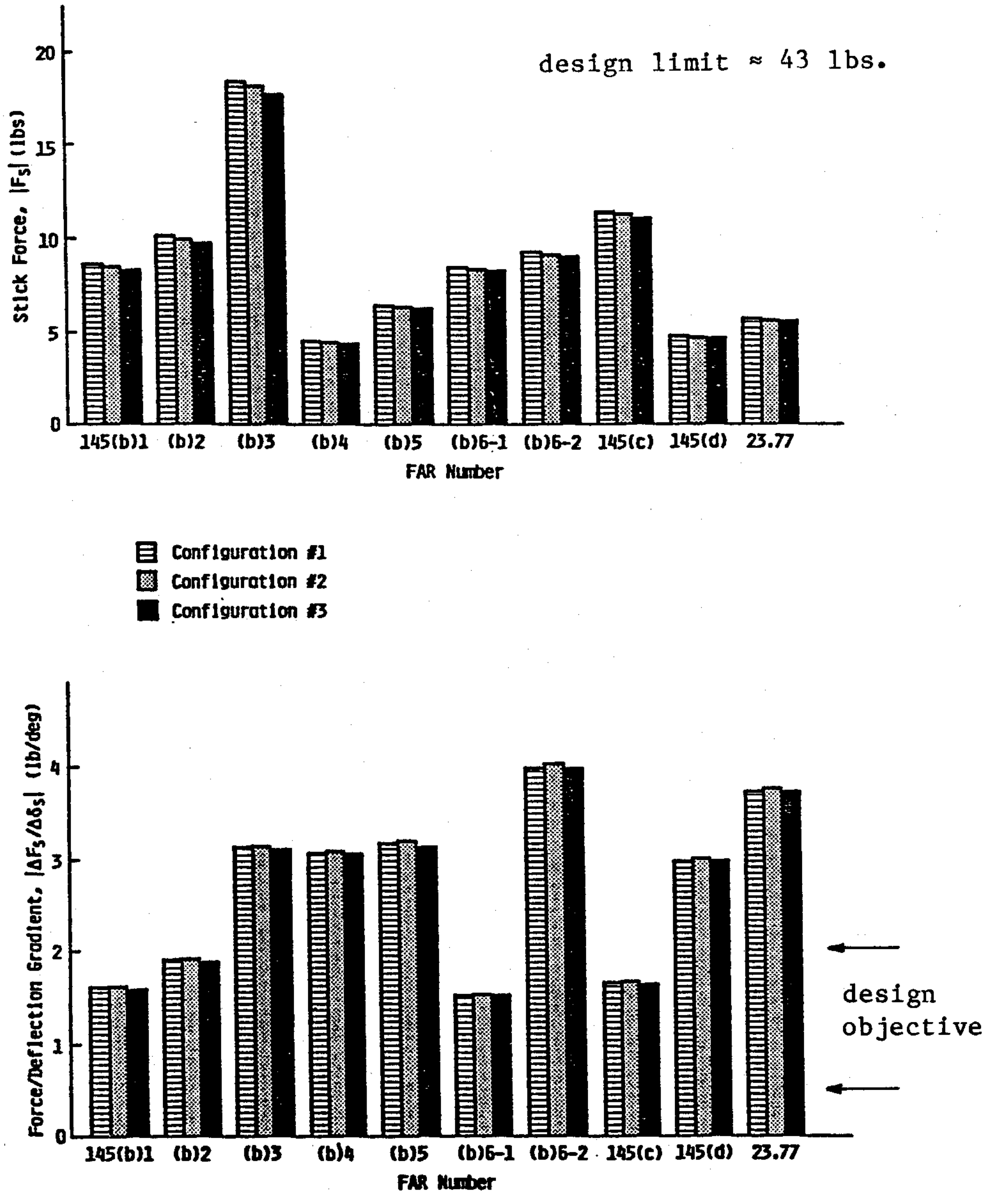

Fig. 4 Comparison of F_s, and $|\Delta F_s/\Delta \delta_s|$ for configurations 1, 2, and 3.

Table 3 Stick force and force/deflection gradient comparison between configurations 1, 2, and 3

Configuration	FAR	G_{T_A}	F_A, lb	$\|\Delta F_A/\Delta\delta_s\|$, lb/deg
1	23.157(a)	-1.7	-7.13	1.17
	23.157(c)	-1.7	-9.99	1.38
2	23.157(a)	-1.45	-3.94	0.54
	23.157(c)	-1.45	-5.52	0.64
3	23.157(a)	-1.35	-2.19	0.270
	23.157(c)	-1.35	-3.06	0.32

Table 4 Predicted characteristics for a rolling maneuver in cruise flight (configuration 3, $G_{T_A} = -1.35$)

Flight parameters: TAS = 145 kts, 5000 ft above sea level

MIL-F-8587B requirements: $\phi(t=0) = 0$ deg, $\phi(t=2.5\text{ s}) = 60$ deg

Results: $F_A = -9.0$ lb, $|\Delta F_A/\Delta\delta_s| = 1.27$ lb/deg,
$\delta_A = 8.4$ deg, $\delta_s = 7.1$ deg

8587C) do not converge to the desired magnitude because of high $\bar{q}$ effects.[9]

The maximum stick force required for a rolling maneuver at cruise speeds reveals that configuration 3 with $G_{T_A} = -1.35$ yields satisfactory results. This finding, combined with acceptable low-speed results (Table 3), clearly indicates that configuration 3 meets the design objectives for a wide range of flight speeds. Any attempt to reduce the cruise value of $|\Delta F_A/\Delta\delta_s|$ further would produce unacceptably low forces and gradients at landing and takeoff airspeeds. Table 4 summarizes the requirements of MIL-8785C and the results for configuration 3. The parameter ϕ represents the bank angle.

Conclusions

Solutions of the aircraft rigid-body equations of motion have been applied to the design study of a sidestick controller system. The data confirm that a geared tab mounted on the elevator can help reduce the longitudinal stick forces to levels well below the initial design objectives. However, for some types of maneuvers, the stick force to stick deflection gradient cannot be brought down to desirable levels. Varying the area of the tab has a minimal effect on the stick forces at the design point. The magnitude of the tab gearing ratio is limited by stick-force reversal and nonlinear aerodynamic effects.

For rolling maneuvers, lateral stick forces have also been reduced to acceptable levels through use of geared tabs on the aileron surfaces. The best compromise for lateral stick force and stick force to stick deflection gradient between low-speed and high-speed maneuvers can be easily reached after a few design iterations.

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