sure will decrease. This is similar to what happens with trailing-edge controls.

It is of interest to compare R_m with the similarly defined ratio for trailing-edge control

$$R_d = C_{mac_d}/C_{l_d}$$

For typical control surface sizes, incompressible thin airfoil theory gives R_d in a range of -0.12 to -0.19. If R_m is more negative than R_d, then the lift effectiveness of boundary-layer blowing would experience greater degradation as a result of flexibility than that of a trailing-edge control surface for the same rigid lift increment. Analysis of some available data for circulation-controlled airfoils suggests that this might be the case.[4] Values for R_m from -0.232 to -0.32 have been obtained. These values have become increasingly negative as blowing is increased. Thus, the potential aeroelastic load effectiveness problems will be exacerbated. The reversal dynamic pressure could be reduced by as much as 50% compared with a trailing-edge control. Another consideration is that, while typical trailing-edge controls extend over only a relatively small outboard portion of the wingspan, circulation control is likely to extend over a substantial portion of the wingspan. This could further amplify the aeroelastic load attenuation characteristics of circulation control. If circulation-controlled airfoil technology is to be considered for future high-*L*/*D* transport vehicles, then aeroelastic effects will have to be given serious attention.

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Sensitivity of Subsonic Stability Derivatives of Free Aircraft to Geometric/Tip-Store Parameters

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Introduction

MODERN-DAY fighter aircraft are designed to carry heavier accessories at the wingtips in the form of warheads/auxiliary fuel tanks, which have a different mass and center of gravity (c.g.), depending on the mission. It is well known that at large flight dynamic pressures, stability derivatives are altered significantly because of structural flexibility. It is also well known[1] that, for a free aircraft, the static aeroelastic corrections to the stability derivatives are substantially different because of elastic deformations caused by inertia forces resulting from accelerations. In this context the inertia configuration of a tip store vis-à-vis the aircraft inertia and wing geometric properties assumes special significance, as it has the potential to alter the overall inertia force distribution and, thereby, the flexible stability derivatives. This is even more important in situations where store configuration changes either during flight or between missions. It is therefore desirable to understand the nature of changes in the flexible stability derivatives because of different wing geometry and tip-store mass configuration for a generic fighter aircraft wing configuration. This study investigates these sensitivities for a small-aspect-ratio wing in a symmetric subsonic flight for different tip-store inertia configurations.

Solution Procedure

The general static aeroelastic problems of freely flying aircraft cannot be solved exactly; a suitable numerical solution procedure is needed. A general-purpose static aeroelastic analysis software STAAC (Ref. 2) has recently been developed, based on the assumed-modes approach of Nicot and Petiau,[1] that uses the doublet-lattice method for aerodynamic analysis and the finite element method for structural analysis. Further, aeroelastic corrections to stability derivatives resulting from inertia forces are based on the rigid modes defined at the aircraft c.g. It has not been possible to completely validate the free aircraft aeroelastic analysis as results, generic or otherwise, because such configurations have not been found in open literature. However, basic checks for a free rectangular plate with uniform mass distribution have been done[2] that, as expected, produce no inertia-related aeroelastic corrections. Further, trends for net c.g. movement toward the leading as well as the trailing edge are consistent with the physics of the problem, just as a forward shift of the c.g. reduces the aeroelastic effect because of a reduction in the overall elastic deformation caused by the inertia forces. These checks have shown that STAAC[2] is a reasonable tool for investigating the aeroelastic efficiencies of freely flying aircraft.

Example, Numerical Results, and Discussion

Figure 1 shows the geometry of a small-aspect-ratio swept and tapered wing as a plate of uniform thickness t (0.01 m), along with the tip store, which is modeled as a lumped mass

Fig. 1 Geometry of a generic swept and tapered wing planform with lumped fuselage mass and a variable inertia tip store. M_f = 10,000 kg and t = 0.01 m.

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M_s, with the c.g. from the midchord as x_s. The half-aircraft fuselage is modeled as an equivalent mass at a distance of x_f from the root midchord. Further, both planform area and aspect ratio were kept as 1.0 so that results for other cases could be extrapolated easily. The material is assumed to be standard aluminum, with properties in SI units. Results are obtained for a symmetric flight maneuver for the stability derivatives $C_{L\alpha}$, $C_{m\alpha}$, C_{Lq}, and C_{mq} (lift and pitching moment coefficient derivatives with respect to angle of attack α and pitch rate q), which are calculated at a flight dynamic pressure of 10^4 N/M^2, significantly lower than the divergence value. Further, although a Mach number M of 0.2 is selected, higher values in the subsonic zone will only mean higher flexible derivatives because of a correspondingly higher load, which could be extrapolated from corresponding rigid load ratios.

The results for flexible derivatives, including the divergence dynamic pressure Q_{div}, are obtained for the parameters Λ, c_r/c_t, x_f/c_r, M_s/M_f, and x_s/c_t, as given in Tables 1–5. Here, the variations in Λ and c_r/c_t are determined such that total wing surface area remains constant. Table 1 shows that both $C_{L\alpha}$ and C_{Lq} reduce with an increase in x_f/c_r (+*ve* for aft movement), while $C_{m\alpha}$ and C_{mq} increase. In contrast, Table 2 shows that both $C_{L\alpha}$ and C_{Lq} increase, while $C_{m\alpha}$ and C_{mq} decrease as taper increases. The results in case of the midchord sweep Λ, presented in Table 3, show that sweepback has a greater influence on the effective aerodynamic coefficients than sweep forward, and that $C_{m\alpha}$ and C_{mq} decrease with an increase in Λ. Table 4 presents the effect of M_s/M_f variation when the store c.g. is on the elastic axis: all quantities are nearly invariant and only the divergence speed reduces noticeably. This also is in conformity with basic free aircraft effect. Finally, the effect of x_s/c_t, shown in Table 5, is the reverse of that observed in Table 1. These results for stability derivatives make it clear that free aircraft flexible force and moment coefficients can be substantially different even with small changes in geometric and mass configurations. Further, it is seen that desirable characteristics for free aircraft are possible by suitably adjusting the various geometry and inertia parameters, making the present study a useful design tool.

Table 1 Sensitivity of stability derivatives to aircraft c.g. shift[a]

x_f/c_r	$C_{L\alpha}$	$C_{m\alpha}$	C_{Lq}	C_{mq}	Q_{div}
−0.20	7.132	0.965	4.711	−0.068	0.309×10^5
−0.10	6.072	1.300	4.432	0.237	0.517×10^5
0.00	4.895	1.453	3.800	0.404	0.352×10^7
0.10	4.862	1.861	3.541	0.618	0.957×10^5
0.20	5.803	2.717	3.804	1.036	0.426×10^5

[a] $M_s/M_f = 0.05$, $\Lambda = 0$ deg, $c_t/c_r = 1.0$, $x_s/c_t = 0.0$, $M = 0.2$, $Q = 10^4$.

Table 2 Sensitivity of stability derivatives to wing taper ratio[a]

c_t/c_r	$C_{L\alpha}$	$C_{m\alpha}$	C_{Lq}	C_{mq}	Q_{div}
1.000	4.895	1.453	3.800	0.404	0.352×10^7
0.800	4.958	1.206	4.412	0.258	0.163×10^7
0.600	5.019	0.881	4.560	0.018	0.157×10^7
0.400	5.059	0.443	5.065	−0.384	0.169×10^7
0.200	5.119	−0.171	5.746	−1.087	0.188×10^7

[a] $M_s/M_f = 0.05$, $\Lambda = 0$ deg, $x_f/c_r = 1.0$, $x_s/c_t = 0.0$, $M = 0.2$, $Q = 10^4$.

Table 3 Sensitivity of stability derivatives to midchord sweep[a]

Λ	$C_{L\alpha}$	$C_{m\alpha}$	C_{Lq}	C_{mq}	Q_{div}
−20.0	7.733	3.476	3.058	0.632	0.241×10^5
−10.0	5.343	2.009	3.135	0.437	0.554×10^5
00.0	4.895	1.453	3.800	0.404	0.352×10^7
10.0	7.848	1.696	5.827	0.553	0.269×10^5
20.0	10.710	1.423	7.650	0.311	0.184×10^5

[a] $M_s/M_f = 0.05$, $x_f/c_r = 0.0$, $c_t/c_r = 1.0$, $x_s/c_t = 0.0$, $M = 0.2$, $Q = 10^4$.

Table 4 Sensitivity of stability derivatives to tip-store mass[a]

M_s/M_f	$C_{L\alpha}$	$C_{m\alpha}$	C_{Lq}	C_{mq}	Q_{div}
0.00	4.920	1.447	3.819	0.399	0.224×10^6
0.01	4.915	1.448	3.815	0.400	0.231×10^6
0.02	4.910	1.450	3.811	0.401	0.239×10^6
0.03	4.905	1.451	3.807	0.402	0.251×10^6
0.04	4.900	1.452	3.804	0.403	0.312×10^7
0.05	4.895	1.453	3.800	0.404	0.352×10^7

[a] $c_t/c_r = 1.0$, $\Lambda = 0$ deg, $x_f/c_r = 0.0$, $x_s/c_t = 0.0$, $M = 0.2$, $Q = 10^4$.

Table 5 Sensitivity of stability derivatives to tip-store c.g. shift[a]

x_s/c_t	$C_{L\alpha}$	$C_{m\alpha}$	C_{Lq}	C_{mq}	Q_{div}
−0.20	4.837	1.411	3.498	0.282	0.929×10^5
−0.10	4.735	1.400	3.605	0.332	0.138×10^6
0.00	4.895	1.453	3.800	0.404	0.352×10^7
0.10	5.418	1.608	4.121	0.511	0.126×10^6
0.20	6.321	1.885	4.582	0.661	0.468×10^5

[a] $c_t/c_r = 1.0$, $\Lambda = 0$ deg, $x_f/c_r = 0.0$, $M_s/M_f = 0.05$, $M = 0.2$, $Q = 10^4$.

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Sensitivity of Aeroelastic Efficiencies of Subsonic Delta Wings to Partial Root Support

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Introduction

MODERN military aircraft employ wings with a delta shape, which provides good aerodynamic and aeroelastic performance. Delta wings are generally constructed using a single spar as the wing torsion box, with a width of about 60–85% of the total chord; thus there is only a partial connection of the wing root to the fuselage. Because the fuselage is much stiffer than the wing, it is possible to model the wing junction with the fuselage as a clamp for structural analysis of the wing. Further, during the preliminary design stage, the position of this torsion box with respect to the center chord is a variable based on many considerations. A study has investigated the sensitivity of the static aeroelastic characteristics of a generic, large-aspect-ratio, forward-swept wing to shape parameters.[1] Another study examined the effect of spar size and location on the bending–torsion modal coupling of small-aspect-ratio, swept, and tapered plates.[2] It is well known that the location and size of the torsion box have a strong influence on the elastic deformation pattern of the wing and, therefore, have the potential to significantly alter the overall aerodynamic lift and pitching moment efficiencies from static aeroelastic corrections. Information about the sensitivity of these efficiencies

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