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Engineering Notes

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Static Aeroelastic Considerations for Circulation Control Airfoils

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Nomenclature

$C_{l_{C_\mu}}$ = derivative of lift coefficient with respect to C_μ
C_{l_α} = airfoil lift curve slope
$C_{\mathrm{mac}_{C_\mu}}$ = derivative of moment coefficient about a.c. with respect to C_μ
C_μ = blowing momentum coefficient
$\bar{c}$ = airfoil chord
e = offset of elastic axis and aerodynamic center, positive for $\bar{c}$ forward of elastic axis
h_j = height of slot on suction surface through which air jet is blown into boundary layer
K_α = airfoil torsional spring stiffness
q = freestream dynamic pressure
q_D = divergence dynamic pressure
q_R = reversal dynamic pressure
R_q = ratio of q to q_D
R_{q_R} = ratio of $\bar{q}_R$ to q_D
S = reference area
V_j = velocity of the blown air jet
α_e = flexible twist
α_0 = initial, rigid, angle of attack
δ = trailing-edge control deflection
ρ_j = density of blown air jet

Subscript
μ = blowing momentum

Introduction

THE U.S. Air Force New World Vistas program envisions future large transports with lift-to-drag (L/D) ratio approaching 40. Large-aspect-ratio wings will likely be a characteristic of such transports as well as any other available high-lift technology. Circulation control in the form of pneumatic blowing of the boundary layer has been under study as a means for augmenting the lift of airfoils. Boundary-layer blowing may also be a viable means of control, replacing the traditional mechanical trailing-edge control surface. The large aspect ratios of likely future large transports may enhance the effect of the blowing technology, in that the flow about such wings is nearly two dimensional over a large portion of the span. The principle is based on the Coanda effect, whereby a high-energy jet of air is injected into the boundary layer on the suction surface of an airfoil. The boundary layer is thereby energized, delaying or even preventing separation of the boundary layer, with the attendant loss in lift. The principal blowing parameter is the momentum coefficient, which is a measure of the momentum flux of the jet of blown air.

Most studies to date have focused on understanding the phenomenon of blowing, as well as on means for achieving effective blowing on actual lifting surfaces.[1–4] However, the combination of long, slender wings and large aerodynamic coefficients attainable through blowing may introduce aeroelastic phenomena that can limit the actual performance of such high-lift technologies. There has been some study of the static aeroelastic effects of circulation control.[5] It is the purpose of this Note to explore the similarity and difference between static aeroelastic effects on circulation-control airfoils and on conventional airfoils with trailing-edge controls. The similarity is used to define two parameters that highlight an important difference in load effectiveness between the two.

Equations Governing the Effect of Flexibility on Load

The effect of blowing is similar to that of deflection of a trailing-edge device such as a flap or aileron. Airfoil pressure distributions and the lift and moment curves of blown airfoils are similar to those of airfoils with deflected trailing-edge devices (Fig. 1). This initial investigation will consider a spring-mounted, typical-section blown airfoil, using the same approach as the classic problem of the spring-mounted, typical-section airfoil with a trailing-edge control surface familiar to the student of aeroelasticity.[6]

Figure 2 shows the airfoil mounted to a base by a torsion spring, representing wing torsional flexibility, at a point called the elastic axis. The elastic axis is at a distance e aft of an aerodynamic reference point. The aerodynamic loads on an airfoil consist of the lift L and the pitching moment M about the reference point. In general, both the lift and moment are functions of angle of attack. If the aerodynamic reference point is the aerodynamic center, then the moment does not change with angle of attack. For an initially symmetric airfoil, the moment is zero. Like the deflection of a trailing-edge control surface, the introduction of boundary-layer blowing will induce an aerodynamic moment. Under these loads, the airfoil deforms in torsion (or pitch) an amount α_e that is added to α_0. Thus, for an initially symmetric airfoil, aerodynamic loads with respect to the aerodynamic center are

$$L = qSC_{l_\alpha}(\alpha_0 + \alpha_e) + qSC_{l_{C_\mu}}C_\mu \tag{1a}$$

$$M = qS\bar{c}C_{\mathrm{mac}_{C_\mu}}C_\mu \tag{1b}$$

where

$$C_\mu = \frac{\rho_j V_j^2 h_j}{q\bar{c}}$$

is the momentum coefficient.

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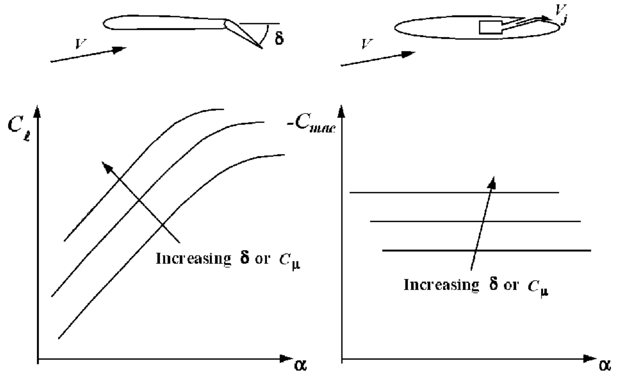

Fig. 1 General effects of trailing-edge control or boundary-layer blowing on airfoil lift and moment curves.

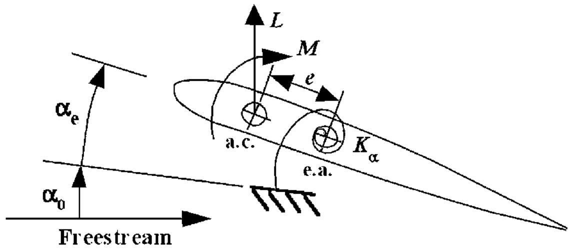

Fig. 2 Flexibly mounted typical-section airfoil.

As the airfoil deforms, the torsion spring develops a resisting torque proportional to its stiffness. Thus, the equation of static equilibrium of the airfoil is

$$(K_\alpha - qSeC_{l_\alpha})\alpha_e = qSeC_{l_\alpha}\alpha_0 + qSeC_{l_{C_\mu}}C_\mu + qS\bar{c}C_{\mathrm{mac}_{C_\mu}}C_\mu \tag{2}$$

From Eq. (2) is obtained the elastic twist, in terms of the initial angle of attack and the momentum coefficient, as

$$\alpha_e = \frac{qSeC_{l_\alpha}}{(K_\alpha - qSeC_{l_\alpha})}\alpha_0 + \frac{qS(eC_{l_{C_\mu}} + \bar{c}C_{\mathrm{mac}_{C_\mu}})}{(K_\alpha - qSeC_{l_\alpha})}C_\mu \tag{3}$$

When Eq. (3) is included in the expression for the lift on the airfoil, then the total, flexible lift coefficient may be obtained as

$$C_l = C_{l_\alpha}\left(1 + \frac{R_q}{1 - R_q}\right)\alpha_0 + C_{l_{C_\mu}} \times \left[1 + \left(\frac{R_q}{1 - R_q}\right)\left(1 + \frac{\bar{c}}{e}\frac{C_{\mathrm{mac}_{C_\mu}}}{C_{l_{C_\mu}}}\right)\right]C_\mu \tag{4}$$

where $R_q = q/q_D$ and $q_D = K_\alpha/SeC_{l_\alpha}$ and is the divergence dynamic pressure of the airfoil. Divergence is a static aeroelastic instability, wherein the incremental nose-up aerodynamic pitching moment exceeds the incremental restoring moment of the spring. The divergence dynamic pressure is the dynamic pressure at which the two moments are equal. At dynamic pressures below q_D, the airfoil is stable. At dynamic pressures above q_D, the airfoil is unstable. Divergence is a possibility only if e is positive.

From Eq. (4) may be identified flexible values of the lift curve slope and the derivative of the lift coefficient with respect to the momentum coefficient. Written as flexible-to-rigid ratios, these are

$$(C_{l_\alpha})_{\mathrm{flex}}/(C_{l_\alpha})_{\mathrm{rigid}} = 1 + [R_q/(1 - R_q)] \tag{5a}$$

$$(C_{l_{C_\mu}})_{\mathrm{flex}}/(C_{l_{C_\mu}})_{\mathrm{rigid}} = 1 + [R_q/(1 - R_q)][1 + (\bar{c}/e)(C_{\mathrm{mac}_{C_\mu}}/C_{l_{C_\mu}})] \tag{5b}$$

Note that for positive e as dynamic pressure increases, the denominators of the aeroelastic terms in Eqs. (5) decrease. This will cause the flexible value of C_{l_α} to amplify. If e is negative, then q_D is negative, divergence cannot occur, and the flexible value of C_{l_α} will attenuate.

The C_μ derivative is a bit more complicated. Although the aeroelastic term for the flexible $C_{l_{C_\mu}}$ has the same denominator as C_{l_α}, the numerator of the aeroelastic term can cause it to completely cancel the rigid 1. This occurs when the dynamic pressure reaches a value

$$R_q = R_{q_R} = -\frac{e}{\bar{c}}\frac{C_{l_{C_\mu}}}{C_{\mathrm{mac}_{C_\mu}}} \tag{6a}$$

or

$$q_R = -\frac{K_\alpha}{\bar{c}SC_{l_\alpha}}\left(\frac{C_{l_{C_\mu}}}{C_{\mathrm{mac}_{C_\mu}}}\right) \tag{6b}$$

This is a condition known as reversal and is exactly analogous to the reversal that trailing-edge control surfaces may encounter. In fact, one has only to replace the ratio of the C_μ derivatives with the ratio of the corresponding control derivatives to obtain the reversal condition for a trailing-edge control surface. Because $C_{\mathrm{mac}_{C_\mu}}$ is typically a negative number, q_R is positive, and reversal can occur just as it can for trailing-edge controls.

Analysis of the Effect of Flexibility on Load

Regardless of whether the elastic axis is forward or aft of the aerodynamic center, reversal can occur for negative $C_{\mathrm{mac}_{C_\mu}}$ because the actual reversal dynamic pressure for an airfoil is not a function of e. Figure 3 shows the flex-to-rigid ratio of $C_{l_{C_\mu}}$ vs dynamic pressure for the cases where q_D is greater or less than q_R. In practice, wings are designed to either be divergence-free or at least have a divergence dynamic pressure so high that the first case in Fig. 3 obtains. Note that, in this case, as dynamic pressure increases from zero, the effectiveness of boundary-layer blowing in augmenting the lift of the airfoil diminishes. This is exactly analogous to the case of a trailing-edge control surface.

For a given dynamic pressure and spring stiffness, lift effectiveness [Eqs. (5)] and reversal [Eqs. (6)] are controlled by the term

$$R = \left(1 + \frac{\bar{c}}{e}\frac{C_{\mathrm{mac}_{C_\mu}}}{C_{l_{C_\mu}}}\right) = 1 + \frac{\bar{c}}{e}R_\mu \tag{7}$$

where

$$R_\mu = C_{\mathrm{mac}_{C_\mu}}/C_{l_{C_\mu}}$$

As R_μ, which is typically negative, becomes increasingly negative, lift degradation will increase and reversal dynamic pres-

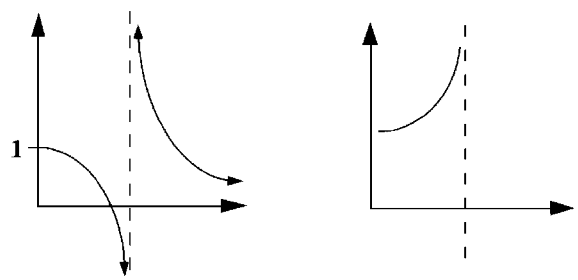

Fig. 3 Aeroelastic lift effectiveness of circulation control: a) $q_R < q_D$ and b) $q_R > q_D$

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

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

$$R_\delta = C_{mac_\delta}/C_{l_\delta}$$

For typical control surface sizes, incompressible thin airfoil theory gives R_δ in a range of -0.12 to -0.19. If R_μ is more negative than R_δ, 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_μ 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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