more prevalent among jet pilots. However, the longer equilibrium time is not normally a factor in long-range cruise for jets. The reason is that compressibility, which has been ignored in this analysis, begins to affect the drag of the airplane. Most modern jets cruise at fairly high subsonic Mach numbers. For example, the McDonnell-Douglas DC-10-10 long-range cruise speed varies, depending upon the weight,[6] from $M = 0.75$ to 0.83. If the pilot of a jet flying at a high subsonic speed dives the aircraft to accelerate to a higher speed with a fixed thrust, the drag coefficient increases more than indicated by the parabolic drag equation resulting from compressibility effects. The derivative term $\partial D/\partial V$ is thus much larger, and this results in a much lower time constant for the jet as it returns to equilibrium. Even with the thrust remaining constant, the larger increase in drag because of compressibility will tend to restore the airplane to its trim condition faster than predicted by incompressible analysis.

Conclusions

Some members of the pilot community have long insisted that it was possible to fly an airplane on the step, whereas engineers have generally ignored or ridiculed these claims. This analysis has shown why pilots have believed in this phenomena. The combination of high aircraft weight, low drag, and long-range cruise speeds typically near the minimum power-required velocity created larger aircraft time constants than previously seen by the pilots. This led to the illusion that they were flying on the step.

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Significance of Wash-Out on the Flutter Characteristics of Composite Wings

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Introduction

THE interest aeroelasticians have shown in exploiting composite materials to enhance aeroelastic stability has grown considerably, as evident from the literature on flutter and divergence characteristics of composite wings.[1–6] A compromise has been identified when altering the ply angles to achieve simultaneously higher flutter and divergence speeds.[1–4] There is a widely held view, that unfortunately is not always true, that ply orientation in a composite wing that results in a wash-in effect, i.e., bend-up/twist-up, has a beneficial influence on flutter, whereas the same effect is detrimental to divergence, with the opposite conclusion applied to wash-out. [For examples, see Fig. 5 of Ref. 1, p. 12, and Fig. 10 of Ref. 2, Conclusion on page 154 (paragraph 4) of Ref. 3 and Figs. 6 and 7 of Ref. 4.] These observations are made without due recognition of the central role of the modal coupling in aeroelastic studies. As a consequence, more attention has been focused on the flutter characteristics of composite wings that exhibit wash-in behavior while making a compromise on the divergence speed. Thus, relatively less emphasis has been placed on the flutter characteristics of composite wings that exhibit wash-out behavior. This Note redresses the imbalance and investigates the flutter characteristics of composite wings that exhibit wash-out behavior. In particular, the circumstances when wash-out can be advantageous in raising the flutter speed are identified, apparently for the first time. This study is particularly relevant because it is well recognized that wash-out is always beneficial for raising the divergence speed of a composite wing, whereas the widely held view is that it has an adverse effect on flutter.[1–4]

Method of Analysis

The method of analysis is similar to the one used by the present authors in Ref. 6. However, to make this Note self-contained, certain features of the method are briefly summarized as follows.

1) The rigidities EI (bending), GJ (torsional) and K (bending-torsion coupling) of a composite wing for various ply angles are computed using the theory of Weisshaar and Foist[7] [see their Eqs. (18–20)]. Variation of these rigidities with ply angle enables the nondimensional uncoupled frequency ratio of the wing (ω_h/ω_α) to vary, which is later used to show the variation of flutter speed. (Note that ω_h is the fundamental uncoupled bending natural frequency, whereas ω_α is the corresponding fundamental uncoupled torsional natural frequency of the wing.) The bending-torsion coupling parameter ψ is defined in the same way as in Ref. 7 to give $\psi = K/\sqrt{EIGJ}$, so that the range for ψ is $-1 < \psi < 1$.

2) Next, the natural frequencies and mode shapes are computed using the dynamic stiffness matrix method put forward by Banerjee and Williams.[8] The normal modes obtained from this analysis are later used in the flutter analysis.

3) The flutter speed (V_F) is computed using the in-house computer program CALFUN,[9] which uses normal modes and generalized coordinates together with strip-theory aerodynamics. The nondimensional flutter speed $V_F/b\omega_\alpha$ (where b is the semichord) is plotted against the static unbalance x_α (defined as the nondimensional distance between the elastic axis and mass axis expressed as a fractional semichord, x_α is negative when the mass axis is behind the elastic axis) for a range of frequency ratios (ω_h/ω_α), and coupling parameters (ψ).

4) Finally, results obtained from using positive ψ, i.e., wash-out in the notation used in this Note, are compared with those obtained from using negative ψ, i.e., wash-in.

Discussion

Figure 1 shows the variation of the nondimensional flutter speed, i.e., $V_F/b\omega_\alpha$ against x_α for three different positive values of ψ, i.e., $\psi = +0.2$, $+0.4$, and $+0.6$, which induce the desired wash-out effect. Several representative values of the frequency ratio ω_h/ω_α were used in obtaining the results as shown in the figure. For comparison purposes, results for negative values of ψ, i.e., for $\psi = -0.2$, -0.4, and -0.6, are shown in Fig. 2. (It should be noted that the values of x_α plotted in Figs. 1 and 2 are all negative so that the mass axis is behind the elastic axis, which is usually the case.) The density ratio $m/\pi\rho b^2$ and the

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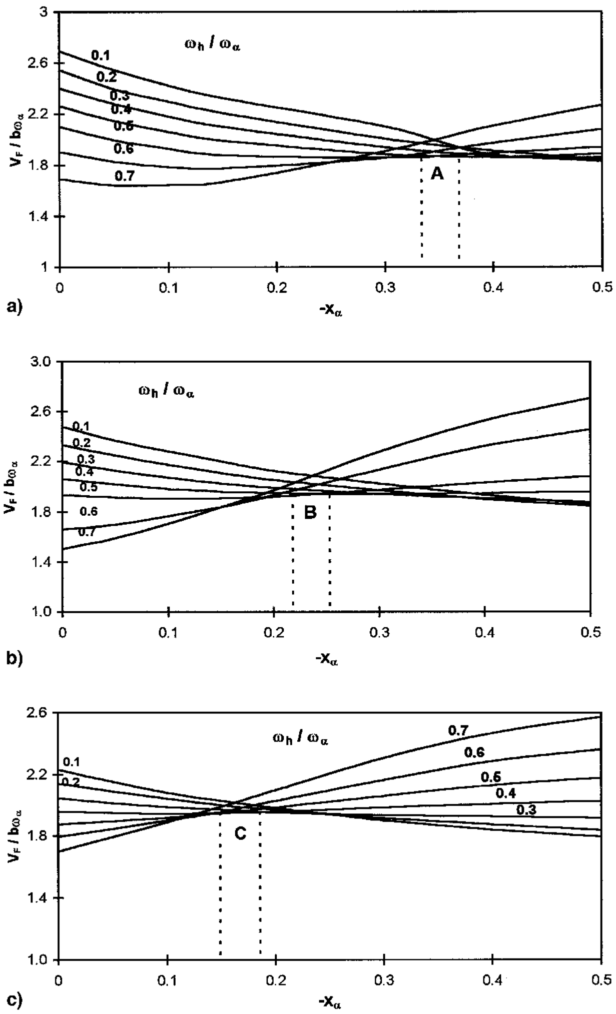

Fig. 1 Dimensionless flutter speed $V_f/b\omega_\alpha$ against static unbalance x_α for various values of frequency ratios ω_h/ω_α for ψ = a) 0.2, b) 0.4, and c) 0.6. $m/\pi\rho b^2 = 20$, $r_\alpha = 0.5$, $a = -0.2$.

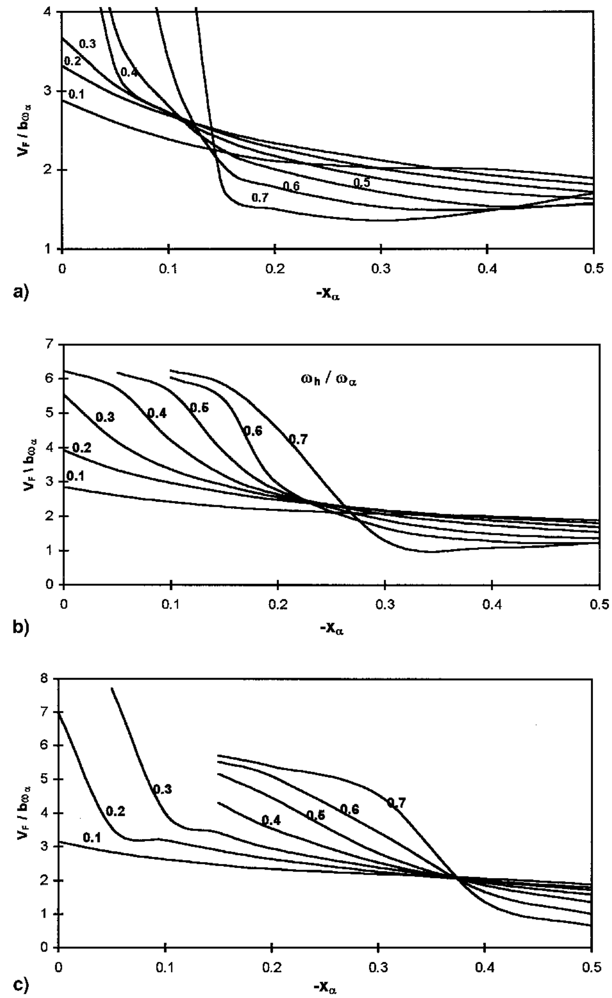

Fig. 2 Dimensionless flutter speed $V_f/b\omega_\alpha$ against static unbalance x_α for various values of frequency ratios ω_h/ω_α for ψ = a) −0.2, b) −0.4, and c) −0.6. $m/\pi\rho b^2 = 20$, $r_\alpha = 0.5$, $a = -0.2$.

radius of gyration defined as $r_\alpha = \sqrt{I_\alpha/mb^2}$ were kept constant at 20 and 0.5, respectively, for all cases. The elastic axis location was assumed to be 20% of the semichord and forward of the midchord position, i.e., $a = -0.2$. The first three normal modes were used in the flutter analysis and were subsequently found to be adequate.

One striking feature of the results shown in Fig. 1 is that at certain combinations of positive ψ and negative x_α, the flutter speed is relatively unaffected by changes in the frequency ratio ω_h/ω_α (see regions A, B and C). The negative value of x_α at which the preceding phenomenon occurs moves toward the origin, i.e., to the left, with the increase in the value of positive ψ as shown in Fig. 1. A detailed investigation was carried out around these intersection points, i.e., regions A, B, and C, and the results confirmed the existence of such intersecting regions where the flutter speed is more or less invariant.

It is interesting to note that the results of Fig. 1, which are all based on wash-out behavior, indicate that for certain values of frequency ratio, an increase in flutter speed is possible (see the right-hand sides of regions A, B, and C of Fig. 1).

The cause of the intersecting regions A, B, and C of Fig. 1 was further investigated and the principal observations are as follows. In these intersecting regions, for a given combination of ψ and x_α, an increase (or a decrease) in the frequency ratio ω_h/ω_α is accompanied by an increase (or a decrease) in the first bending and first torsional frequencies. The increase (or decrease) in value of these two frequencies is such that, although the flutter frequency increases (or decreases) as expected, the flutter speed remains constant.

Another important but related observation made from the results shown in Fig. 1 is that for certain moderate-to-high values of ω_h/ω_α, the flutter speed is generally unaffected by changes in x_α, see, for example, the case with $\omega_h/\omega_\alpha = 0.5$ in Fig. 1b. In other words, the mass can be favorably distributed in a chordwise sense without adversely affecting the flutter speed. Furthermore, for high values of ω_h/ω_α, the flutter speed increases with an increase in the negative value of x_α, see, for example, the graph for $\omega_h/\omega_\alpha = 0.7$ in Fig. 1b. This is in contrast to the results obtained using a negative ψ, i.e., wash-in, shown in Fig. 2, where the flutter speed decreases with increase in negative x_α. It is interesting to note that when high negative x_α is present, e.g., $x_\alpha = -0.5$, positive ψ gives higher flutter speeds than the negative ψ, particularly when the frequency ratio is high (see, for example, Figs. 1c and 2c). For such values of x_α, ψ, and ω_h/ω_α, composite wings exhibiting wash-out behavior give higher flutter speeds than the ones that exhibit wash-in behavior. Thus, the common oversimplification[1–4] that wash-in is always good for flutter, whereas wash-out is detrimental, is not true.

An in-depth investigation has been carried out to obtain further results. It was observed that when negative x_α is combined with positive ψ or vice versa, frequency separation occurs between the fundamental bending and torsional modes (when compared to the case with $x_\alpha = 0$), and as a consequence a higher flutter speed is reached. This is illustrated in Fig. 3a, where the frequency of the fundamental bending and torsional modes for $\psi = 0.4$ are plotted against negative x_α for selected values of the uncoupled frequency ratio ω_h/ω_α. Note that ω_h

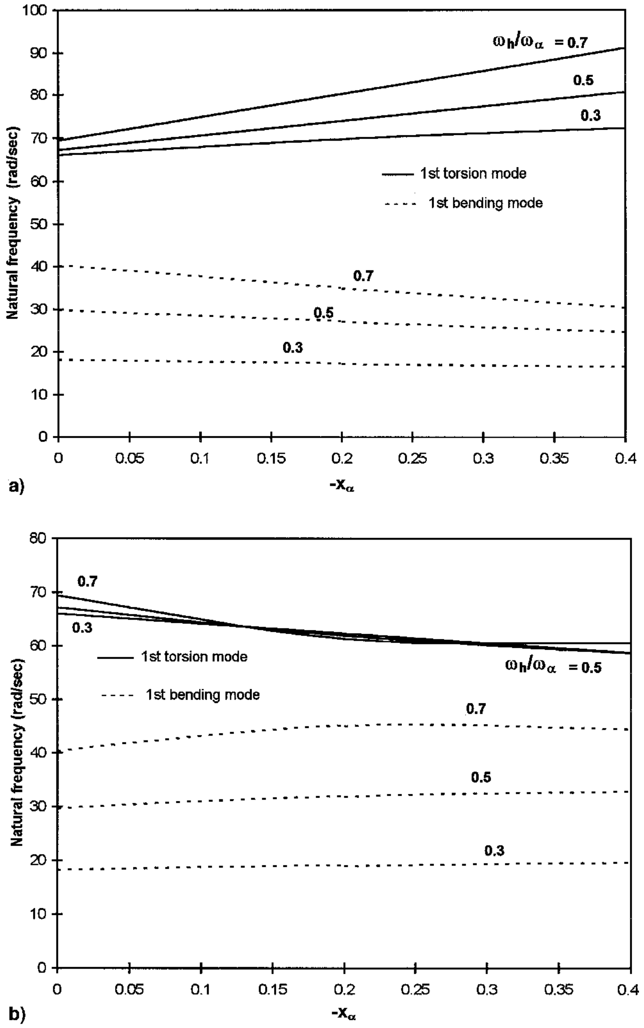

Fig. 3 Natural frequencies for the first bending and torsional modes against x_α for selected values of frequency ratio ω_h/ω_α for ψ = a) 0.4 and b) −0.4.

and ω_α are uncoupled fundamental bending and torsional natural frequencies that are both independent of x_α and ψ, whereas the plotted graphs shown by solid and dashed lines represent fundamental bending and torsional coupled natural frequencies, respectively. It is clear from Fig. 3a that as the negative x_α increases, the frequency difference between the two vibrational modes of interest increases and as a consequence flutter speed also increases, thus reinforcing the importance of modal coupling in such studies.[10]

In contrast, when negative ψ ($\psi = -0.4$ in this case) is present together with negative x_α (see Fig. 3b), frequency convergence occurs between the two modes of interest, and as a result the flutter speed reduces. The preceding frequency phenomenon was also noticed by Weisshaar and Foist,[7] but not from an aeroelastic point of view, so that its effect on flutter behavior was not reported.

From the preceding results, it can be concluded that the wash-out behavior of a composite wing can be useful in increasing its flutter speed when the mass axis is well behind the shear center of the wing cross section as opposed to the corresponding case when the wing exhibits wash-in behavior. The investigation has also revealed that for certain combinations of positive ψ and negative x_α, the flutter speed is unaffected by changes in the frequency ratio ω_h/ω_α.

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Perturbation Solution of Dynamic Stability Derivatives over Pointed Bodies of Revolution

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Introduction

THE unsteady Euler and Navier–Stokes equations represent adequate mathematical models for unsteady transonic flow. Time-accurate solutions of the Euler and Navier–Stokes equations are computationally expensive, particularly in the low-frequency range. But the linearized theory fails in calculating transonic flows. For engineering applications, a compromise perturbation theory that considers the nonlinear effects for transonic flow and also avoids massive time-accurate computation for low reduced frequencies is developed in this paper.

The theory is simplified by introducing a perturbation approach. The unsteady flow is decomposed into a mean steady motion and unsteady perturbation components. The mean steady flow is then described by a nonlinear equation, and the unsteady perturbed flow is described by a complex linear equation, with variable coefficients determined by the mean steady flow.

Here, for simplicity, the sharp-nosed body of revolution undergoing pitching oscillations around zero incidence is considered. Because the flow past a body of revolution at zero in-

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