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Aeroelastic Stability Analysis of the AD-1 Manned Oblique-Wing Aircraft

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The AD-1 manned flight test program being conducted jointly by the Ames and Dryden Flight Research Centers of NASA is intended to evaluate the stability, control, and handling characteristics of oblique-wing aircraft. The results of the aeroelastic stability analysis carried out at Ames in support of the AD-1 program are presented for the oblique wing, both with and without ailerons. When the wing is swept, the significant mode of instability is low-frequency, oblique-wing flutter. With the oblique unswept, however, the critical mode is bending-torsion-aileron flutter. The latest version of the NASTRAN computer code, as well as the Ames PASS/FLUT program, was used in these studies.

Nomenclature

$\bar{c}$ = reference chord length, m
E = Young's modulus, N/m^2
f = frequency, Hz
G = shear modulus, N/m^2
g = artificial structural damping
I_x, I_y, I_z = fuselage mass moments of inertia, kg-m^2
I_β = aileron mass moment of inertia, kg-m^2
K_β = aileron spring constant, N-m/rad
k = reduced frequency = $\omega\bar{c}/2V$
V = velocity, m/s
γ = relative damping ratio
ρ = density, kg/m^3
ω = circular frequency, rad/s
ω_β = aileron natural frequency, rad/s

Introduction

ALTHOUGH the oblique-wing concept proposed by Jones[1] is somewhat unconventional, it appears to be a feasible innovation for the next generation of aircraft. Wind-tunnel tests carried out over the past several years at Ames Research Center have helped to validate the potential of oblique-wing aircraft for improved aerodynamic efficiency over conventional swept-wing aircraft because the oblique wing has less wave drag at transonic and low supersonic speeds.[2] In addition, design studies performed under contract, as well as in-house at Ames, have demonstrated the mission flexibility of the oblique wing in both civilian and military applications. Nelms[3] summarizes this research, which has been directed at developing the technological base for possible oblique-wing aircraft of the future.

Research has also been carried out to investigate the aeroelastic behavior of the oblique wing. Several early studies concentrated on the stability and control characteristics of oblique-wing aircraft.[4-6] Initially, there was also some question about the possible undesirable aeroelastic stability characteristics of oblique wings because of the well-known static aeroelastic divergence of symmetrically swept-forward wings.[7] Jones and Nisbet,[8] however, used a simplified three-degree-of-fredom model to demonstrate that when the oblique wing is allowed the rigid-body roll degree of freedom, the mode of instability changes from static divergence to a low-frequency flutter.[9] They found that the roll moment of the fuselage has an important influence on the instability speed of an oblique wing. These findings were confirmed by Weisshaar and Crittenden[10] who used a sophisticated aerodynamic and structural model. Further studies[11,12] of an oblique-wing transport aircraft design showed no significant difference in flutter behavior when rigid-body plunge and pitch were also included.

An important part of the oblique-wing technology program is the manned flight verification of oblique-wing flight characteristics. The flight-test program is being carried out jointly by the Ames and Dryden Flight Research Centers. A low-cost, experimental, jet-powered vehicle, designated the AD-1, is being built to evaluate the low-speed flight characteristics of the oblique wing. The AD-1 aircraft was delivered to Dryden in March 1979; the first flights are planned for mid-1979. Later, a supersonic fighter aircraft may be fitted with the oblique wing to validate the concept at transonic speeds.

This paper presents the results of the aeroelastic stability analysis[13] performed in support of the AD-1 flight-test program. This study was carried out using the PASS and FLUT computer programs,[14,15] as well as the aeroelastic analysis capability available in the MacNeal-Schwendler Corporation's NASTRAN computer program (MSC-V43).[16] In the initial analysis of the aeroelastic behavior of the AD-1, the oblique wing was modeled as a beam with the fuselage mass and inertial properties concentrated at the wing pivot, which was allowed three rigid-body degrees of freedom: plunge, pitch, and roll. For comparison, the wing was also considered to be clamped at the root, which made the swept-forward wing susceptible to static aeroelastic divergence.

In an additional study, the effect of ailerons on the flutter analysis was investigated. Two rigid ailerons, each with a rotational degree of freedom, were added to the model of the AD-1 wing, thus allowing for the consideration of oblique-wing-aileron flutter.

Methods of Flutter Analysis

The aeroelastic capability that has been added to NASTRAN provides three different methods of flutter analysis: the K method, the KE method, and the PK method.[17] The K method in NASTRAN is a slight variation of the traditional American method of flutter analysis, which introduces an artificial damping parameter g into the equations of motion. Typically, in the K method, plots of V vs

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g are used to determine the onset of flutter (when the damping goes through zero and becomes positive) or static divergence (when both the damping and the frequency approach zero). However, the solutions obtained by this method are valid only when $g=0$, since the aerodynamic terms are not valid for other than sinusoidal motion. This K method of flutter analysis is essentially the one used in FLUT, except that FLUT assumes that no viscous damping is present.

The NASTRAN aeroelastic capability also includes a very efficient form of the K method of flutter analysis called the KE method. With this method, it is assumed that there is no viscous damping. In addition, the solution obtained by this method is restricted to eigenvalues only; eigenvectors are not calculated. Thus, the KE method is considerably less expensive to use than the other two methods in NASTRAN.

The third method of flutter analysis implemented in NASTRAN is the PK method, which is based on the "lined-up" British method. References 18 and 19 describe the British method and compare it with the American or K method. (A variation of the British method, called the p-k method, was developed by Hassig[20]; however, Hassig's method is different from that followed in NASTRAN.) In the PK method, a flutter instability is indicated by a negative value of the relative damping ratio γ which is approximately equal to $g/2$.[19,20]

AD-1 Model

A sketch of the AD-1, the flight vehicle to be used in the initial manned verification of the oblique-wing concept, is shown in Fig. 1. The experimental aircraft will be 11.1 m (36.4 ft) long, will weigh about 773 kg (1700 lb), and will be powered by two Ames Industrial Corporation TRS-18 jet engines each with a thrust of 890 N (200 lb). The oblique wing of the AD-1 will weigh 142 kg (313 lb), will have a 9.8 m (32.3 ft) span, and will have an unswept aspect ratio of 11.2 (Fig. 2). The wing sweep will be variable in flight from 0 to 60 deg. The 12% thick wing with a modified four-digit airfoil section will be composed of a fiberglass skin (E-glass) over a foam core. This skin will consist of from 4 to 17 piles of lamina built up with a ratio of about one ±45 deg bias ply, 0.030 cm (0.012 in.) thick, to every three unidirectional plies, 0.023 cm (0.009 in.) thick. The 25% chord ailerons of the AD-1 run from 3 m (10 ft) either side of midspan to the wing tips. These ailerons will be mass balanced and controlled by torque tubes and cables.

The mass and stiffness distributions used in the aeroelastic analysis of the AD-1 wing were generated from the wing geometry and the following material properties:

E $= 2.62\times10^{10}$ N/m^2 (3.8×10^6 psi) (measured specimen)
G $= 0.55\times10^{10}$ N/m^2 (0.8×10^6 psi) (estimated)
ρ (laminate) = 1938 kg/m^3 (0.07 lb/in.^{3})
ρ (foam) = 32 kg/m^3 (2 lb/ft^3)

The center of mass and the elastic axis of the wing were calculated to be at the 47.9 and 40.7% chord, respectively.

In the analysis using the NASTRAN program, each half of the wing was modeled by 10 bar elements, each with constant-stiffness properties and lumped-mass properties. When the PASS program was used, however, a somewhat better representation of the mass and stiffness distributions was obtained by considering the elements to have linearly varying properties. With both of these programs, the fuselage was considered to be lumped at the wing pivot (located at the 40% chord) and to have the following mass properties:

mass = 621.1 kg (42.56 slugs)
I_x = 105.5 kg-m^2 (77.8 slug-ft^2)
I_y = 2683.8 kg-m^2 (1979.6 slug-ft^2)
I_z = 2702.8 kg-m^2 (1993.6 slug-ft^2)

In the aeroelastic analyses, which included the effects of the ailerons on the stability of the AD-1 wing, the NASTRAN computer program was used exclusively. The ailerons were considered as rigid-body elements with a single rotational degree of freedom about the hinge line. Rotation of each aileron was assumed to be restrained by a torsional spring with constant K_β. The mass moment of inertia I_β and spring constant were taken as

I_β = 0.013 kg-m^2 (9.7×10^{-3} slug-ft^2)
K_β = 259-432 N-m/rad (40-66.7 in.-lb/deg)

which yields an uncoupled frequency of free vibration for the ailerons of

$$\omega_\beta = (K_\beta / I_\beta)^{1/2} = 22.3\text{-}28.7 \text{ Hz}$$

A torsional spring constant of 0.67 N-m/rad (0.10 in.-lb/deg) was also considered. This value of K_β yields a low frequency of 1.1 Hz and results in an aileron that is essentially free.

With both the NASTRAN and FLUT programs, the unsteady aerodynamic matrices were calculated using the doublet-lattice method developed by Giesing, Kalman, and Rodden.[21,22] These matrices were computed at a freestream Mach number of $M=0.5$ at sea-level density for different values of the reduced frequency $k=\omega\bar{c}/2V$. Although it is realized that it is possible to perform a more accurate analysis by computing results for a series of Mach numbers and altitudes, no attempt was made to carry out a matched flutter analysis. Because the critical speeds obtained in the present flutter analysis were found to fall roughly around $M=0.5$,

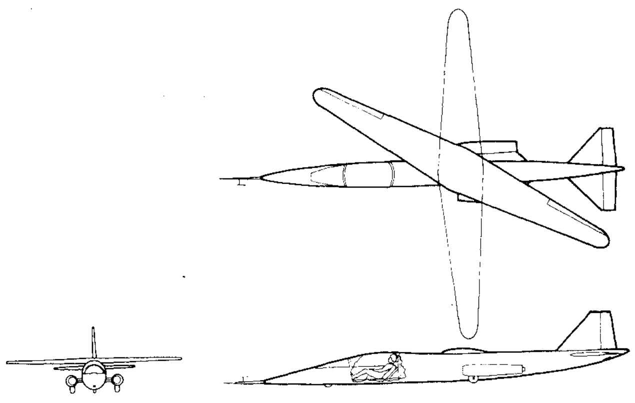

Fig. 1 AD-1 oblique-wing research aircraft.

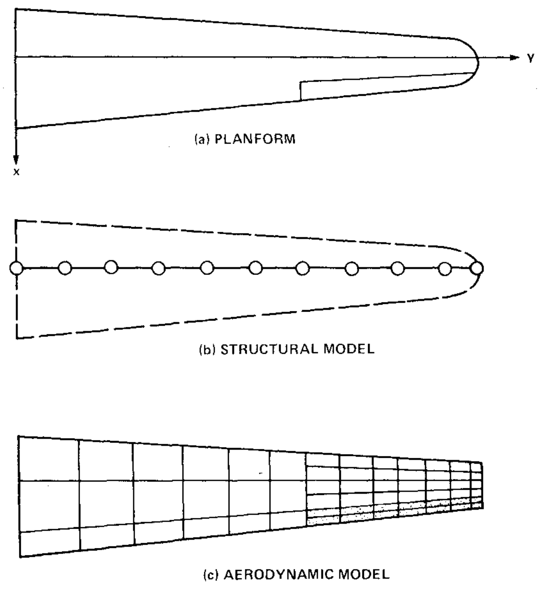

Fig. 2 AD-1 wing-aileron model.

this Mach number was considered to be adequate. Also, since the AD-1 is to be nominally flown at 175 knots equivalent airspeed at an altitude of 4572 m (15,000 ft), it was felt that there would be no appreciable loss in accuracy by considering sea-level density in the present analysis.

Results and Discussion

Coupled Wing-Body Flutter

The results of the aeroelastic stability analysis of the AD-1 wing are summarized in Fig. 3, which illustrates the variation of flutter speed with sweep angle for the oblique-wing aircraft. When the wing is considered to be clamped at the root, the primary mode of instability for virtually all sweep angles is seen to be static divergence, which occurs at zero reduced frequency, that is, $k=0$. When the oblique-wing aircraft is allowed rigid-body plunge, roll, and pitch degrees of freedom, however, a change in the mode of instability occurs. For angles of sweep up to about 25 deg, the instability behavior is typical of classical swept-wing bending-torsion flutter. For larger sweep angles, however, the mode of instability is characterized by a coupling between the rigid-body and the bending-torsion degrees of freedom. These coupled oscillations occur at a frequency (≈ 4 Hz) that is near the AD-1's lowest natural frequency (≈ 7 Hz) and is considerably less than the classical flutter frequency (≈ 30 Hz).

Figure 3 also shows how increasing the torsional rigidity GJ of the wing affects the flutter results. For illustrative purposes, doubling the shear modulus G to 1.1×10^{10} N/m^2 (1.6×10^6 psi) causes the results for bending-torsion flutter, which is of interest at low-sweep angles, to be increased by about 50%. On the other hand, the results for low-frequency flutter are only slightly affected by the value of G, since this mode is primarily due to a coupling between bending and rigid-body roll.

Figure 4 presents a V-g diagram of the critical modes of instability for the AD-1 wing. PASS/FLUT results, which are in excellent agreement with those obtained using the KE method in NASTRAN, are shown for unswept wings and for wings swept 45 deg, with the fuselage both clamped and free to plunge, roll, and pitch. For 45-deg sweep, with freedom to plunge, roll, and pitch, the results for the first eight elastic modes from a PASS/FLUT analysis are presented in Figs. 5 and 6. Each numbered curve is a mode that corresponds to a root of the flutter equation. These coupled modes appear in pairs, which are associated with each half of the wing and represent the symmetric and antisymmetric behavior of the entire wing. The numbering of the modes in Fig. 6 corresponds to the numbering in Fig. 5. For this case the mode of primary interest is the low-frequency-flutter mode, which exhibits an instability at about 163 m/s (317 knots). Additional higher frequency modes are shown in the figure, but their flutter speeds are beyond the range where subsonic flow can be assumed and are outside the area of concern for the AD-1.

The results presented in Figs. 3-5 are qualitatively similar to results obtained for a transport aircraft design utilizing an oblique wing.[12] As pointed out in Ref. 12, the asymmetric nature of the oblique wing readily lends itself to aeroelastic tailoring by means of differential stiffness for each half of the wing. For example, for the AD-1, the flutter speed of the low frequency body-freedom type of flutter, which is critical for sweep angles greater than about 25 deg could be increased by increasing the bending stiffness of the swept-forward wing only. As will be shown in the next section, however, classical wing-aileron flutter with the wing unswept is more critical, and a bending-stiffness change will not be needed for the AD-1.

Wing-Aileron Flutter

The aeroelastic analysis of the AD-1 wing with one aileron degree of freedom included (pivot elastic torsion, no damping) was carried out using the NASTRAN computer code exclusively. The PK method of flutter analysis was used in this study primarily because of its apparent superiority in the

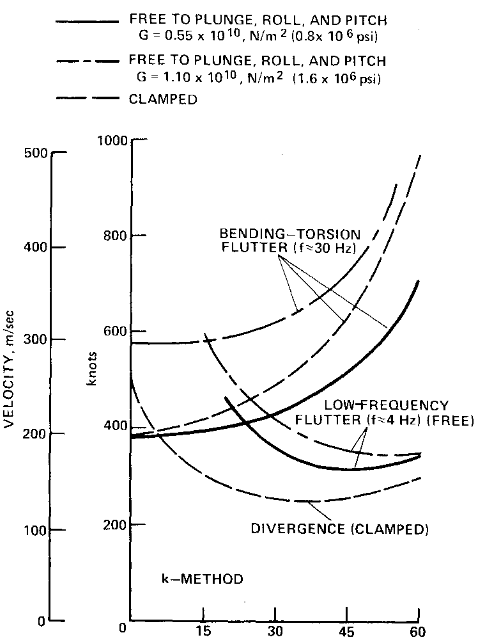

Fig. 3 AD-1 wing-flutter speed boundary.

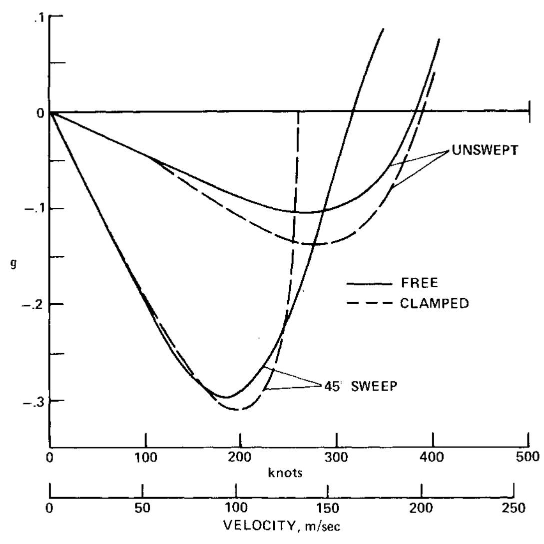

Fig. 4 AD-1 wing critical modes, V-g diagram, K method.

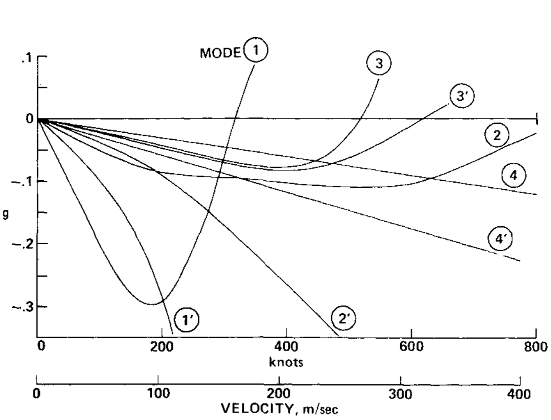

Fig. 5 AD-1 wing, 45 deg sweep, free to plunge, roll, and pitch, V-g diagram, K method.

ordering of the modes and because it produced results directly for given values of velocity where the other methods required interpolation.

The amount of computer time required to carry out an aeroelastic analysis increases very rapidly as the number of aerodynamic boxes is increased. As shown previously for the wing alone, however, the fuselage inertia has very little effect on the classical wing-aileron flutter at small angles of sweep where the fuselage can be considered to be clamped; only half a wing need be analyzed for this condition. The low-frequency-flutter mode, on the other hand, occurs at relatively low values of reduced frequency, and since the aileron pivot torsional stiffness does not have much effect on this mode, a very large number of aerodynamic boxes are not necessary for this condition.

Initially, an aerodynamic model with 60 boxes over each half of the wing (Fig. 2c) was used in the aeroelastic analysis of the AD-1 wing aileron. For the unswept condition, the critical mode of instability was found to be the classical wing-aileron mode, which gave a flutter speed of 138 m/s (269 knots) at a frequency of 35.4 Hz. The reduced frequency for this condition was relatively high (>0.7); therefore, an improved aerodynamic model was considered with 153 boxes over half of the wing. The velocity-damping diagram of the first five coupled elastic modes of this configuration is shown in Fig. 7 for the AD-1 wing unswept and clamped at the fuselage. The corresponding velocity-frequency diagram for this case is given in Fig. 8. The critical mode is the wing bending and torsion plus aileron pivot stiffness mode (mode 3), which has a flutter speed of 153 m/s (296 knots) at a frequency of 34.2 Hz and a reduced frequency of 0.63.

Figure 9 presents the flutter speed boundary for the AD-1 wing-aileron configuration. A comparison of this figure with Fig. 3 shows that the introduction of the aileron degree of freedom has significantly reduced the flutter speed of the classical wing bending-torsion mode, which is the critical mode of instability for the oblique wing unswept and at a small angle of sweep. As in the case of the oblique wing without aileron, the flutter speed for this mode increases as the wing is swept; again, the critical mode changes to a low-frequency body-coupled flutter mode (or a divergent mode for a clamped condition). In the present case, however, the inclusion of the aileron is seen to have a slight stabilizing effect on this low-frequency-flutter mode.

When the AD-1 wing is assumed to be clamped at the fuselage, the flutter boundary remains relatively constant at 150 to 160 m/s (290 to 310 knots) as the sweep angle is increased. By allowing the fuselage the rigid-body plunge, roll, and pitch degrees of freedom, a somewhat higher flutter boundary of about 175 m/s (340 knots) at sweep angles over 30 deg resulted. In addition, the transition from the classical wing-aileron-flutter mode to the low-frequency body-coupled flutter mode, which occurs at about 20 deg without the aileron degree of freedom, occurs at about 35 deg.

The variation of the damping of the bending-torsion-aileron flutter mode with the aileron pivot torsional stiffness is shown in Fig. 10 for the unswept AD-1 wing aileron with a clamped fuselage. For all values of the torsional spring constant K_β considered, this mode becomes unstable rapidly at velocities above 190 m/s (370 knots). For low values of K_β, this hump mode also becomes slightly unstable at 141 to 154 m/s (275 to 300 knots). Even for the predicted K_β range of 259 to 432 N-m/rad (40 to 66.7 in.-lb/deg), this mode is only marginally stable at velocities as low as 116 to 129 m/s (225 to 250 knots). As shown previously for the AD-1 wing alone, however, the stability of this classical wing-aileron mode is

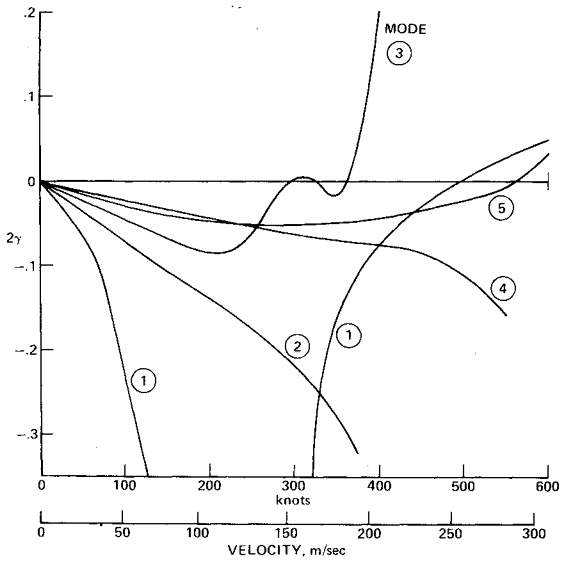

Fig. 7 AD-1 wing aileron, unswept, clamped, V-2γ diagram, PK method.

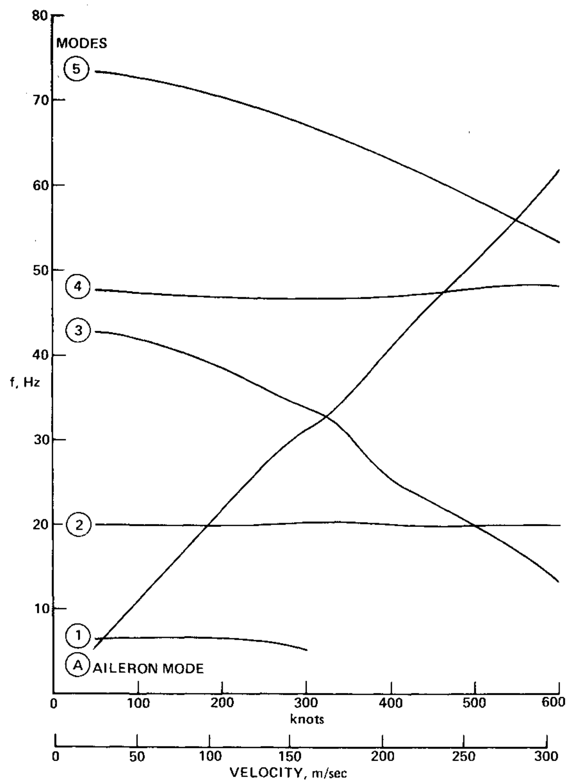

Fig. 8 AD-1 wing aileron, unswept, clamped, V-f diagram, PK method.

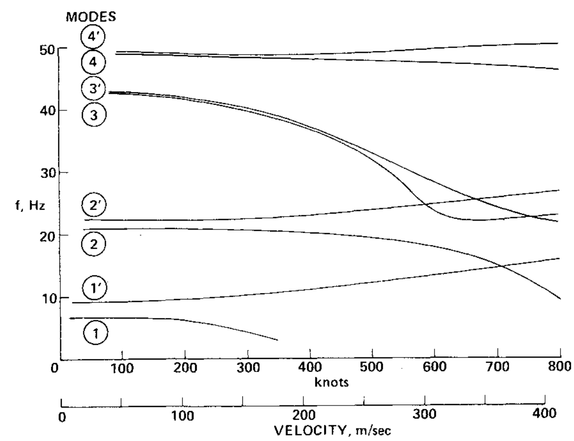

Fig. 6 AD-1 wing, 45 deg sweep, free to plunge, roll, and pitch, V-f diagram, K method.

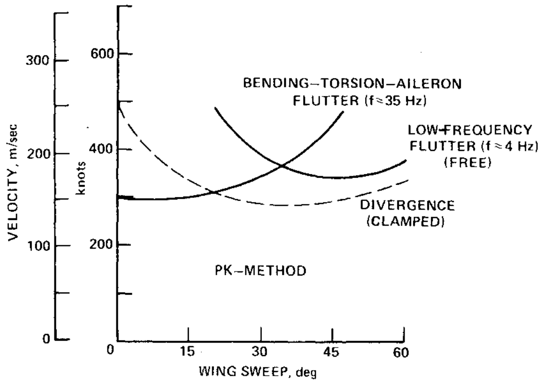

Fig. 9 AD-1 wing-aileron-flutter speed boundary.

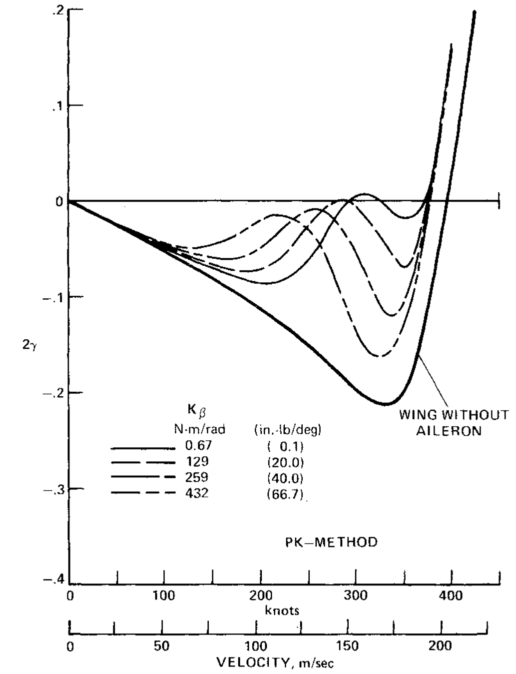

Fig. 10 Variation of wing-aileron mode with K_β.

strongly influenced by the wing's torsional rigidity. Thus, if this mode of instability were a problem, the velocity at which flutter occurs could be increased by using a material with a greater shear modulus for the skin of the wing. No such modification appears necessary for the AD-1 however, since the nominal flight velocity is to be 175 knots.

Conclusions

The initial aeroelastic analysis of the AD-1, manned, oblique-wing aircraft, considered coupled wing-body flutter. At low sweep angles the critical behavior of the wing was similar to that associated with classical bending-torsion flutter. At increased angles of sweep, however, the critical behavior changed to a low-frequency flutter, which was characterized by a coupling between the wing bending and the rigid-body roll degrees of freedom. This mode of instability differs from that found for the divergence of swept-forward wings and occurs at a higher critical speed. These wing-body results are qualitatively similar to results previously obtained for the design of an oblique-wing transport aircraft.

In a subsequent aeroelastic analysis of the AD-1, ailerons were introduced to study their effect on the flutter of the oblique wing. It was found that the coupled low-freqency-flutter mode was only slightly affected by the addition of the ailerons. This small effect, however, was stabilizing so that with the oblique wing swept, the critical speed is slightly greater than that obtained in the initial analysis without ailerons. In contrast, the addition of the ailerons had a very significant effect on the classical bending-torsion flutter. The flutter speed of the bending-torsion-aileron mode was considerably lower than in the analysis without ailerons. Consequently, the critical aeroelastic instability for the AD-1 wing was bending-torsion-aileron flutter, which occurred with the oblique wing unswept.

Although the different flutter analysis methods available in the NASTRAN aeroelastic package all predict virtually identical flutter speeds, the PK method was much preferred because it appeared to yield better ordered solutions than either the KE or the K method. That is, the eigenvalues which the PK method outputs are sorted so that a better continuity of the modes is maintained. An additional advantage of the PK method is that results are obtained directly for given values of velocity with this method, whereas the other methods require interpolation. Finally, the subcritical damping predicted by the PK method was substantially greater than that obtained using either of the *g* methods. As discussed in Ref. 12, although the PK method is preferred because it more accurately predicts subcritical damping substantially greater than that obtained by either of the *g* methods, there is still a need for methods that better predict off-critical behavior. The introduction of techniques that give more accurate aerodynamic forces such as developed by Edwards et al.,[23] however, should improve aeroelastic analysis in the future.

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