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NOMENCLATURE

a_n, a_{n+1}	successive amplitudes of oscillation
[B]	damping matrix
$\bar{c}$	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, $kg\text{-}m^2$
I_β	aileron mass moment of inertia, $kg\text{-}m^2$
[K]	stiffness matrix
K_β	aileron spring constant, N-m/rad
k	reduced frequency, $k = \frac{\omega \bar{c}}{2V}$
[M]	mass matrix
p	complex eigenvalue, PK-method
[Q]	aerodynamic force matrix
$[Q^I]$	aerodynamic damping matrix
$[Q^R]$	aerodynamic stiffness matrix
{q}	generalized displacement vector
V	velocity, m/sec
γ	transient decay rate coefficient
Λ	sweep angle, deg
λ	complex eigenvalue, k-method (and KE-method)
μ	real part of p
ρ	air density, kg/m^3

ω circular frequency, rad/sec

ω_β aileron natural frequency, rad/sec

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SUMMARY

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 and 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 both the wing alone and the wing with ailerons. In addition, a comparison is made between the results obtained using the traditional k-method of flutter analysis and the results using the PK or British method of flutter analysis. These studies were performed using the latest version of the NASTRAN computer code as well as the Ames program PASS/FLUT.

INTRODUCTION

Although the oblique-wing concept proposed by R. T. Jones (ref. 1) is somewhat unconventional, it appears to be a viable innovation for use in the next generation of aircraft. Wind-tunnel tests carried out over the past several years by the NASA Ames Research Center have helped to validate the oblique wing's potential for increased aerodynamic efficiency over conventional swept-wing aircraft due to reduced wave drag at transonic and low supersonic speeds. 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. A summary of these and other ongoing research programs which are directed at developing the technological base for possible oblique-wing aircraft of the future is presented in reference 2. One of the most important ongoing programs is the manned flight verification of the oblique-wing concept being carried out jointly by the Ames and Dryden Flight Research Centers of NASA. In the initial flight test program, 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 concept. Later, if funding is available, a F-104 aircraft may be fitted with an oblique wing as a final validation of this concept at transonic speeds.

This report presents the results of the aeroelastic stability analysis performed in support of the AD-1 flight-test program. This study was carried out using the PASS and FLUT computer programs (refs. 3 and 4) as well as the aeroelastic analysis capability available in the MacNeal-Schwendler Corporation's NASTRAN computer program (MSC-V43). The application of this NASTRAN capability to the oblique-wing configuration served not only to substantiate the results obtained from PASS/FLUT, but also to evaluate two different flutter analysis methods available in the NASTRAN aeroelastic package — the KE-method and the PK-method.

In the initial analysis of the aeroelastic behavior of the AD-1, the oblique wing alone was considered. The entire asymmetric wing was modeled as a beam with the fuselage mass and inertia properties concentrated at the wing pivot which was allowed 3 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 analysis, ailerons were included in order to study their effects on the aeroelastic stability of the AD-1.

COMPUTER CODES

Two different computer codes were used in the aeroelastic analysis of the AD-1: NASTRAN and PASS/FLUT. NASTRAN is a large, general purpose, finite element computer program for structural analysis. The MacNeal-Schwendler Corporation's version of NASTRAN (MSC-V43) used in the present analysis has three different flutter methods implemented in its aeroelastic package: the k-method, the KE-method, and the PK-method. In addition, this version of NASTRAN contains several different unsteady aerodynamic analysis theories. Besides the Doublet-Lattice Method used exclusively in the present subsonic analysis, the Mach Box Method, Strip Theory, Subsonic Wing-Body Interference Theory, and Piston Theory are also available.

The PASS/FLUT code is actually two computer programs, a structural analysis program (PASS) and a flutter analysis program (FLUT). The PASS computer code is a program for Preliminary Aircraft Structural Synthesis and applies specifically to aircraft structures which can be adequately modeled by beam finite elements. Unlike typical finite element programs, however, the inertial and stiffness properties for the beam element used in PASS can be represented by polynomials rather than constants. This important feature of PASS enables one to obtain accurate results for nonuniform structures with but a few elements.

The FLUT computer program is used for evaluating the aeroelastic stability of aircraft structures in subsonic flow. Input data from a structural vibration analysis (e.g., output from PASS) are synthesized in FLUT with an unsteady aerodynamics analysis based on the Doublet-Lattice Method developed by Giesing, Kalman, and Rodden (refs. 5 and 6). A complex eigenvalue analysis is then performed based on the k-method of flutter solution.

METHODS OF FLUTTER ANALYSIS

The basic equation used in flutter analysis is the matrix equation of motion

$$[M]\{\ddot{q}\} + [B]\{\dot{q}\} + [K]\{q\} - \frac{1}{2}\rho V^2[Q]\{q\} = 0 \qquad (1)$$

where [M], [B], [K], and [Q] are the generalized mass, damping, stiffness, and aerodynamic matrices, respectively; {q} is the generalized displacement vector and $(1/2)\rho V^2$ is the dynamic pressure. The aerodynamic matrix [Q] is a function of reduced frequency and Mach number.

The k-Method

In the traditional American method of flutter analysis known as the k-method, an artificial structural damping parameter, g, is introduced into equation (1) which, for simple harmonic motion ($\{q\} = \{\bar{q}\}e^{i\omega t}$), can be written as

$$\left\{- \left[[M] + \frac{1}{2}\rho\left(\frac{\bar{c}}{2k}\right)^2[Q]\right]\frac{\omega^2}{1 + ig} + \frac{i\omega}{\sqrt{1 + ig}}[B] + [K]\right\}\{q\} = 0 \qquad (2)$$

where $\bar{c}$ is the reference chord length and $k = \omega\bar{c}/2V$ is the reduced frequency. The k-method of flutter analysis is an iterative procedure in which equation (2) is solved for the complex eigenvalues $\lambda = \omega^2/(1 + ig)$ for given values of reduced frequency, Mach number, and density. The damping, frequency, and velocity are then obtained from the relations

$$\left.\begin{aligned} g &= -\frac{\text{Im}\ \lambda}{\text{Re}\ \lambda} \\ \omega^2 &= (1 + g^2)\text{Re}\ \lambda \\ V &= \frac{\omega\bar{c}}{2k} \end{aligned}\right\} \qquad (3)$$

The procedure is repeated with new values of the three sets of input parameters: density ratio, Mach number, and reduced frequency. Typically in the k-method plots of V versus 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). It should be noted, however, that the solutions obtained by this method are only valid 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 the program solves for $1/\lambda$ and derives g, ω, and V from this variable. In addition, it is assumed in FLUT that no viscous damping is present; therefore, the damping matrix [B] is neglected.

The k-method in NASTRAN considers a slight variation of equation (2), namely

$$\left\{\left[\left(\frac{2k}{\bar{c}}\right)^2 [M] + \frac{\rho}{2} [Q]\right] - \left(\frac{V^2}{1 + ig}\right) + \left(\frac{2k}{\bar{c}}\right)[B] \frac{iV}{\sqrt{1 + ig}} + [K]\right\} \{q\} = 0 \qquad (4)$$

which has eigenvalues

$$p^2 = - \frac{V^2}{1 + ig} \qquad (5)$$

It is assumed in NASTRAN that the artificial structural damping, g, is small and equation (5) is approximated by

$$p = V \left(\frac{g}{2} + i\right) \qquad (6)$$

Equation (6) is then evaluated to give g, V, and ω.

The KE-method

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, that is, [B] = 0 in equation (1). In addition, the solution obtained by this method is restricted to eigenvalues only so that eigenvectors are not calculated.

The PK-method

The third method of flutter analysis implemented in NASTRAN is the British or PK-method. The NASTRAN terminology for this method was adopted from Hassig (ref. 7) who developed a variation of the British method. A description of the British method as well as a comparison with the American or k-method can be found in reference 8. This method assumes responses to be of the form

$$\{q\} = \{\bar{q}\}e^{pt} \qquad (7)$$

where p is complex. It is further assumed that the aerodynamic matrix can be divided into real and imaginary parts, that is,

$$[Q] = [Q^R] + \frac{1}{2}\left(\frac{\bar{c}}{Vk}\right) [Q^I]p \qquad (8)$$

where $[Q^R]$ and $[Q^I]$ are the aerodynamic stiffness and damping matrices, respectively.

The introduction of equations (7) and (8) into equation (1) yields

$$\left\{[M]p^2 + \left[[B] - \frac{1}{4}\left(\frac{\rho\bar{c}V}{k}\right)[Q^I]\right]p + \left([K] - \frac{1}{2}\rho V^2[Q^R]\right)\right\}\{q\} = 0 \qquad (9)$$

The solution of equation (9), which is the basic equation for modal flutter analysis by the PK-method, yields complex eigenvalues of the form

$$p = \mu + i\omega \qquad (10)$$

Equation (10) is then evaluated to give the transient decay rate coefficient

$$\gamma = \frac{1}{2\pi}\,\ell n\,\frac{a_{n+1}}{a_n} = \frac{\mu}{\sqrt{\mu^2 + \omega^2}} \qquad (11)$$

where a_n and a_{n+1} are the amplitudes of successive cycles of oscillation.

If the ratio u/ω is assumed to be small so that $\gamma \approx \mu/\omega$, then equation (10) reduces to the eigenvalue considered in NASTRAN

$$p \approx \omega(\gamma + i) \qquad (12)$$

Equation (12) is then evaluated to give ω, γ, and k. For real roots, $\omega = 0$ and the decay rate coefficient is taken to be

$$\gamma = \frac{\bar{c}p}{V\ \ell n\ 2} \qquad (13)$$

As noted in reference 7, the artificial structural damping, g, from the k- (or KE-) method can be compared with the decay rate coefficient, γ, by the relation given in reference 9

$$\frac{\mu}{\omega} \approx \frac{g}{2}\left(1 - \frac{V}{\omega}\frac{d\omega}{dV}\right) \qquad (14)$$

Then, if V and μ/ω are assumed small, equations (11) and (14) yield

$$\gamma \approx \frac{\mu}{\omega} \approx \frac{g}{2} \qquad (15)$$

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 figure 1. This 11.1 m (36.4 ft) long experimental aircraft will weigh approximately 773 kg (1700 lb) and be powered by two Ames Industrial Corporation TRS-18, 890 N (200 lb) thrust jet engines. The 142 kg (313 lb) oblique wing for this aircraft will have a

9.8 m (32.3 ft) span and an unswept aspect ratio of 11.2 (fig. 2). The 12-percent thick wing (fig. 3) will be composed of a fiberglass skin (E glass) over a foam core. This skin will consist of from 4 to 17 plys of lamina built up with a ratio of approximately one ±45° bias ply 0.030-cm (0.012-in.) thick to every three unidirectional plies 0.023-cm (0.009-in.) thick. The 25-percent 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 (figs. 4 and 5, respectively) were generated from the wing geometry and the following material properties:

$$E = 2.62\times10^{10}\ \text{N/m}^2\ (3.8\times10^6\ \text{psi})$$

$$G = 0.55\times10^{10}\ \text{N/m}^2\ (0.8\times10^6\ \text{psi})$$

$$\rho(\text{laminate}) = 1938\ \text{kg/m}^3\ (0.07\ \text{lb/in.}^3)$$

$$\rho(\text{foam}) = 32\ \text{kg/m}^3\ (2\ \text{lb/ft}^3)$$

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-percent chord and to have the following mass properties:

$$\text{Mass} = 621.1\ \text{kg}\ (42.56\ \text{slugs})$$

$$I_x = 105.5\ \text{kg-m}^2\ (77.8\ \text{slug-ft}^2)$$

$$I_y = 2683.8\ \text{kg-m}^2\ (1979.6\ \text{slug-ft}^2)$$

$$I_z = 2702.8\ \text{kg-m}^2\ (1993.6\ \text{slug-ft}^2)$$

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 to be rigid-body elements with a single rotational degree of freedom about the hinge line. 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

$$I_\beta = 0.013\ \text{kg-m}^2\ (9.7\times10^{-3}\ \text{slug-ft}^2)$$

$$K_\beta = 259\text{–}432\ \text{N-m/rad}\ (40\text{–}66.7\ \text{in.-lb/deg})$$

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

$$\omega_\beta = \sqrt{\frac{K_\beta}{I_\beta}} = 22.3\text{–}28.7 \text{ Hz}$$

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 which is essentially free.

With both the NASTRAN and FLUT programs the unsteady aerodynamic matrices were calculated using the Doublet-Lattice Method. These matrices were computed at a free-stream Mach number of $M = 0.5$ at sea level density for different values of the reduced frequency parameter k. Several rules to follow in developing an aerodynamic model using the Doublet-Lattice Method are discussed in reference 6. These rules include the requirement of at least 4 chordwise aerodynamic boxes per strip, each with an aspect ratio of one or less. As noted in reference 4, these rules tend to be conservative, particularly at low reduced frequencies. At higher reduced frequencies, however, an increased number of boxes is necessary, especially near control surface hingelines.

RESULTS AND DISCUSSION

Wing Alone

The results of the aeroelastic stability analysis of the AD-1 wing alone are summarized in figure 6 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 very noticeable change in the mode of instability occurs. For angles of sweep up to about 25°, 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 ($f \approx 4$ Hz) which is near the AD-1's lowest natural frequency ($f \approx 7$ Hz) and is considerably less than the "classical" flutter frequency ($f \approx 30$ Hz).

The change in mode of aeroelastic instability from static divergence to a low frequency flutter when rigid-body roll is allowed was originally demonstrated by Jones and Nisbet (ref. 10) using a simplified three-degree-of-freedom model. They found that the roll moment of the fuselage has an important influence on the instability speed of an oblique wing. Further studies (refs. 11 and 12) showed that there is no significant difference in flutter behavior when rigid-body plunge and pitch are also included.

Figure 7 presents a V-g diagram of the critical modes of instability for the AD-1 wing. PASS/FLUT results are shown for unswept and 45° sweep with both a clamped and a free to plunge, roll, and pitch condition at the fuselage. For 45° sweep, free to plunge, roll, and pitch, the results for the first 8 modes from a PASS/FLUT analysis are presented in figures 8 and 9. For this case the mode of primary interest is the one which exhibits an instability at approximately 163 m/sec (317 KIAS): the low-frequency flutter mode. 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 in any case.

The results presented in figures 6, 7, and 8 are qualitatively similar to results obtained for a transport aircraft design utilizing an oblique wing (ref. 12). As pointed out in reference 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, critical for sweep angles greater than about 25°, can be increased by increasing the bending stiffness of the swept forward wing only.

The damping of the low-frequency flutter mode at several different sweep angles is shown in figure 10. For sweep angles greater than about 18° this so-called "hump" mode is seen to first cross the $g = 0$ axis into an unstable range of velocities and then recross back into a stable region. The minimum flutter speed for this low-frequency mode occurs at a sweep angle of around 45°. For sweep angles less than approximately 18° this mode is seen to remain entirely stable at all velocities.

It should be noted that the 8 elastic modes presented in figures 8 and 9 appear in pairs which are associated with each half of the wing and represent the symmetric and antisymmetric behavior of the entire wing. Therefore it is important to consider, for example, 13 modes (3 rigid-body modes plus 5 pairs of elastic modes) rather than 12 modes when carrying out an aeroelastic analysis with the fuselage free to plunge, roll, and pitch.

One qualification which must be made with respect to the quantitative results presented herein for the AD-1 concerns the value of the shear modulus G. Since the torsional rigidity of the wing, GJ, is directly proportional to G, any significant change in the shear modulus will have a direct effect on the flutter results. Consider, for example, the effect of doubling the shear modulus to 1.1×10^{10} N/m^2 (1.6×10^6 psi) which would roughly correspond to the value of G for an isotropic material with the same modulus of elasticity of 2.62×10^{10} N/m^2 (3.8×10^6 psi). In particular, as shown in figure 11, the results for bending-torsion flutter, which is of interest at low sweep angles, are increased by approximately 50 percent. 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.

Finally, although the AD-1 wing planform will have a straight 25-percent chord, for convenience the elastic axis, which is at the 40.7-percent chord and very near to the wing pivot at the 40-percent chord, was assumed straight. This slight difference in planform, however, was found to have very little effect on the aeroelastic analysis.

Wing/Aileron Flutter

The aeroelastic analysis of the AD-1 wing with the aileron degree of freedom included was carried out using the NASTRAN computer code exclusively since this general purpose program readily allows for the inclusion of control surfaces and PASS/FLUT does not. The PK-method of flutter analysis was used in this study primarily because of its apparent superiority in the ordering of the modes and because it produces results directly for given values of velocity where the other methods require 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 case, however, the fuselage inertia has very little effect on the bending-torsion-aileron flutter at small angles of sweep so that the fuselage can be considered to be fully constrained and 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 does not have much effect on this mode, a very large number of aerodynamic boxes is not necessary for this condition.

Initially, an aerodynamic model with 60 boxes over each half of the wing (fig. 2(c)) was used in the aeroelastic analysis of the AD-1 wing aileron. For the oblique-wing unswept, the critical mode of instability was found to be the bending-torsion-aileron mode which gave a flutter speed of 138 m/sec (269 KIAS) at a frequency of 35.4 Hz. The reduced frequency for this condition was relatively high (>0.7), however, therefore an improved aerodynamic model with 153 boxes over half of the wing was considered. The velocity-damping diagram of the first 5 modes of this configuration is shown in figure 12 for the AD-1 wing unswept and clamped at the fuselage. The corresponding velocity-frequency diagram for this case is given in figure 13. The critical mode is the third (bending-torsion-aileron) mode which has a flutter speed of 152 m/sec (296 KIAS) at a frequency of 34.2 Hz and a reduced frequency of 0.63.

Figure 14 presents the flutter speed boundary for the AD-1 wing/aileron configuration. A comparison of this figure with figure 6 shows that the introduction of the aileron degree of freedom has significantly reduced the flutter speed of the bending-torsion mode which is the critical mode of instability for the oblique wing unswept and at small angles of sweep. As in the case of the oblique wing alone, the flutter speed for this mode increases as the wing is swept; again the critical mode changes to a low-frequency flutter mode (or a divergent mode for a clamped fuselage condition). In the present case, however, the inclusion of the aileron is seen to have a slight stabilizing effect upon this low-frequency flutter mode.

When the AD-1 wing is assumed to be clamped at the fuselage, the speed placard is seen to remain relatively constant at between about 150-160 m/sec (290-310 KIAS) as the sweep angle is increased. Allowing the fuselage the rigid-body plunge, roll, and pitch degrees of freedom result in a somewhat higher flutter boundary of about 175 m/sec (340 KIAS) at sweep angles over 30°. In addition, the transition from the bending-torsion-aileron flutter mode to the low-frequency flutter mode occurs at approximately 35° as compared with about 20° with the clamped condition.

The variation of the damping of the bending-torsion-aileron flutter mode with the aileron torsional stiffness is shown in figure 15 for the unswept AD-1 wing/aileron with a constrained fuselage. For all values of K_β considered, this mode goes unstable rapidly at velocities above 190 m/sec (370 knots). For low values of K_β this "hump" mode also becomes slightly unstable at 141-154 m/sec (275-300 knots). Even for the predicted K_β range of 259-432 N-m/rad (40-66.7 in.-lb/deg), this mode is only marginally stable at velocities as low as 116-129 m/sec (225-250 knots). As shown previously for the AD-1 wing alone, however, the stability of the bending-torsion-aileron mode is strongly influenced by the wing's torsional rigidity. Thus by using a material for the wing's skin with a higher shear modulus, the velocity at which flutter occurs can be increased.

Comparison of Methods

The aeroelastic results obtained for the AD-1 wing alone using PASS/FLUT are in excellent agreement with those obtained using the KE-method in NASTRAN. The NASTRAN results, however, were obtained at roughly four times the computer cost. This difference in expense is due to the fact that NASTRAN was specifically designed to treat large problems with many degrees of freedom, whereas the less cumbersome PASS/FLUT program was developed as a preliminary design tool for structures which can be modeled by beam elements. These beam elements in PASS/FLUT also have the advantage of allowing for a polynomial representation of the inertial and stiffness properties so that accurate results can be achieved for nonuniform structures with very few elements.

One important requirement in the use of the FLUT program is that the structural modes must be placed at the centers of the aerodynamic boxes. This limitation is not present in NASTRAN which interpolates between the structural and aerodynamic degrees of freedom using the theory of splines. This would seem to be a worthwhile improvement which could be made to FLUT. In addition, as mentioned in the preceding section, PASS/FLUT cannot readily handle a wing/control surface interaction problem whereas NASTRAN can. However, since the Doublet-Lattice aerodynamics package contained in FLUT is basically the same as that in NASTRAN, it would appear that with some slight modifications FLUT could be adopted to analyze this type of configuration also.

A comparison of the results obtained using the PK- and KE-methods of flutter analysis in NASTRAN indicates very good agreement in general, however, significant differences can occur. As shown in figure 16 for the

AD-1 wing alone at 45° sweep, the low-frequency flutter modes for the free to plunge, roll, and pitch case are quite similar for the two methods. In contrast, the results obtained for the clamped divergence mode are quite different. While the V-g plot obtained with the KE-method exhibits what might be termed typical behavior, the comparable $V-2\gamma$ result with the PK-method consists of two distinct branches. The first branch shows the damping increasing rapidly with velocity to very large values. This branch can be compared directly with the result from the KE-method by means of equation (14) applied to the $V-\omega$ data from figure 17. The second branch, however, which returns from very large to moderate values of damping before crossing the $2\gamma = 0$ axis, cannot be directly related with KE-method results since it was obtained by means of an empirical relation, equation (13).

The difference between the eigenvalues obtained by the two flutter methods can be readily seen in the root locus plot of figure 18. For the PK-method the real and imaginary parts of the complex eigenvalue, p, are plotted directly. The results from the KE-method, on the other hand, are plotted for comparison as a locus of points which have an imaginary value equal to ω and an angle $\theta = \sin^{-1} g/2$ measured counterclockwise from the imaginary axis. With the rigid-body plunge, roll and pitch degrees of freedom included, the eigenvalues for the two methods both initially indicate damped oscillations and then a change to undamped oscillations at some critical velocity. For the clamped condition, however, the behaviors predicted by the two methods are quite different. Again both methods indicate solutions which start off with damped oscillations. With the KE-method these damped oscillations continue until both the damping and the frequency go to zero at the origin which indicates divergence. With the PK-method, however, there is a transition to a nonoscillatory transient response which is first convergent and then, above some critical speed, becomes divergent.

Although in NASTRAN the PK-method is approximately twice as costly to run as the KE-method, the roots obtained by the PK-method appear to be more well ordered than with the KE-method. This is especially true when the modal frequencies of interest are close together (e.g., fig. 9) which can lead to confusion in the interpretation of results. While this lack of order usually does not seriously impair the evaluation of flutter points, it can lead to a great deal of frustration when V-g (or $V-2\gamma$) curves are desired. With both methods the ordering of the modes can be improved by increasing either the number of velocities or reduced frequencies as appropriate. An additional advantage of the PK-method over the KE-method (or k-method) is that results are obtained directly for given values of velocity with this method whereas the other methods require interpolation.

Finally, although both methods predict the same flutter speed, the damping given by γ in equation (12) appears to be a better approximation to the decay rate than the parameter g in equation (6). Thus, the PK or British method of flutter analysis is felt to offer more realistic estimates of damping than does the American method (ref. 13), which in some cases can yield subcritical predictions which are very misleading (ref. 14).

CONCLUSIONS

In the aeroelastic analysis of the AD-1 manned oblique-wing aircraft, coupled wing/aileron flutter as well as wing-alone flutter were considered. 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 primarily between the bending and the rigid-body roll degrees of freedom. This mode of instability is comparable to that found for the divergence of swept forward wings but at a higher critical speed. These wing-alone results are qualitatively similar to results previously obtained for the design of an oblique-wing transport aircraft.

The introduction of the aileron degree of freedom to the AD-1 aeroelastic analysis had a slight stabilizing effect on the low-frequency flutter mode; such an effect is important when the oblique wing is swept. Of primary significance, however, was the bending-torsion-aileron mode of instability which occurred at a considerably lower speed than the classical bending-torsion flutter. Consequently, the critical instability for the AD-1 wing was bending-torsion-aileron flutter which occurred with the oblique wing unswept.

For the aeroelastic analysis of the AD-1 wing alone, the PASS/FLUT program was a very useful and comparatively inexpensive tool for predicting flutter speeds. The inclusion of the ailerons degrees of freedom, however, necessitated the use of the much larger and more general NASTRAN program. Of the different flutter analysis methods available in the NASTRAN aeroelastic package, the PK-method proved to be much preferred since it gives results directly for given velocities and also seems to yield better ordered solutions.

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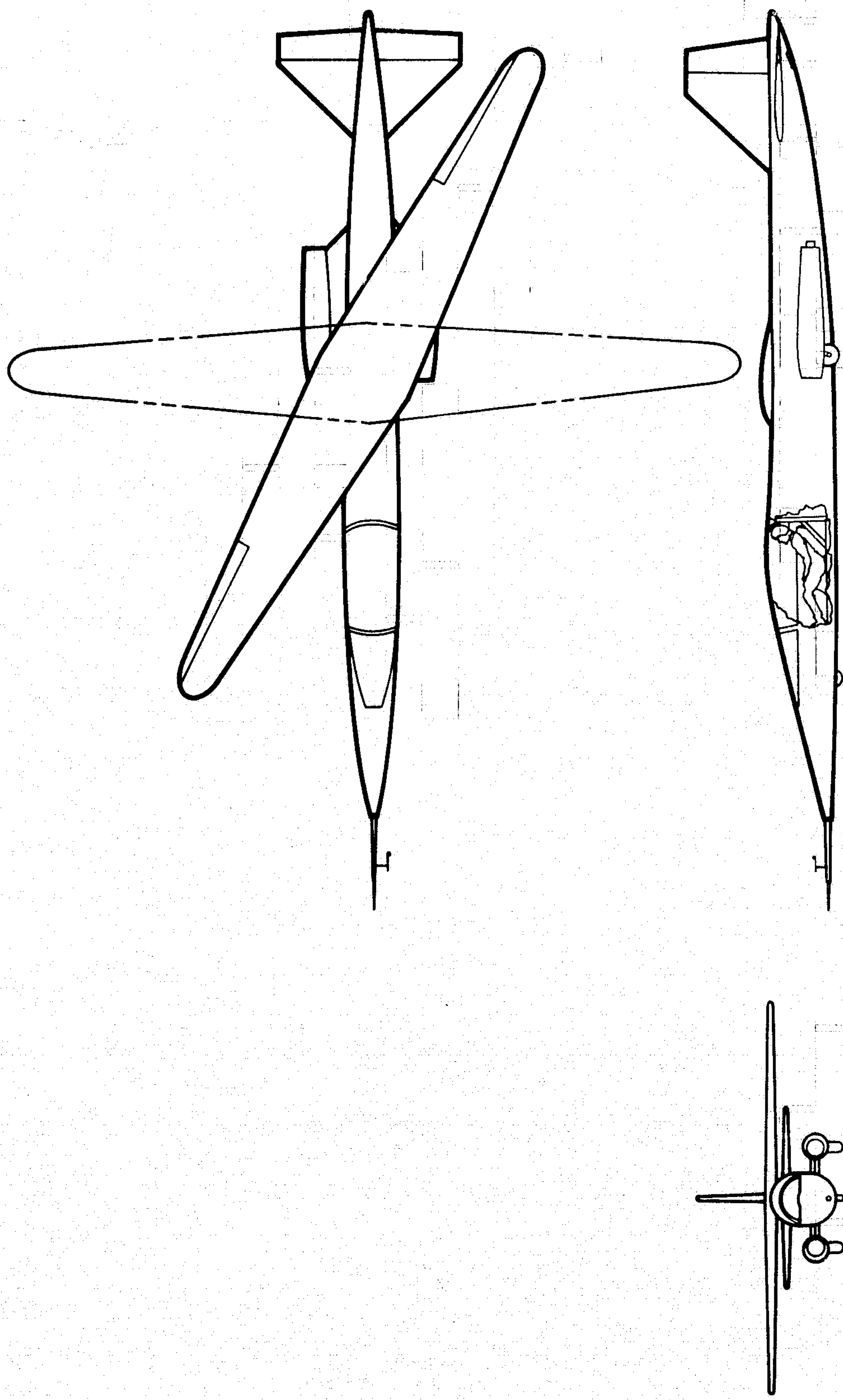
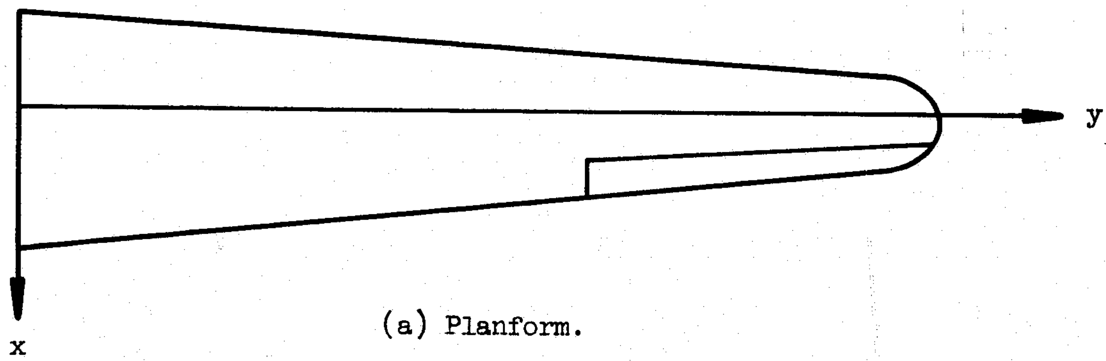
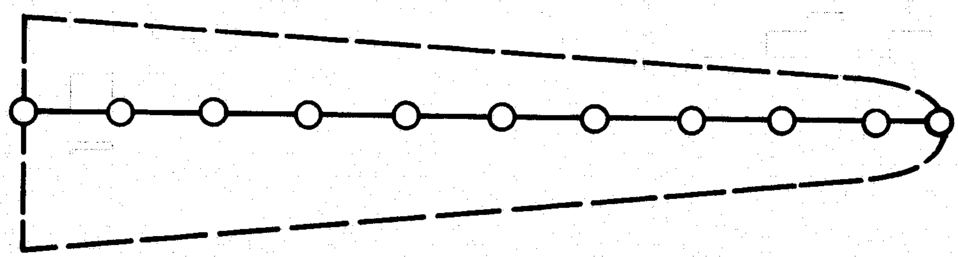


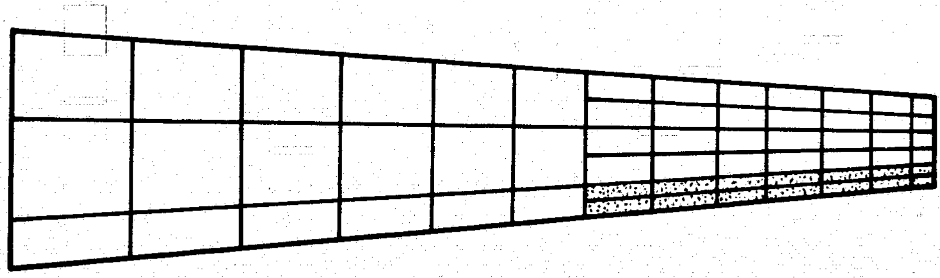
Figure 1.- AD-1 Oblique Wing research aircraft.



(a) Planform.

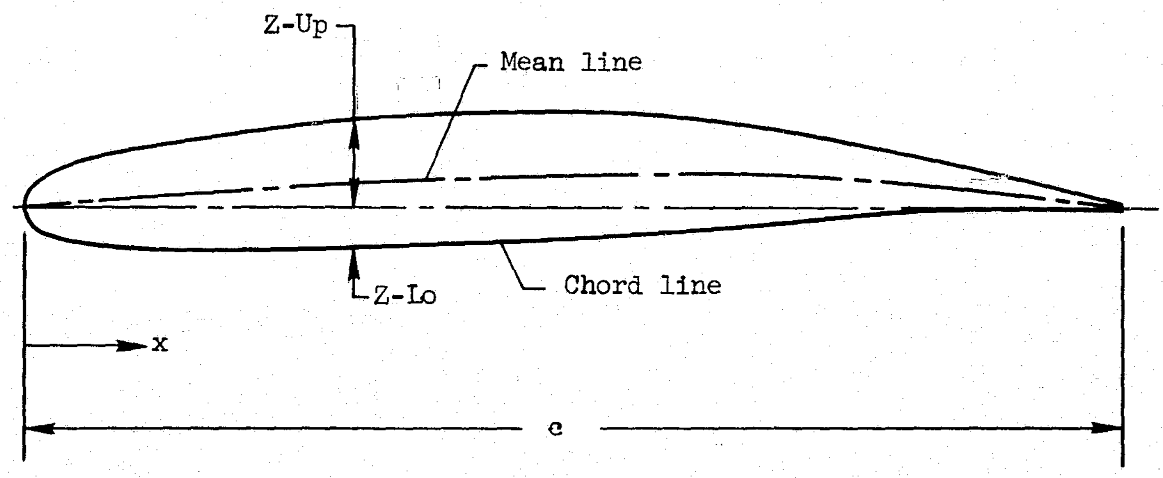


(b) Structural model.



(c) Aerodynamic model.

Figure 2.- AD-1 wing/aileron model.



x/c	t/c	Camber/c	Z-up/c	Z-lo/c
0.001	0.01444	0.00008	0.00730	-0.00714
0.010	0.04072	0.00078	0.02114	-0.01958
0.025	0.05819	0.00195	0.03104	-0.02715
0.050	0.07343	0.00389	0.04060	-0.03282
0.075	0.08269	0.00582	0.04716	-0.03553
0.100	0.08934	0.00772	0.05239	-0.03695
0.150	0.09899	0.01144	0.06093	-0.03806
0.200	0.10622	0.01498	0.06808	-0.03813
0.300	0.11625	0.02129	0.07942	-0.03683
0.400	0.11997	0.02621	0.08619	-0.03378
0.500	0.11571	0.02925	0.08711	-0.02861
0.600	0.10263	0.02995	0.08127	-0.02136
0.700	0.08144	0.02785	0.06856	-0.01287
0.800	0.05467	0.02246	0.04980	-0.00487
0.900	0.02687	0.01334	0.02677	-0.00009
1.000	0.00456	0.00000	0.00228	-0.00228

$$\frac{\text{L.E. radius}}{c} = 0.0288$$

Figure 3.- AD-1 12-percent thick wing section geometry.

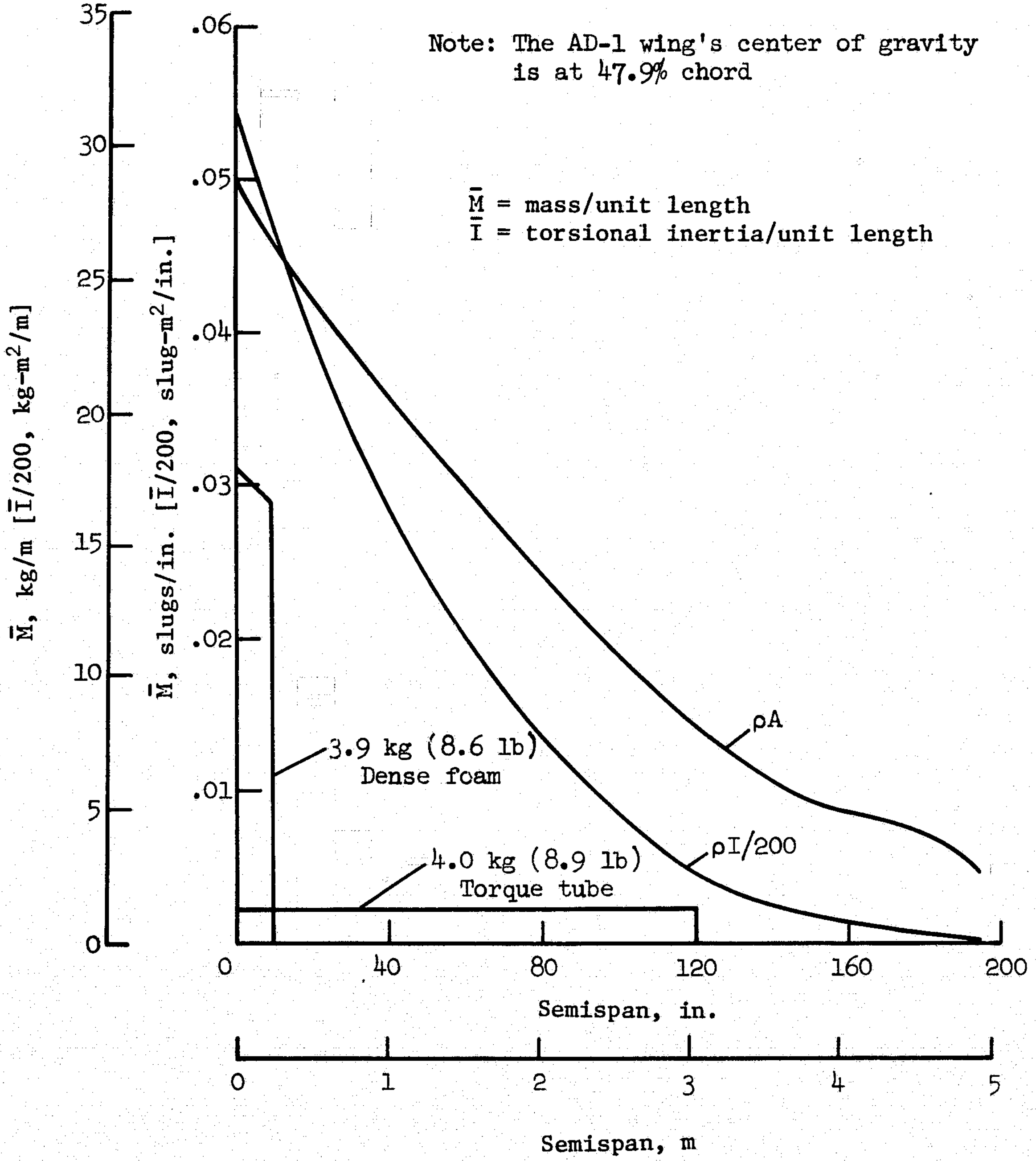


Figure 4.- AD-1 wing mass properties.

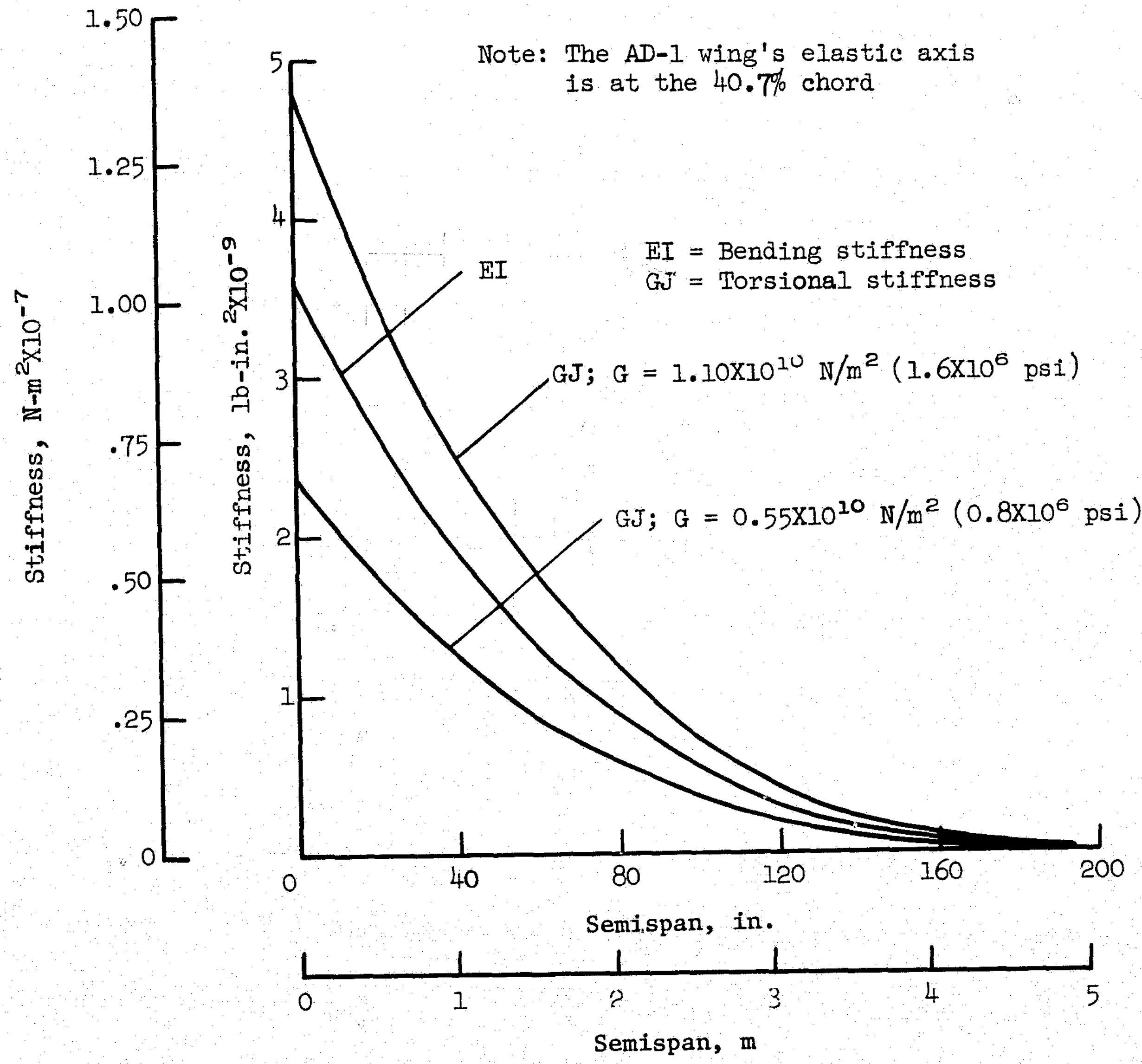


Figure 5.- AD-1 wing stiffness properties.

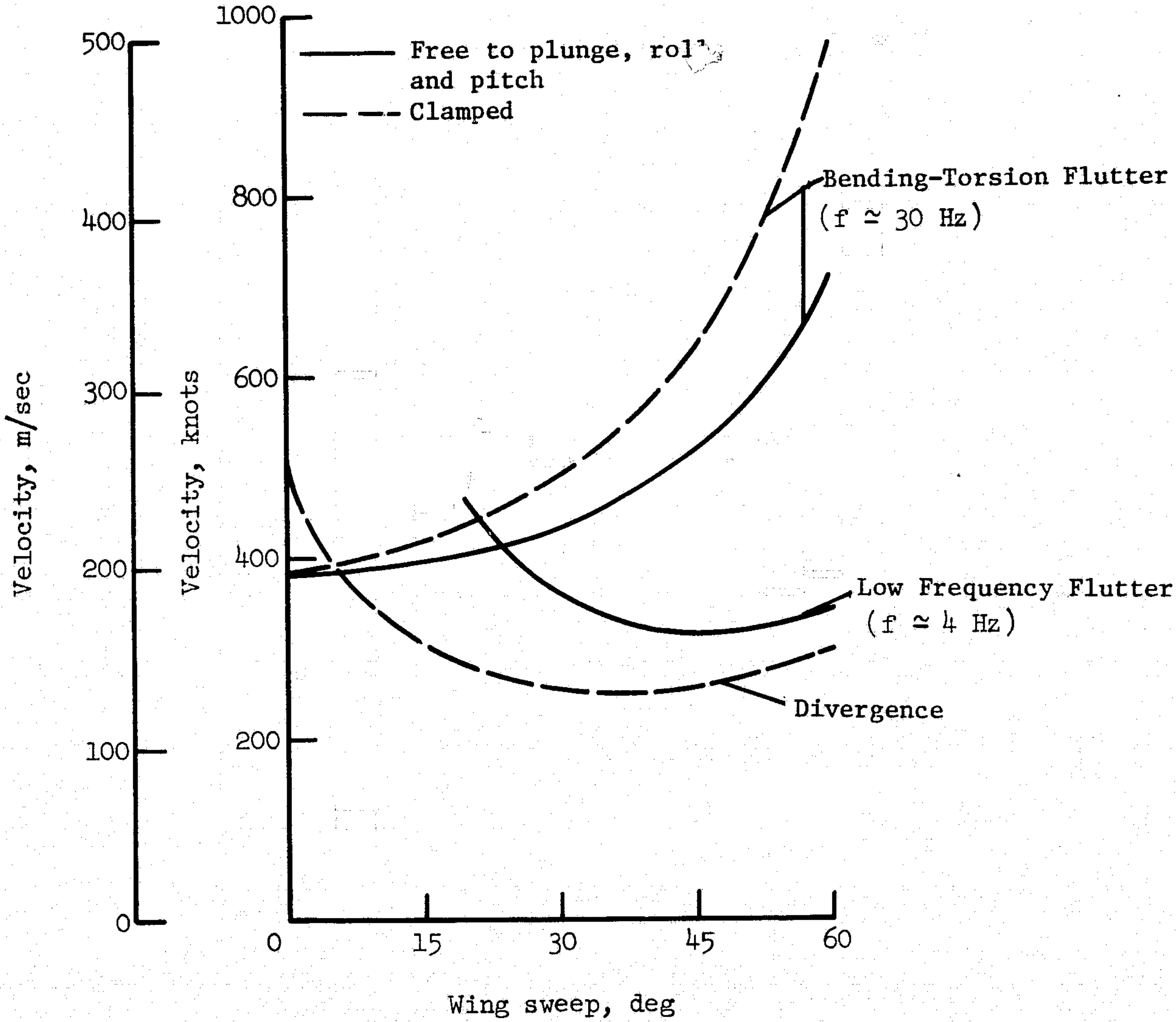


Figure 6.- AD-1 wing flutter speed boundary.

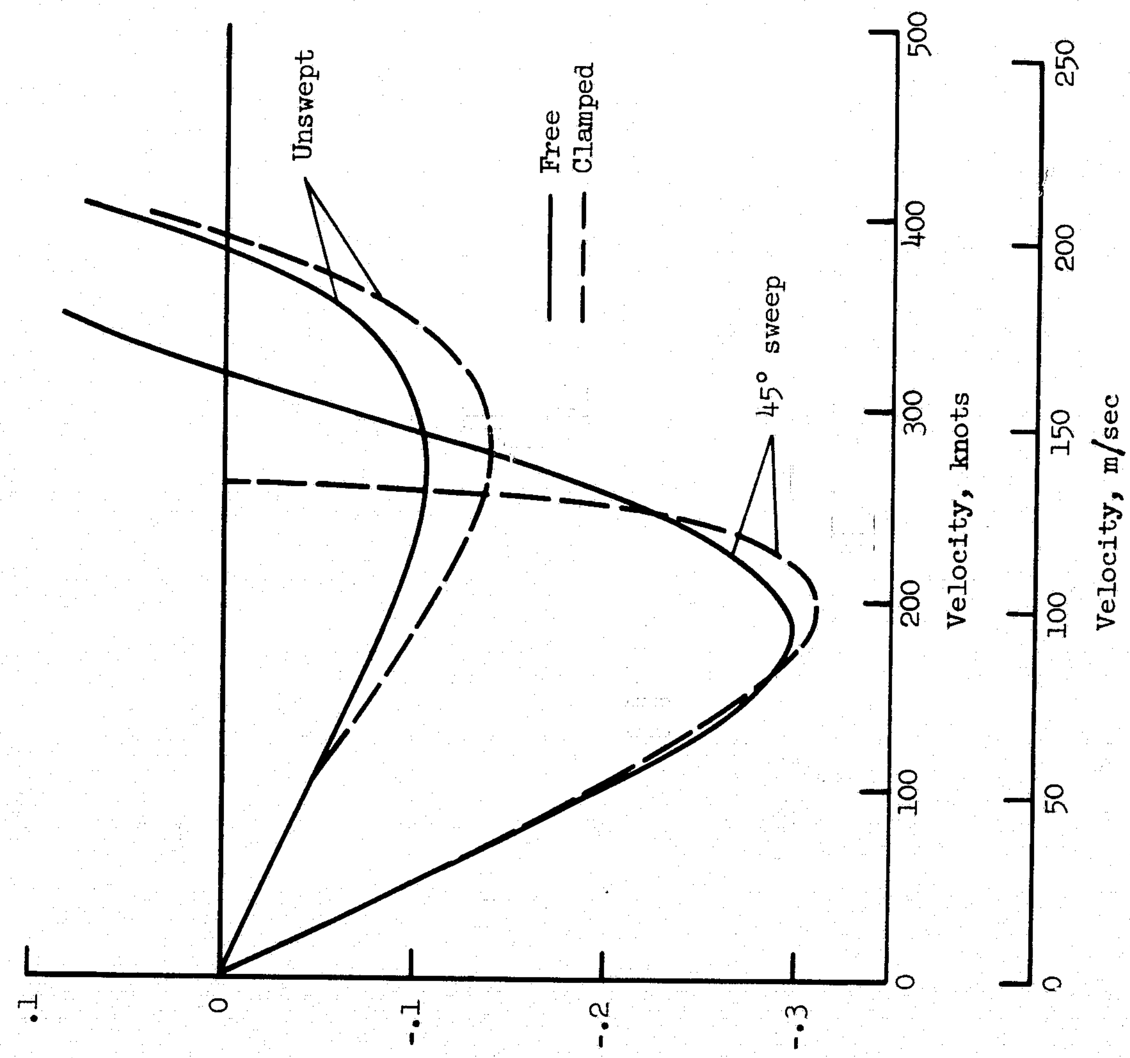


Figure 7.- AD-1 wing critical modes, V-g diagram.

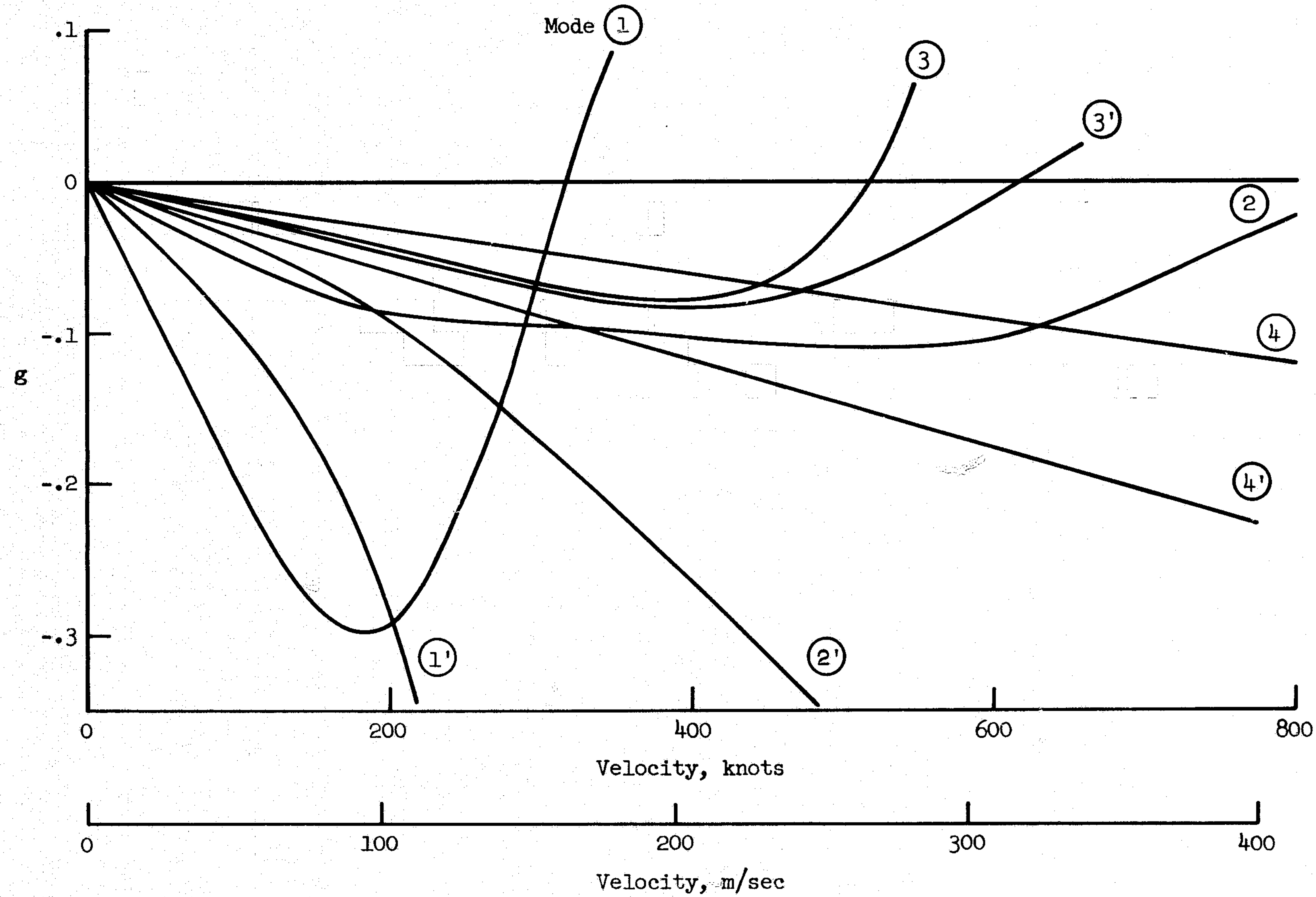


Figure 8.- AD-1 wing, 45° sweep, free to plunge, roll, and pitch, V-g diagram.

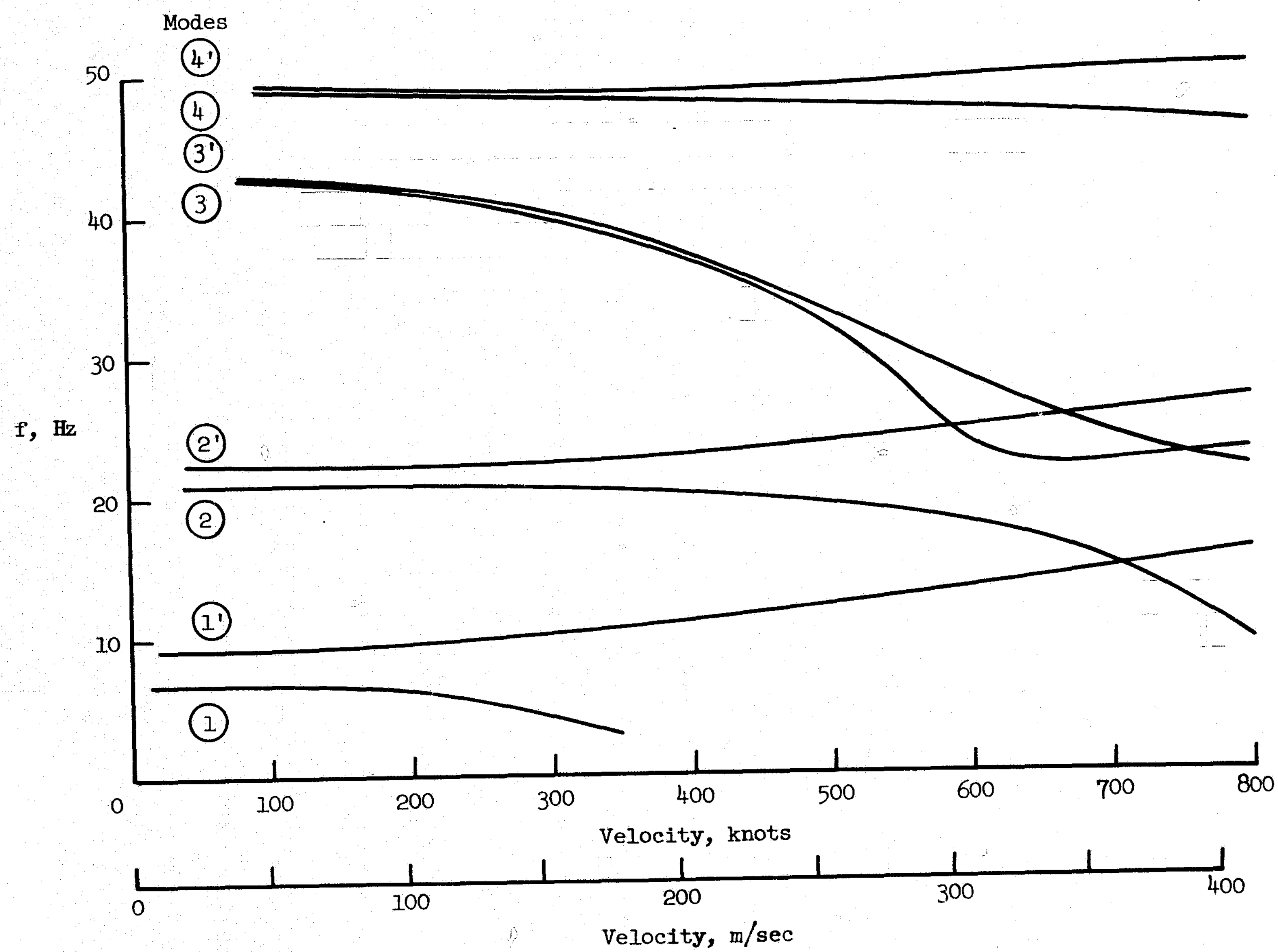


Figure 9.- AD-1 wing, 45° sweep, free to plunge, roll, and pitch, V-f diagram.

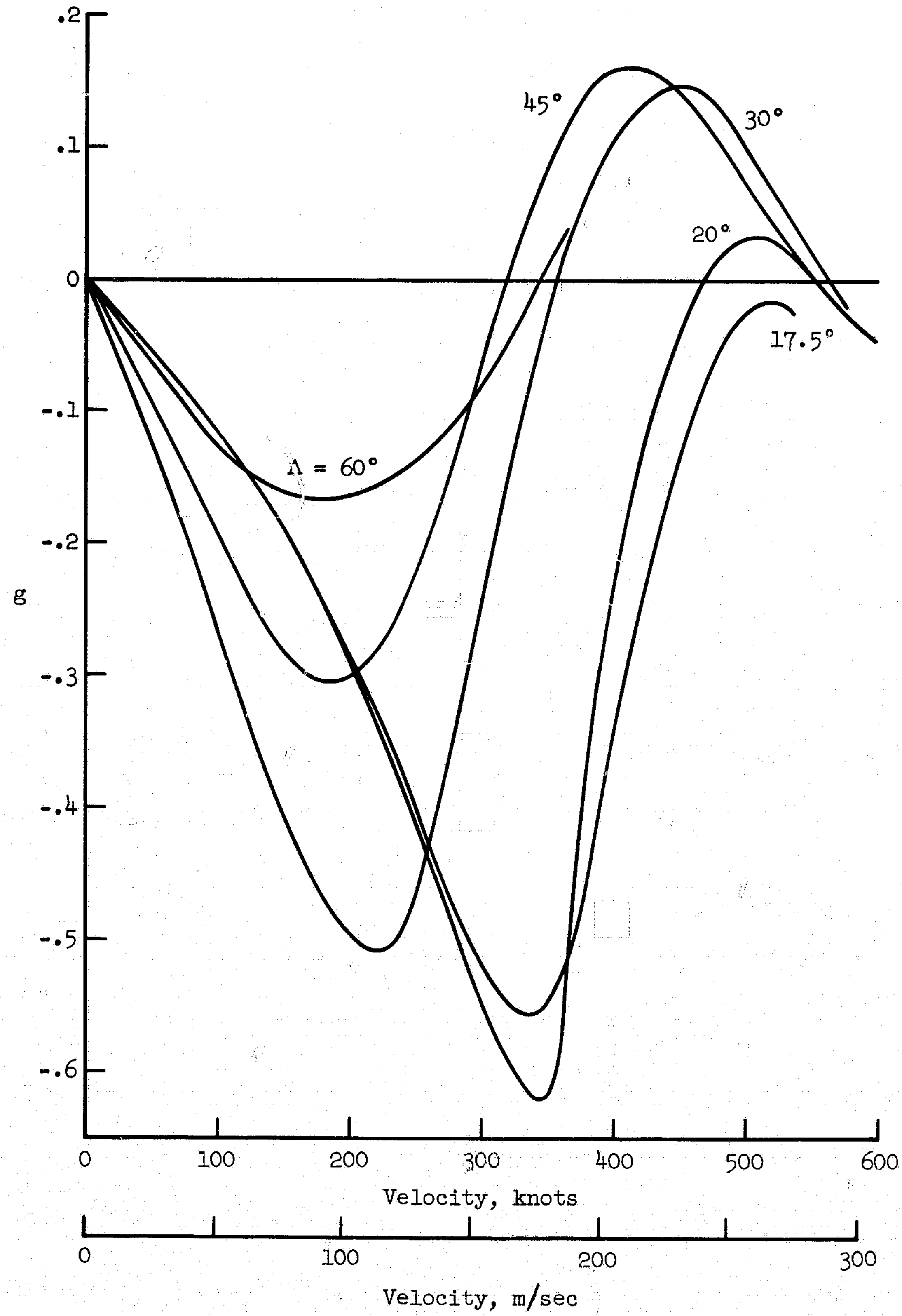


Figure 10.- AD-1 wing low-frequency flutter mode, V-g diagram.

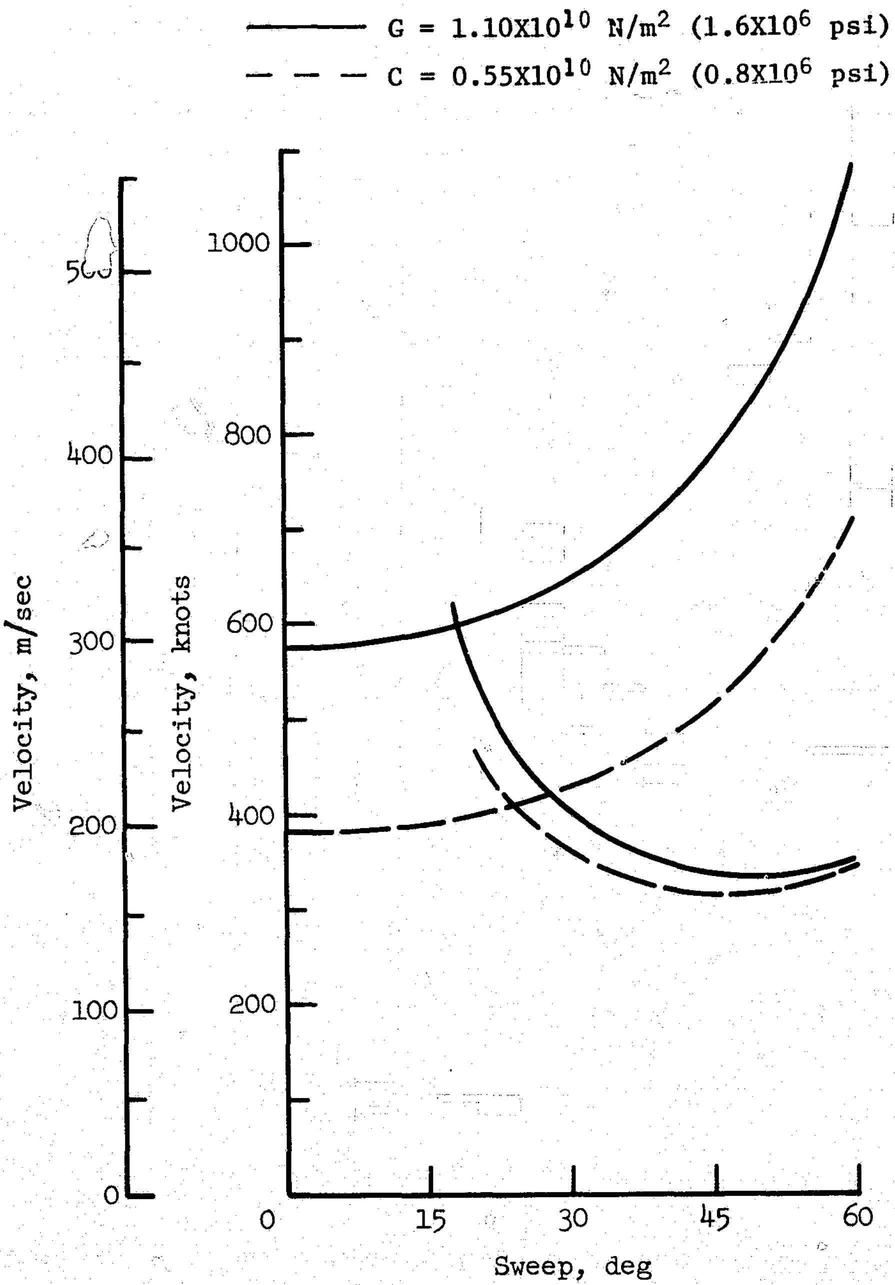


Figure 11.- Effect of shear modulus on AD-1 wing flutter speed.

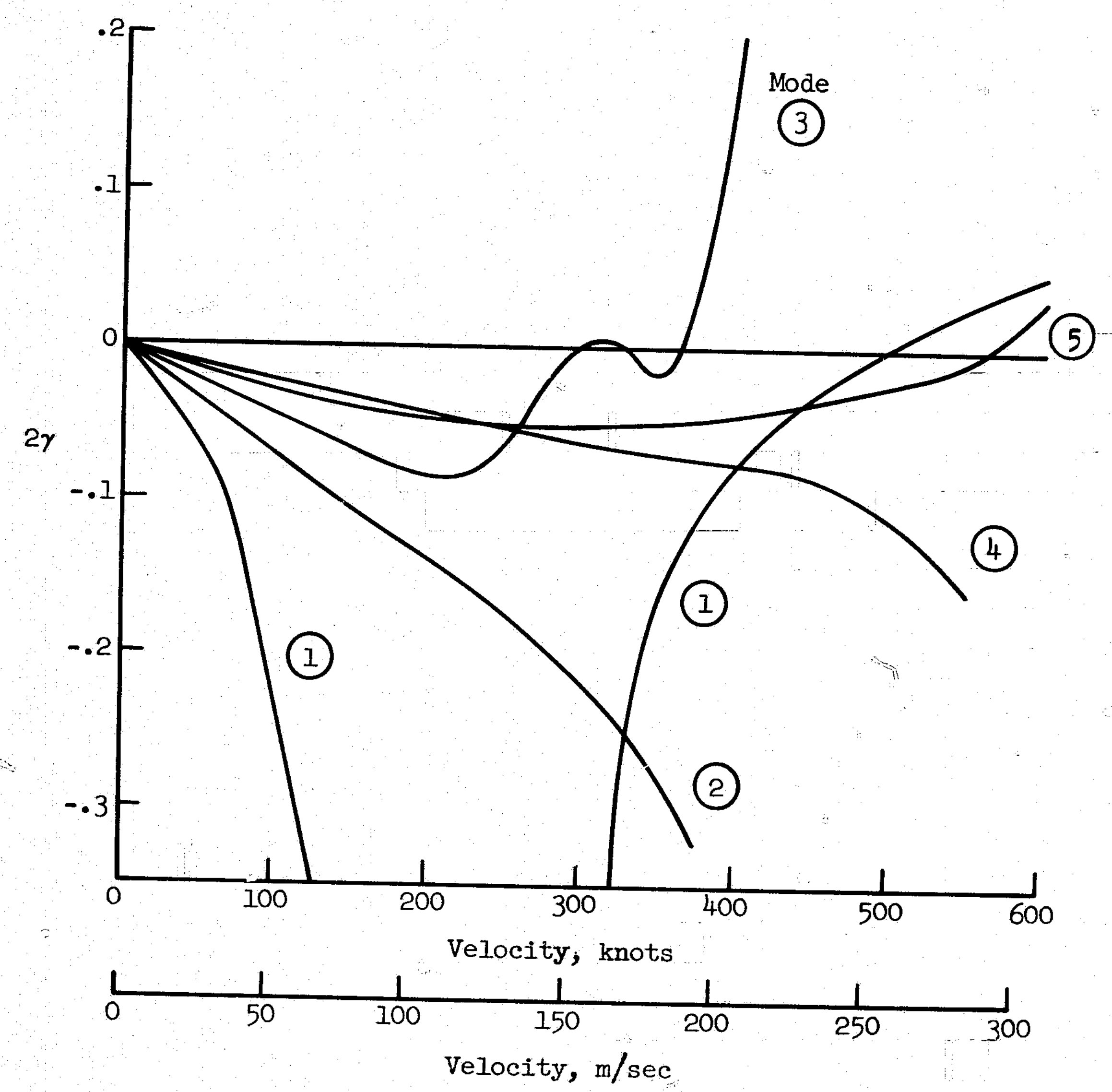


Figure 12.- AD-1 wing/aileron, unswept, clamped, V-2γ diagram.

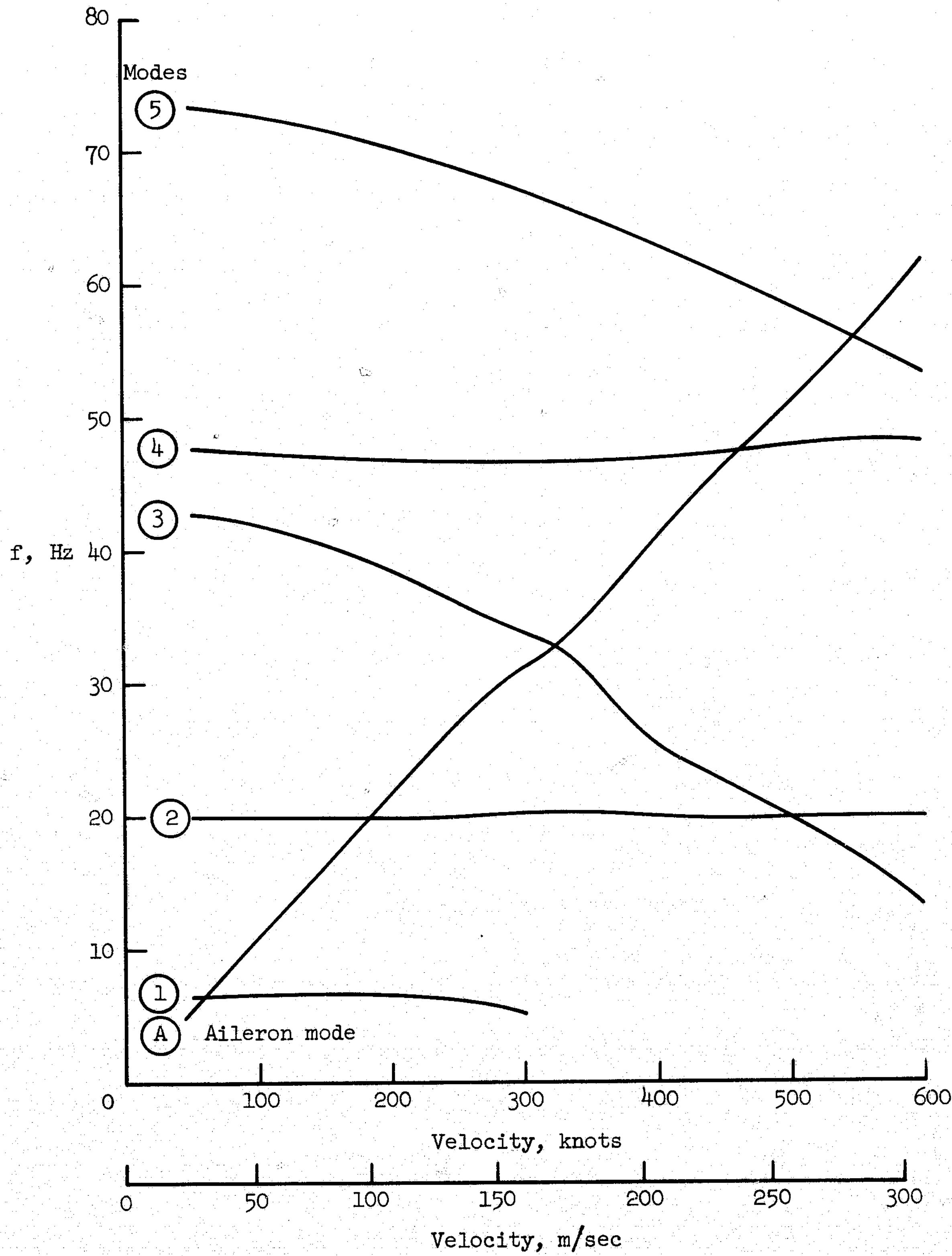


Figure 13.- AD-1 wing/aileron, unswept, V-f diagram.

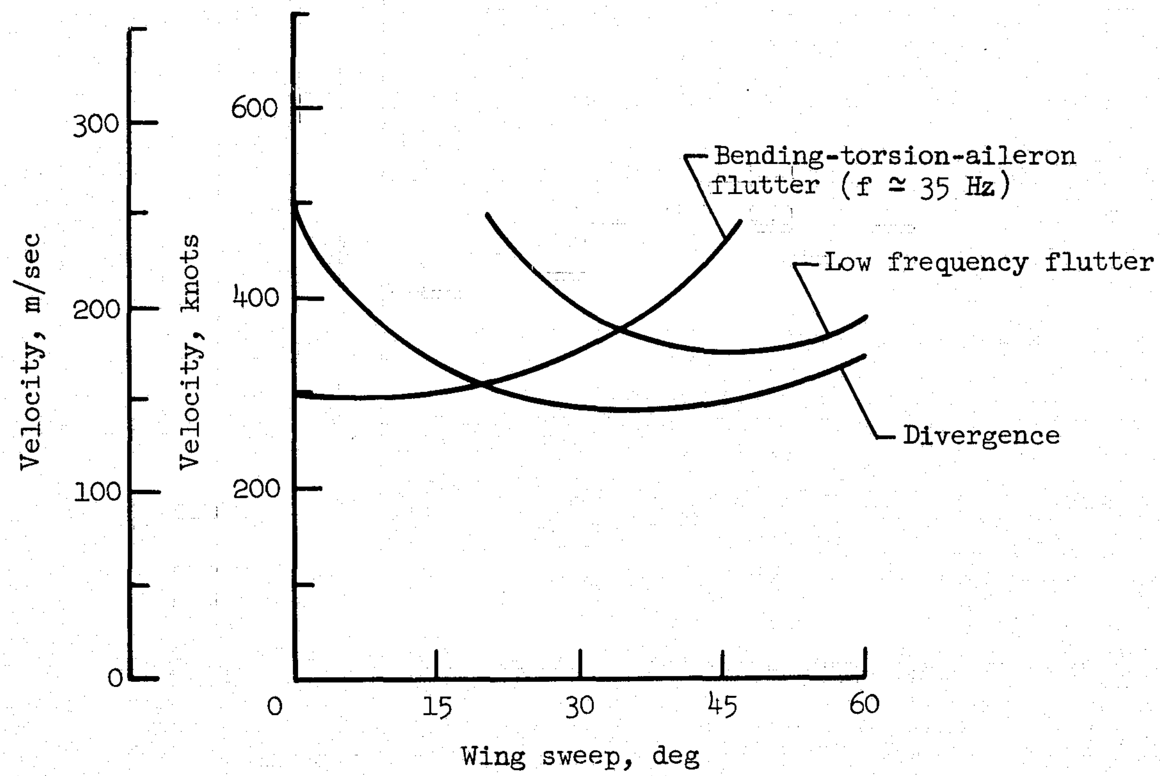


Figure 14.- AD-1 wing/aileron flutter speed boundary.

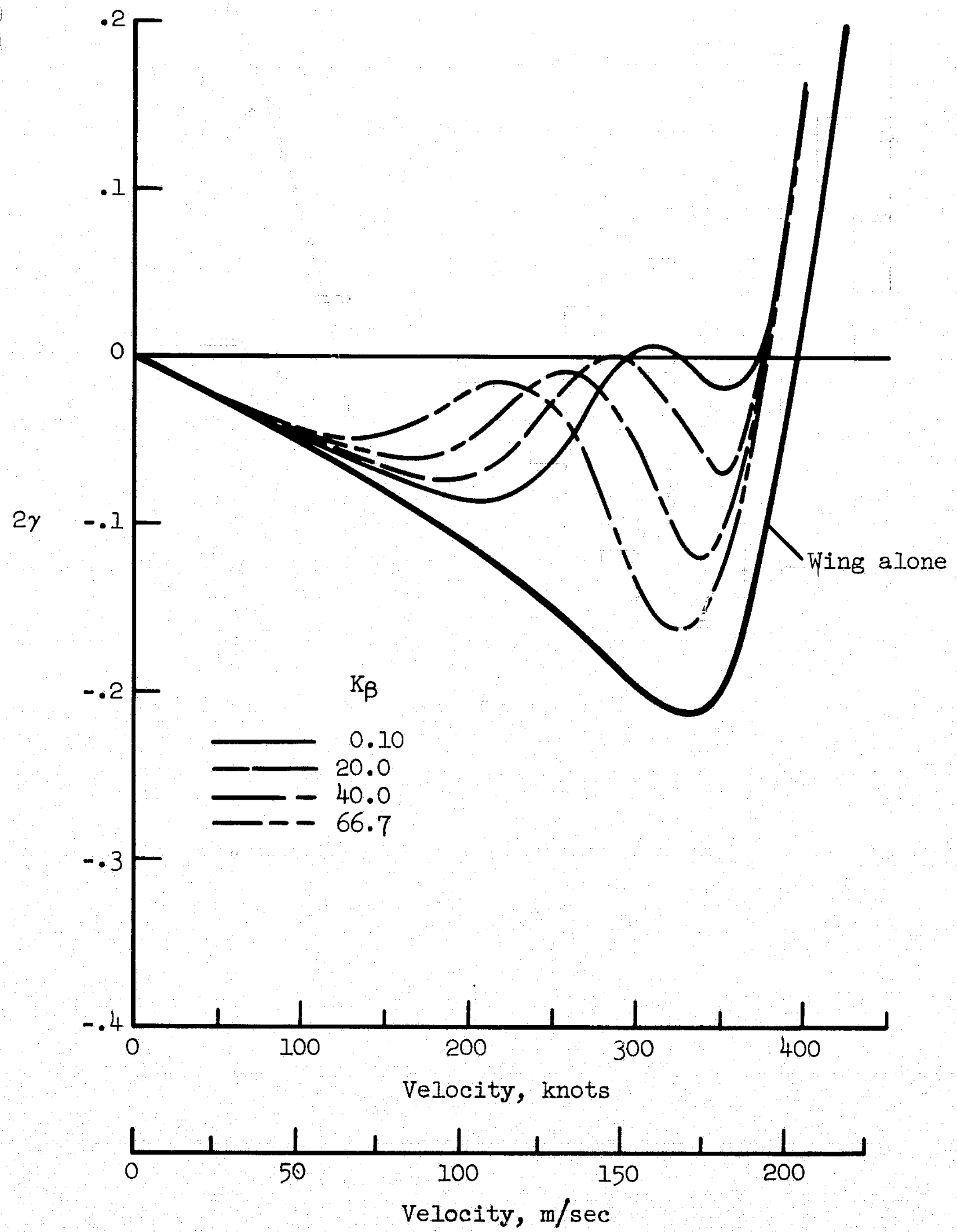


Figure 15.- Variation of bending-torsion-aileron flutter mode with K_β.

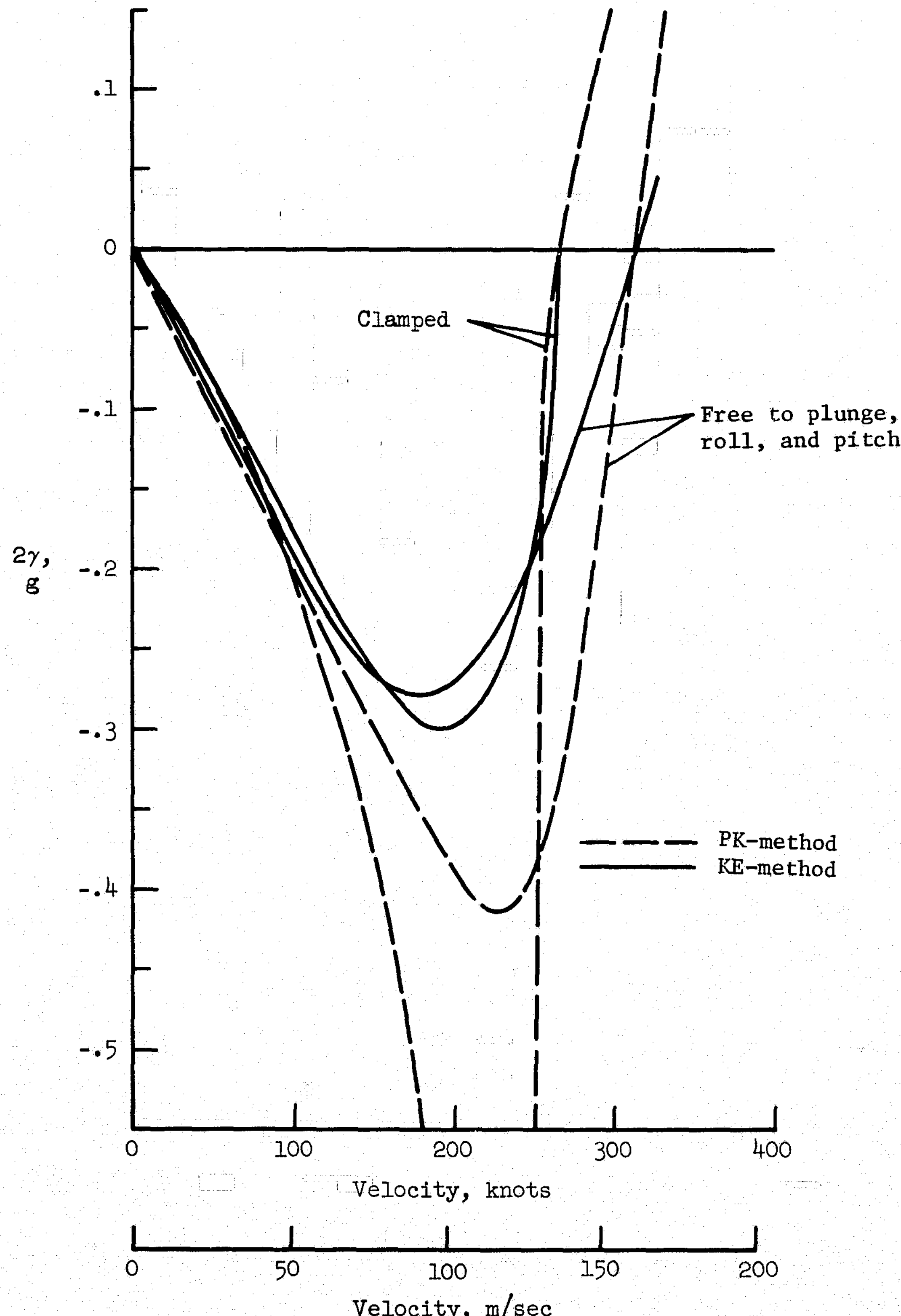


Figure 16.- Comparison between PK-method and KE-method for AD-1 wing at 45° sweep, velocity-damping diagram.

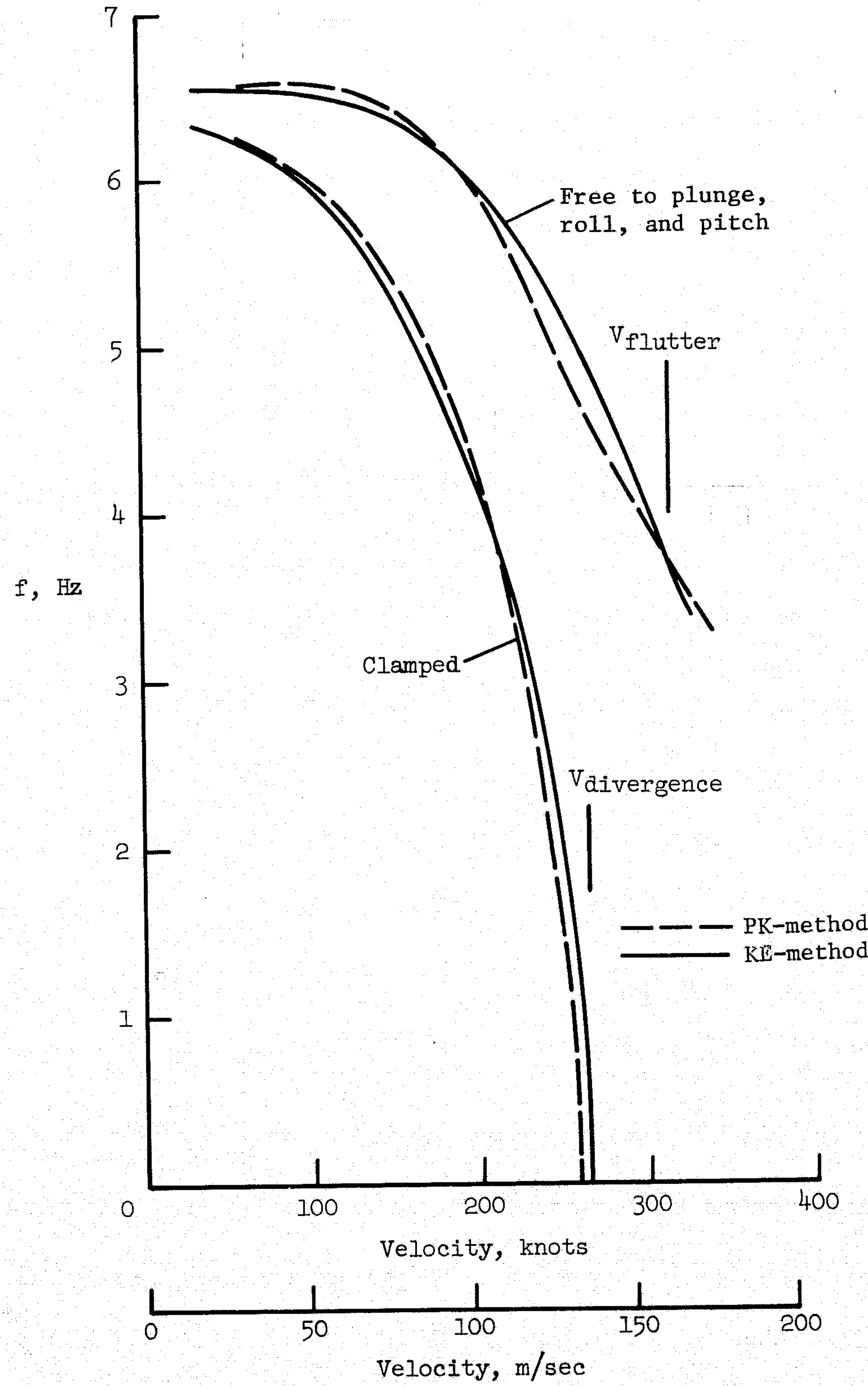


Figure 17.- Comparison between PK-method and KE-method for AD-1 wing at 45° sweep, V-f diagram.

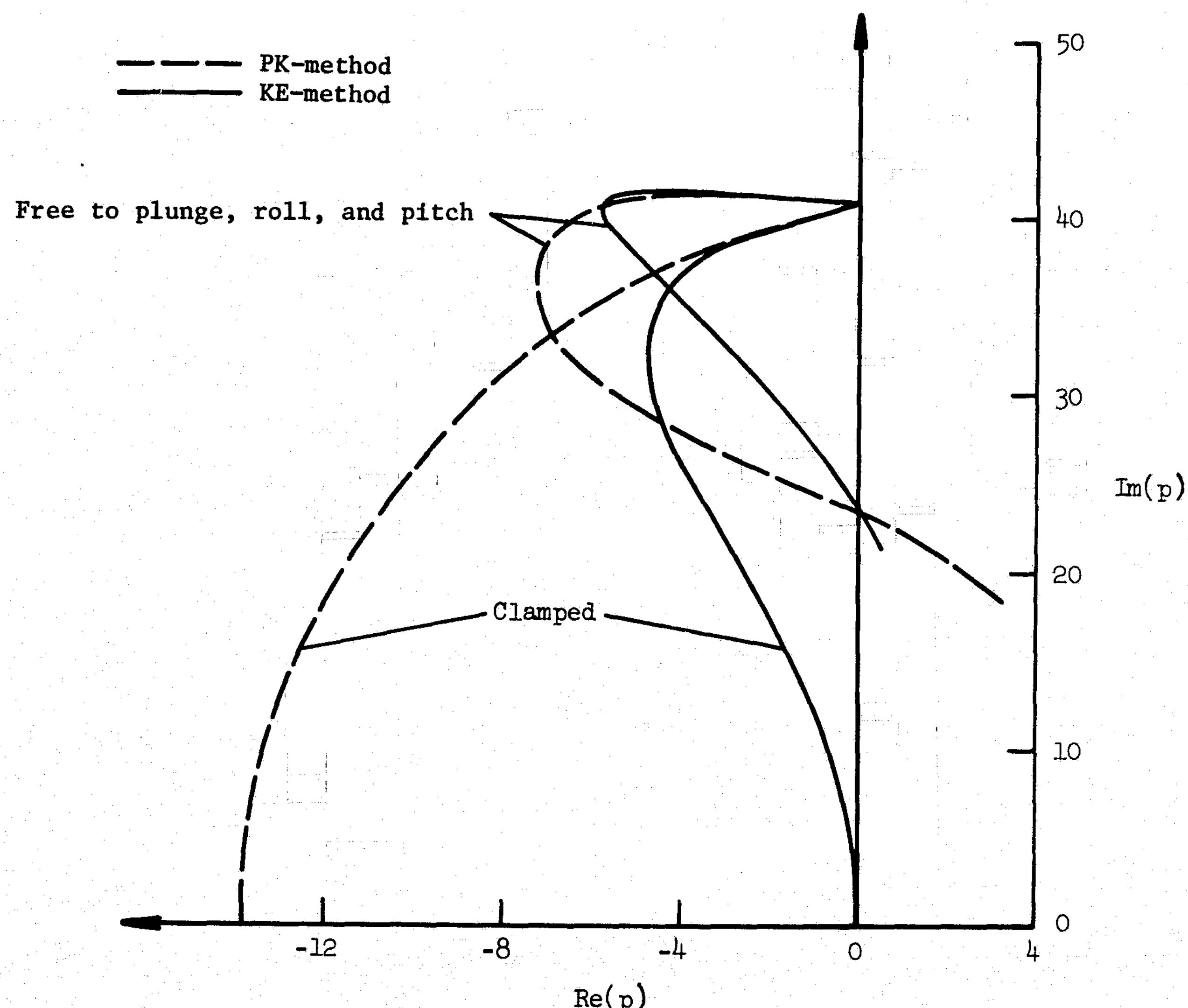


Figure 18.- Comparison between PK-method and KE-method for AD-1 wing at 45° sweep, root-locus diagram.

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15. Supplementary Notes

*National Research Council Postdoctoral Research Associate.

16. Abstract

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 and 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 both the wing alone and the wing with ailerons. In addition, a comparison is made between the results obtained using the traditional k-method of flutter analysis and the results using the PK or British method of flutter analysis. These studies were performed using the latest version of the NASTRAN computer code as well as the Ames program PASS/FLUT.

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