Engineering Notes

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The Role of Structural and Aerodynamic Damping on the Aeroelastic Behavior of Wings

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Introduction

ONE of the most important and interesting aspects of the theory of stability of elastic systems subjected to nonconservative forces relates to damping effects. In the early days of the flutter era, attempts were made to prevent flutter by the introduction of artificial damping. It was thought that since damping absorbed energy, it could provide a relatively simple means of passive flutter suppression. However, calculations and subsequent wind tunnel tests have shown that damping could not be relied on as a flutter preventive.

Usually, structural damping is omitted from the modal analysis of flutter because it is very difficult to assess the magnitude of damping in the structure and the complexity of the solving procedure in the computation phase. Thus, it is usually assumed that damping has a negligible influence on the flutter speed of the system.

The influence of structural damping on the stability behavior of the system is closely related to the way the aerodynamic forces are modeled in the analysis. Adopting an extreme simplification of the aerodynamic forces, Rocard[1] and Pines[2] have suggested that flutter of a multi-degree-of-freedom system can be explained by entirely discarding aerodynamic energy dissipation (applying steady aerodynamics). Evidently, for an undamped system, instability is associated with merging of the aeroelastic modes. This coalescence must occur at the critical (flutter) speed due to the fact that the coefficients of the governing equations are real. At a speed greater than the critical speed, the frequencies became complex conjugates, one decaying and the other divergent. It was shown[1,3] that adding certain types of damping is always destabilizing, in the sense that it reduces the airspeed at which instability will occur. It should be mentioned that with damping present, the frequencies do not merge by the time the stability boundary is reached (the coefficients of the governing equations are not real anymore).

As mentioned, the instability behavior of the system is affected by the unsteady aerodynamic model incorporated in the analysis. Dugundju[4] studies the effect of a quasi-steady aerodynamic model on an incompressible bending-torsion flutter analysis. It was shown that in certain conditions, the quasi-steady aerodynamic theory gives a fair estimate of the flutter speed as obtained applying nonsteady aerodynamic model. Many researchers use the quasisteady aerodynamic for investigating the instability behavior of the system without assessing the effect of neglecting the unsteadiness of the wake on their results. This note will demonstrate the significant influence the unsteadiness of the wake has on the flutter speed of the system. Another topic studied is the influence of structural damping on the flutter speed as related to the aerodynamic damping modeled by the aerodynamic air forces incorporated in the analysis.

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Analytical Model

This analysis considers a high-aspect-ratio rectangular wing idealized by a box beam, as considered by Ref. 5. Following the complex stiffness concept for structural damping[6] of an oscillating system, the nondimensional partial differential equations of motion are as follows (see Ref. 5):

$$\left(1+\frac{\eta_e}{\sigma}\frac{\partial}{\partial\tau}\right)\frac{\partial^4 h}{\partial\eta^4}+\frac{\partial^2 h}{\partial\tau^2}+x_\alpha\frac{\partial^2\alpha}{\partial\tau^2}+Q(L_h h+L_\alpha\alpha)=0$$

$$-x_\alpha\frac{\partial^2 h}{\partial\tau^2}-g_\theta\left(1+\frac{\eta_G}{\sigma}\frac{\partial}{\partial\tau}\right)\frac{\partial^2\alpha}{\partial\eta^2}+I_\theta\frac{\partial^2\alpha}{\partial\tau^2}$$

$$-Q(M_h h+M_\alpha\alpha)=0 \qquad (1)$$

where $\eta=y/1$ and $\tau=\sqrt{EI_b/m1^4}\ t$ are the nondimensional spanwise coordinate and time.

The nondimensional parameters in Eqs. (1) are $x_\alpha=X_\alpha/b$, center of mass offset from its elastic axis; $g_\theta=g_\alpha(Æ)^2$ $(g_\alpha=GJ/EI_b)$, the torsional stiffness; $I_\theta=I_\alpha/mb^2$, sectional mass moment of inertia about its elastic axis; m, wing mass per unit span; $Q=\pi\rho v^2 1^4/EI_b$, aerodynamic nondimensional force coefficient. Here 1 stands for wing semispan and b is its semichord, EI_b is the beam bending stiffness, and $Æ=1/b$ is the aspect ratio of the wing. The expressions L_h, L_α, M_h, and M_α stand for aerodynamic coefficients that will be subsequently defined. η_e and η_G are the structural damping coefficients for the bending and torsional modes, respectively.

The boundary conditions for the fixed-root cantilevered wing and the general procedure for computing the flutter speed of the system are outlined in Ref. 5. The fixed-root cantilevered wing of Goland.[7,5] is taken as a basis for the present investigation.

Many useful conclusions can be drawn from close examination of the idea of computing the critical velocity of the system by frequency coalescence. To get this type of flutter, one has to entirely discard aerodynamic dissipation, as was done by Rocard[1] and Pine.[2] This means that the aerodynamic forces have to be simulated by steady-state aerodynamics, hence,

$$L_h=0,\quad L_\alpha=2,\quad M_h=0,\quad M_\alpha=2a_2 \qquad (2)$$

where $a_2=1/2+a$ is the distance between the wing's axis of rotation and the aerodynamic center (it is usually referred to as e). As stated in Ref. 5, to solve the differential equations [Eq. (1)] subject to the boundary conditions of the problem, solutions of the following form is assumed:

$$h/b=He^{r\eta}e^{\sigma\tau},\qquad \alpha=Ae^{r\eta}e^{\sigma\tau} \qquad (3)$$

where $\sigma=\delta+i\omega$, δ is the damping, and ω is the frequency of the oscillating wing (assumed real).

Figure 1 shows the variation of the frequencies and damping of the first bending and torsional modes vs the nondimensional velocity of the airflow ($u=v/v_{\rm ref}$ where $v_{\rm ref}=400$ mph). It is seen that until $u_f=0.571$, the damping of the modes is zero (due to the fact that the coefficients of the governing equations are real) and then the frequencies of the modes coalesce at $u = u_f$. For $u > u_f$ the frequencies become complex conjugates where one decays and the other diverges (flutters). To introduce a light aerodynamic damping, the noncirculatory terms of the air forces are incorporated in the analysis. The aerodynamic forces for this simulation are as follows:

$$L_h = k^2, \quad L_\alpha = k - ak^2 + 2, \quad M_h = ak^2$$

$$M_\alpha = -a_1 k - a_3 k^2 + 2a_2 \tag{4}$$

where k is the reduced frequency of the oscillating wing, a is the location of the elastic axis, $a_1 = 1/2 - a$, and $a_3 = 1/8 + a^2$ (see Ref. 5). The frequencies and damping of the first aeroelastic modes as computed for the above aerodynamic forces are displayed in Fig. 1. As predicted by Rocard,[1] the light aerodynamic damping introduced by the noncirculatory terms lowers the flutter speed of the wing ($u_f = 0.519$) as compared to the flutter predicted by the steady aerodynamic (see Fig. 1).

The flutter of the system is computed next while incorporating the unsteady or the quasisteady aerodynamics in the analysis. The unsteady aerodynamic forces are given as follows (see Ref. 5):

$$L_h = k^2 + 2C(k)k \qquad L_\alpha = k - ak^2 + 2C(k)(1 + a_1 k)$$

$$M_h = ak^2 + 2C(k)a_2 k$$

$$M_\alpha = -a_1 k - a_3 k^2 + 2C(k)a_2(1 + a_1 k) \tag{5}$$

where $C(k)$ is the Theodorsen circulation function simulating the unsteadiness of the wake. The quasisteady aerodynamics is simulated by setting to unity the Theodorsen function $C(k) = 1$. Figure 2 depicts the stability behavior of the system applying the unsteady and quasi-steady aerodynamics in the anaysis. The results of Fig. 2 indicate that the deficiency of the quasi-steady aerodynamics to predict the flutter is very large as compared to the unsteady aerodynamics calculation. It should be noted that there are large discrepancies in the prediction of the flutter speed for the various aerodynamic theories applied in the analysis (compare results of Figs. 1 and 2). A similar statement on the effect of quasisteady and unsteady aerodynamics in flutter can also be found in Refs. 4 and 9.

The influence of structural damping on the flutter speed of the system is considered next. Rocard[1] and others[9] were able to show that adding damping is always destabilizing. It should be mentioned that the above statement was made while comparing stability behavior of an undamped system with a very lightly damped one. To simulate Rocard's findings, the flutter of the system is computed applying steady aerodynamics while including the structural damping in the analysis. Figure 3 shows the sharp destabilizing effect (more than 20% reduction in flutter speed) of the light damping introduced to the undamped system. The influence of structural damping on the stability behavior of the wing in the presence of light aerodynamic damping is presented in Fig. 4. The results depicted in Fig. 4 are computed applying noncirculatory aerodynamics. In this case, the damping of the bending mode (η_e) has a stabilizing effect while the damping of the torsional mode (η_G) has a destabilizing effect on the flutter speed of the wing. Incorporating the quasisteady or the unsteady aerodynamic strip theory into the analysis reveals that structural damping has a very light stabilizing influence on the system's flutter speed. The thorough parametric study reveals

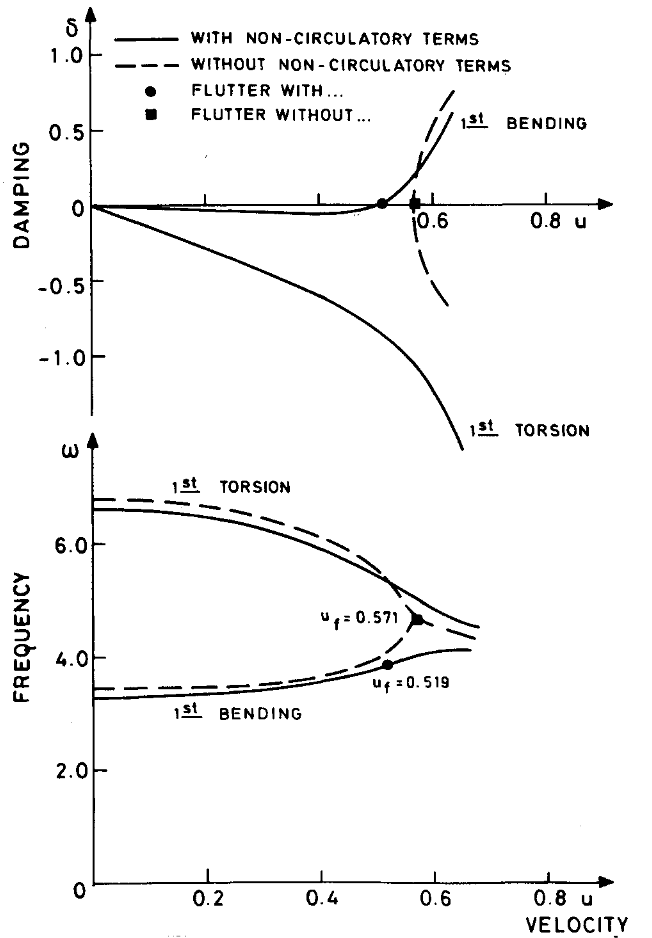

Fig. 1 The variation of frequencies and damping of the first bending and torsion modes vs the airflow velocity, applying steady and noncirculatory aerodynamics.

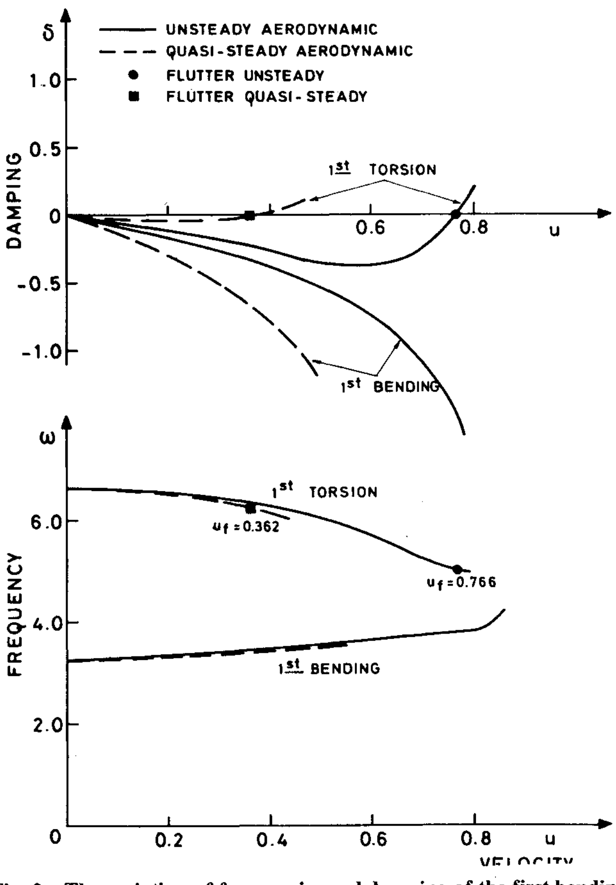

Fig. 2 The variation of frequencies and damping of the first bending and torsion modes vs the airflow velocity, applying quasisteady or unsteady aerodynamics.

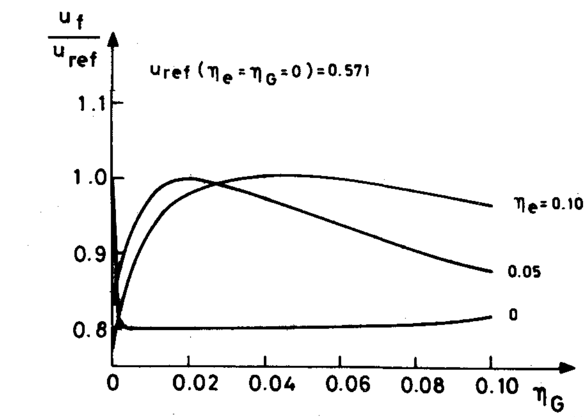

Fig. 3 The influence of structural damping on the flutter speed of the system, applying steady aerodynamics.

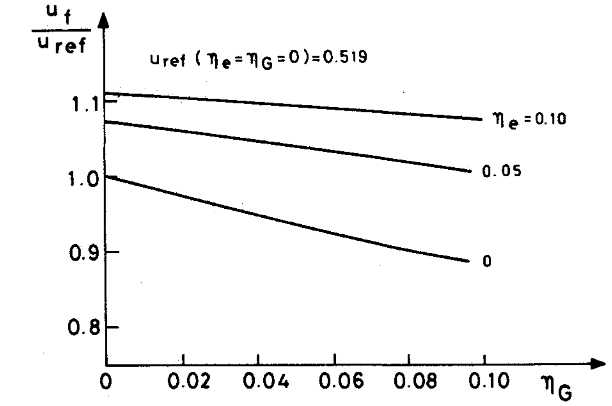

Fig. 4 The influence of structural damping on the flutter speed of the system, applying noncirculatory aerodynamics.

a consistent stabilizing tendency of the structural damping (η_e and η_G) while applying quasisteady or unsteady aerodynamics. Figure 5 shows a typical stabilizing effect of the structural damping while applying unsteady aerodynamics in the analysis. Thus, the results represented in Figs. 3-5 emphasize the strong interaction existing between structural damping and the aerodynamic lags incorporated into the aerodynamic forces applied in the analysis. A similar behavior is reported in Ref. 10 simulating the role of damping on supersonic panel flutter.

Conclusions

The strong effect of the aerodynamic lag terms on the flutter speed of the system is demonstrated. It is shown that quasi-

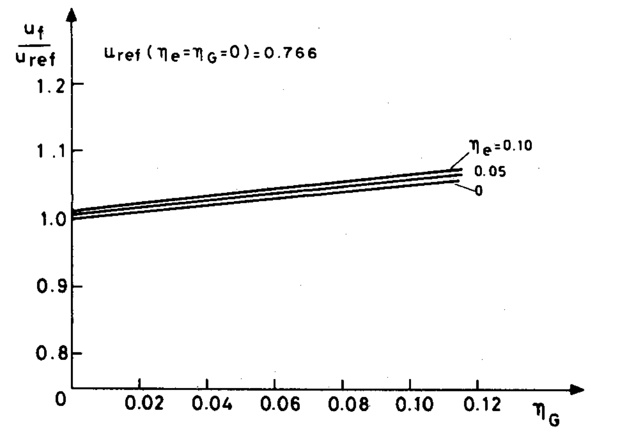

Fig. 5 The influence of structural damping on the flutter speed of the system, applying unsteady aerodynamics.

steady aerodynamics can appreciably offset the critical speed of the system. The strong coupling between aerodynamic and structural damping is demonstrated. It is shown that structural damping generally has a stabilizing effect on a fixed-root wing when applying unsteady or quasisteady aerodynamics.

References

[1]Rocard, Y., *General Dynamics of Vibrations,* Frederick Ungar Publishing Co., New York, 1960 (translated from French).

[2]Pines, S., "An Elementary Explanation of the Flutter Mechanism," *Proceedings of the National Specialists Meeting on Dynamics and Aeroelasticity,* Institute of the Aeronautical Sciences, Ft. Worth, TX, Nov. 1958, pp. 52-58.

[3]Nissim, E., "Effect of Linear Damping on Flutter Speed. Part I: Binary System," *Aeronautical Quarterly,* Vol. 16, May 1965, pp. 159-178.

[4]Dugundji, J., "Effect of Quasi-Steady Air Forces on Incompressible Bending-Torsion Flutter," *Journal of Aeronautical Sciences,* Vol. 25, Feb. 1985, pp. 119-121.

[5]Lottati, I., "Flutter and Divergence Aeroelastic Characteristics for Composite Forward Swept Cantilevered Wing," *Journal of Aircraft,* Vol. 22, Nov. 1985, pp. 1001-1007.

[6]Neumark, S., "Concept of Complex Stiffness Applied to Problems of Oscillations with Viscous and Hysteretic Damping," Royal Aeronautical Establishment, R&M 3269, Sept. 1957.

[7]Goland, M., "The Flutter of a Uniform Cantilever Wing," *Journal of Applied Mechanics,* Vol. 12, Dec. 1945, pp. 197-208.

[8]Bisplinghoff, R.L., Ashley, H., and Halfman, R.L., *Aeroelasticity,* Addision-Wesley Publishing Co., Reading, MA, 1955, pp. 568.

[9]Bolotin, V.V. and Zhinzher, N.I., "Effects of Damping on Stability of Elastic Systems Subjected to Nonconservative Forces," *International Journal of Solids Structures,* Vol. 5, 1969, pp. 965-989.

[10]Lottati, I., "The Role of Damping on a Supersonic Panel Flutter," *AIAA Journal,* Vol. 23, Oct. 1985, pp. 1640-1642.

Errata

Noise of Counter-rotation Propellers with Nonsynchronous Rotors

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TABLE 1 should have appeared at the top of page 1098 as it does at the right.

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Table 1 Mode properties at frequencies near BPF

Mode indices m	k	Frequency, $\omega_{m,k}$	Cutoff ratio, ξ	Spin rate, ϕ	Number of lobes, $\lvert m-k \rvert /B$	Modal efficiency, η^a
0	± 1	$(1+\epsilon)B\Omega_2$	M_T	$-(1+\epsilon)\Omega_2$	B	0.13
± 1	0	$B\Omega_2$	M_T	Ω_2	B	0.13
± 2	∓ 1	$(1-\epsilon)B\Omega_2$	$M_T/3$	$((1-\epsilon)/3)\Omega_2$	$3B$	2×10^{-7}
± 3	∓ 2	$(1-2\epsilon)B\Omega_2$	$M_T/5$	$((1-2\epsilon)/5)\Omega_2$	$5B$	1×10^{-15}

$^a\eta = J_{(m-k)B}[(m+k)Bz_0M_T\sin\theta]$ calculated for $B=4$, $z_0=1$, $M_T=0.8$, $\theta=70$ deg.