Dynamic Behavior of Angle-of-Attack Vane Assemblies

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Nomenclature

A = aspect ratio, w^2/S
b = semichord, i.e., chord $=2b$
$C_{L\alpha}$ = wing lift curve slope, $dC_L/d\alpha = \pi A/2$ for very small A
f_n = natural frequency in Hz, $\omega_n/2\pi$
$\dot{h}$ = transverse velocity of vane pivot axis, positive down
$\ddot{h}$ = transverse acceleration of vane pivot axis
J = mass rotary moment of inertia of the vane assembly
K = emperical stiction factor in dry friction term
$\mathcal{L}$ = distance between vane pivot axis and vane center of pressure
M = Mach number
q = freestream dynamic pressure
S = vane planform area
U = freestream velocity, usually $U_{EQV} = (2q/\rho_o)^{1/2}$
w = spanwise width
α = angular displacement with respect to freestream direction, positive clockwise
$\dot{\alpha}$ = angular velocity, $d\alpha/dt$
$\ddot{\alpha}$ = angular acceleration, $d^2\alpha/dt^2$
μ_D = dry friction coefficient
μ_V = viscous friction coefficient
π = 3.14159 . . .
ρ_o = sea level density of air
ζ = damping coefficient
ω_n = natural frequency, rad/sec

Introduction

RECENT events in flight tests have generated the need for a verified model of the dynamic behavior of angle-of-attack vanes. For example, dynamic performance flight testing[1] is being considered to reduce the duration and cost of test programs. Also, angle-of-attack vanes have been used to obtain gust data in thunderstorm penetration studies.[2] Extraneous angular motions due to vibration of the vane's support (usually a somewhat flexible boom) are a further concern.

Dynamic Model

A mathematical model of a vane's dynamic behavior was developed based on the equations of motion of a plunging, rotating, two-dimensional flat plate in an inviscid, incompressible fluid.[3] Combining the aerodynamic moments [for example, from Eq. (5-348) of Bisplinghoff et al.[4]] with the vane's rotary inertia and some viscous and dry friction terms to account for mechanical damping due to bearings and the like, one can obtain

$$\ddot{\alpha} + (2\zeta\omega_n + \mu_v)\dot{\alpha} + \omega_n{}^2\alpha + \mu_d \min(K\dot{\alpha}, \operatorname{sgn}\dot{\alpha}) = -\frac{\omega_n^2}{U}\left[\dot{h} + \frac{(2\mathcal{L}+b)}{4\mathcal{L}}\frac{b}{U}\ddot{h}\right] \tag{1}$$

where

$$\omega_n = \left\{C_{L\alpha}\mathcal{L} q S/\left[J + \left(2\frac{\mathcal{L}}{b}+1\right)^2 \frac{\pi}{8}\rho_o b^3 S\right]\right\}^{1/2} \tag{2}$$

and

$$\zeta = [(2\mathcal{L}^2 + 3\mathcal{L}b + b^2)/4\mathcal{L}^2][\mathcal{L}/U]\omega_n \tag{3}$$

For typical vanes (relatively small inertias) and reasonable airspeeds (greater than 50 mph), the frictional terms should become negligible as do the $\ddot{h}$ term and the aerodynamic inertia term, so these equations simplify to

$$\ddot{\alpha} + 2\zeta\omega_n\dot{\alpha} + \omega_n{}^2\alpha = -\omega_n{}^2(\dot{h}/U) \tag{4}$$

where

$$\omega_n = (C_{L\alpha}\mathcal{L}\, q\, S/J)^{1/2} \tag{5}$$

and ζ is still given by Eq. (3). The key assumption made was that the two-dimensional predictions of aerodynamic moments would still be valid if the finite wing lift curve slope $C_{L\alpha}$, and the actual distance from the pivot point to the center of pressure $\mathcal{L}$ were used in lieu of their infinite wing counterparts. While Eqs. (3) and (5) have previously been developed[5,6]. . . at least as the limiting value of $\zeta = (\mathcal{L}/2)(\omega_n/U)$ for $\mathcal{L} \gg b$, this more complete form provides guidance as to the second order terms neglected in more straight-forward developments.

In applying this model, several comments are in order. First, if expressed in terms of equivalent airspeed at sea level, the damping is independent of airspeed. Secondly, since vanes are invariably of very low aspect ratio, the slender body $C_{L\alpha} = \pi A/2$ should be used. Unfortunately, predicting the center of pressure location for such low aspect ratios is difficult at best. An extrapolation of the results of Table 1 of Gersten[7] may be used for rectangular vanes, while the slender body prediction of Jones[8] may be used for triangular or delta vanes. Fortunately, Jones'[8] slender body theory also may infer that this model would be valid for all airspeeds (except maybe transonic) in spite of its incompressible development.

Experimental Verification

A rectangular, flat plate vane used by the 4950th Test Wing at Wright-Patterson AFB for thunderstorm penetration studies was dynamically tested in the Air Force Institute of Technology 5 ft diam, low subsonic wind tunnel. The vane assembly was mounted on the upstream end of the horizontal member of a cruciform mounting assembly. The vane is a fiberglass and balsa rectangle pivoted about its leading edge. Its chord ($2b$) is 4.75 in. and its aspect ratio is 0.5. A steel cylindrical counterweight is attached so that the vane is statically balanced. The vane assembly's inertia was calculated and experimentally verified to be 0.0012 in lb$f$ sec.[2]

An initial series of tests were run with the cruciform stationary ($\dot{h} \equiv 0$), and the vane was released from an initial angle of attack of about 5°. The upper part of Fig. 1 is a typical response. As expected, the response is essentially that of a damped second-order system. The test results are shown in Fig. 2 which also includes the predictions of the model. The damping coefficient was determined from the log decrement

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Index categories: Aircraft Testing (including Component Wind Tunnel Testing); Research Facilities and Instrumentation.

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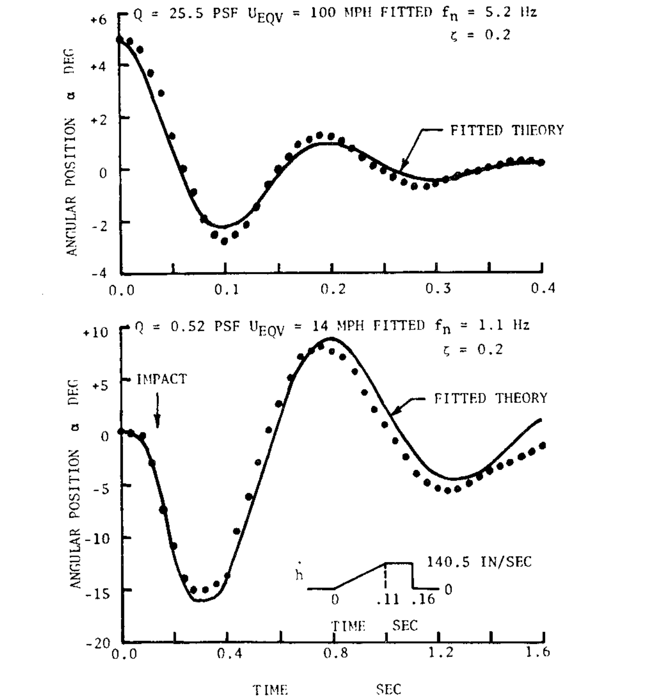

Fig. 1 Typical experimental initial angle of attack (upper) and base motion (lower) time histories of the Wright-Patterson rectangular plate vane.

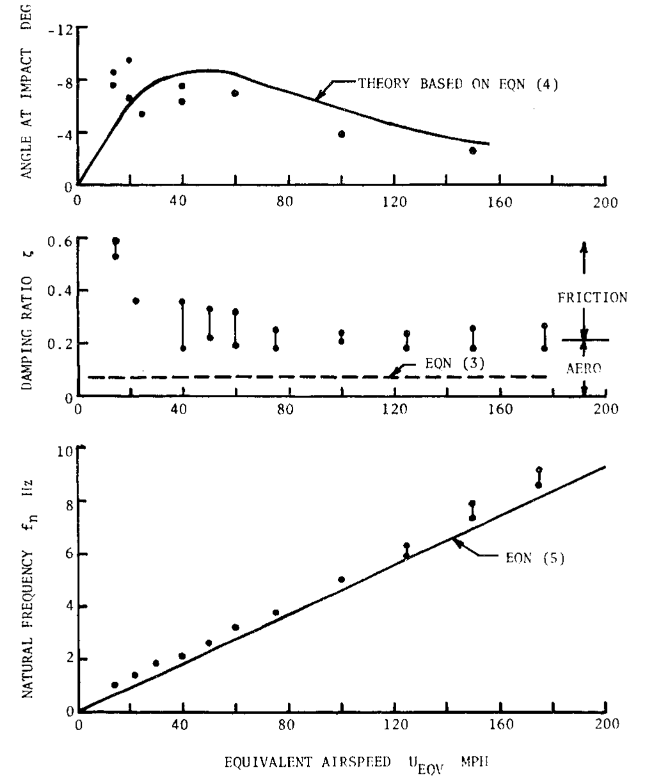

Fig. 2 Dynamic characteristics of Wright-Patterson rectangular plate vane.

of adjacent extrema, and then the natural frequency was found from the damped period. The natural frequency prediction agrees well with experiment (about 10% low). Frictional effects are noted but only at very low airspeeds as expected. The aerodynamic damping is independent of airspeed but is about three times that estimated by Eq. (3). This is probably due to viscous and tip effects which are not included in the model.

Next, a series of tests were run where the cruciform mounting assembly was rapidly driven by an air piston in a direction transverse to the tunnel axis. The interest here was in angular motions of the vane due to transverse motions of its pivot axis rather than due to changes in the airstream direction. High-speed photos showed the velocity of the pivot axis to be essentially a short duration, saturating ramp. The cruciform traveled about 15 in. in about 160 msec. A typical response for the initial few tests is shown in the lower half of Fig. 1. Unfortunately, subsequent tests had a rapid reversal in angular position noted immediately following the end of the cruciform travel. It is speculated and qualitatively justified[3] that this behavior was due to the vane's bearing instantaneously locking up under the greater than 50g impact loads at the end of motion. These loads would then cause the vane to deform and lead to aerodynamic forces in the opposite direction. In support of this contention, some cracks were indeed noted in the vane's paint just aft of where it attached to the pivot arm. To provide a comparison with the model, only the response of the vane prior to impact was assumed to be representative. The vane's angular position at impact is presented in the upper part of Fig. 2. Qualitative agreement is again noted.

Richardson[2] tested an all-balsa vane used by NASA Langley for gust measurements. The NASA vane is geometrically identical to the Wright-Patterson vane, but it has a smaller inertia ($J = 1.4 \cdot 10^{-4}$ in lb$f$ sec^2). Release from an initial angle tests were conducted at Mach numbers $M = 0.18$, 0.27, and 1.6. The natural frequencies predicted by Eq. 5 were again close (no more than 12% low) for all airspeeds. The damping was again 2 to 3 times that predicted by Eq. (3).

Another configuration of vane is the dual triangle arrangement used by the AF Flight Test Center at Edwards AFB. This vane is used in conjunction with flight path accelerometers for dynamic aircraft performance testing. Olsen[1] reported the results of release from an initial angle tests conducted at $M = 0.3$, 0.5, 0.7, 1.5, 2.5, and 3. The natural frequency prediction of $f_n = 0.87\,(q)^{1/2}$, with q in psf, is within 10% except for two of the supersonic cases where the disagreement is about 20%. For these triangular vanes, the subsonic damping is close to the $\zeta = 0.043$ predicted by Eq. (3) but lies closer to its limiting ($\mathcal{L} \geq b$) prediction of $\zeta = 0.018$ for the supersonic conditions. Further details of all the theoretical calculations and the experimental tests on the Wright-Patterson vane are available.[3]

Conclusions and Recommendations

1) A simple model of the dynamic behavior of an angle-of-attack vane assembly has been developed and experimentally verified by wind tunnel tests of three vane designs. The model is valid for all airspeeds (except possibly transonic). The natural frequency is predicted within ±20%. Most of this error results from estimating the lift curve slope and center of pressure for the very small aspect ratio planforms in use. This error could be reduced to less than 10% if the actual $C_{L\alpha}\mathcal{L}$ product of the vane were known. Note that a single low subsonic value is sufficient to predict behavior at all airspeeds. The damping ratio is only predicted within a factor of 2 to 3. 2) At the airspeeds in common use, extraneous angular motions introduced by typical transverse motions of the vane's pivot axis may not be negligible. 3) The freestream velocity used with the model should be equivalent, rather than actual, airspeed. 4) Mechanical friction effects should be negligible for vanes in use at reasonable airspeeds except for very small angular deflections. 5) If the predicted aerodynamic damping is less than desired, viscous damping

can be enhanced, e.g., by perforating the vane, or an alternate measurement scheme should be considered, e.g., the constrained vane discussed by Lenschow.[9]

Reference

[1] Olsen, W.M., "An Interim Report on Dynamic Performance Flight Testing," unpublished report, June 1973, Air Force Flight Test Center, Edwards Air Force Base, Calif.

[2] Richardson, N.R., "Dynamic and Static Wind Tunnel Tests of a Flow-Direction Vane, TN D-6193, April 1971, NASA.

[3] Karam, J.T., Jr., "Dynamic Behavior of Angle-of-Attack Vane Assemblies," AFIT TR-74-8, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio.

[4] Bisplinghoff, R.L., Ashley, H., and Halfman, R.L., *Aeroelasticity,* Addison-Wesley, Reading, Mass., 1955, pp. 262-279.

[5] Dunlap, E.W. and Porter, M.B., "Theory of the Measurement and Standardization of In-Flight Performance of Aircraft," FTC-TD-71-1, April 1971, Air Force Flight Test Center, Edwards Air Force Base, Calif., pp. V-53-V-55.

[6] Pinsker, W.J.G., "The Static and Dynamic Response Properties of Incidence Vanes with Aerodynamic and Internal Viscous Damping," Aeronautical Research Council C.P. No. 652, Aug. 1962, Ministry of Aviation, London.

[7] Gersten, K., "Nonlinear Airfoil Theory for Rectangular Wings in Incompressible Flow," RE 3-2-59W, Feb. 1959, NASA.

[8] Jones, R.T., "Properties of Low-Aspect Ratio Pointed Wings at Speeds Below and Above the Speed of Sound," TN 1032, March 1946, NACA.

[9] Lenschow, D.H., "Vanes for Sensing Incidence Angles of the Air from an Aircraft," *Journal of Applied Meteorology,* Vol. 10, Dec. 1971, pp. 1339-1343.

Errata

Fatigue—A Test Integrated Damage Modeling Approach

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EQUATION (5) on page 567 of the subject paper should read as follows:

$$\frac{1}{N} \simeq \left(\frac{1}{N_{\text{approx}}} \right) = \lambda \left(\frac{1-\kappa_o f_m}{f_a} \right)^{\beta_o} + \lambda_o \ln \left(\frac{1-\kappa_o f_m}{f_a} \right) \left(\frac{1-\kappa_o f_m}{f_a} \right)^{\beta_o} (\beta - \beta_o) - \lambda_o \beta_o \frac{f_m}{f_a} \left(\frac{1-\kappa_o f_m}{f_a} \right)^{\beta_o - 1} (\kappa - \kappa_o) \tag{5}$$

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