A PASSIVE WINGTIP LOAD ALLEVIATION SYSTEM

by

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Introduction

A passive wingtip load alleviation system was devised, tested, and analyzed for its effect on the reduction of structural deformations and the extension of flutter speed. The sensors responded to changes in angle of attack and vertical movement of the wingtip and were used to deflect a trailing edge flap to alleviate the induced loads.

System Description

The vane-flap system was installed on an existing flutter test wing having a semispan of two feet and a chord of one foot. The wing originally was segmented at two inch intervals, but the outer ten inches of the lift panel was made rigid to accomodate the flap. The flap span was seven inches and the chord was 1.5 inches (see Figure 1). The wing airfoil was symmetric and had a maximum thickness of 1.2 inches at approximately four inches behind the leading edge. The wing weighed 4.25 lb. and had a moment of inertia about the elastic axis of .0112 slug ft^2.

The gust alleviation system consisted of a two by five inch vane mounted nearly even with the leading edge, but pivoted four inches ahead of it. The vane moved one element of a differential through a control horn and cable system. The differential, in turn, drove the flap through a similar system. Also coupled to the differential was a spring-mass-dashpot system which performed as a wingtip displacement sensor and provided an equivalent of angle of attack information at the wing bending frequency in order to ensure flap effectiveness. The flap was approximately aerodynamically balanced to minimize feedback to the sensors.

The vane was very lightly constructed of balsa wood ribs and spars and a quarter-mil Mylar covering to minimize the moment of inertia and ensure fast response. The vane and arm weighed 0.031 oz. and had a moment of inertia of $.78 \times 10^{-4}$ slug ft^2. The airfoil was an NACA 0009.

The inertial mass weighed 1.5 oz. and had a moment arm of 1.0 inch. The dash-pot was manufactured by Airpot Corporation of Norwalk, Connecticut, and was capable of several orders of magnitude of damping force. A value near .05 lb-sec/in. was used for the test wing.

Flutter Speed Extension Analysis

The effect of the vane-flap system on the flutter speed of a wing can be examined by assuming the motion is influenced only by steady aerodynamic forces. The equations of motion for the plain wing, with no flap, are

$$M\ddot{w}_R + C_1 U\dot{w}_R + M\omega_w^2 w_R - S_\alpha \ddot{\Theta}_R - C_2 U^2 \Theta_R = 0$$

$$-S_\alpha \ddot{w}_R + C_3 U\dot{w}_R \qquad + I_\alpha \ddot{\Theta}_R + (I_\alpha \omega_\Theta^2 - C_4 U^2)\Theta_R = 0$$

where M, S_α, and I_α are the generalized mass , static unbalance, and moment of inertia relevant to the first bending and torsion modes described by the reference station bending and twisting variables, w_R and Θ_R. C_1 and C_2 are the bending velocity and angle of attack dependent generalized lift force coefficients, and C_3 and C_4 are the corresponding generalized moment coefficients.

The root locus, developed as a function of the loop gain $(-S_\alpha{}^2/MI_\alpha)$, exhibits open loop "torsion" poles and "bending" zeros on the imaginary axis. Their positions are determined by the free stream velocity

$$Z_{\text{bend.}} = i[C_2 U^2/S_\alpha]^{\frac{1}{2}}$$

$$P_{\text{twist}} = i\left[\frac{I_\alpha \omega_\Theta^2 - C_4 U^2}{I_\alpha}\right]^{\frac{1}{2}}$$

When those roots are equal, there is no loop gain for which the torsion roots are stable and the flutter speed can be calculated from this relationship.

$$U_F = \omega_\theta\left[\frac{C_2}{S_\alpha} + \frac{C_4}{I_\alpha}\right]^{-\frac{1}{2}}$$

If the vane-flap system is introduced, the equations of motion become

$$M\ddot{w}_R + (C_1-C_7)U\dot{w}_R + M\omega_w^2 w_R - S_\alpha\ddot{\theta}_R + (C_2-C_6)U^2\theta_R = 0$$

$$-S_\alpha\ddot{w}_R + (C_3-C_7C_8+C_{10})U\dot{w}_R + I_\alpha\ddot{\theta}_R + [I_\alpha\omega_\theta^2-(C_4-C_6C_8+C_9)U^2]\theta_R = 0$$

where C_6 and C_7 are the generalized flap lift coefficients dependent on bending velocity and angle of attack, C_9 and C_{10} are the corresponding generalized flap pitching moment coefficients, and C_8 is the distance from the center of lift to the elastic axis.

The flap reduces both the lift curve slope and the angle-of-attack dependent pitching moment. The resulting flutter speed is

$$U_F = \omega_\theta\left[\frac{C_2-C_6}{S_\alpha} + \frac{C_4-C_6C_8+C_9}{I_\alpha}\right]^{-\frac{1}{2}}$$

C_9 is less than C_6C_8, with the consequence that the flutter speed is increased. The root locus for the test wing, is shown in Figure 2. The flutter speed is extended approximately nine miles per hour.

Frequency Response and Flutter Speed Tests

The flutter model wing was tested in the Wright Brothers 7 x 10 ft wind tunnel at 35 mph by perturbing the air flow with an oscillating wing. This wing essentially covered the test section width and was located about eight feet directly upstream of the test wing. Peak angle-of-attack oscillations for the forcing wing were either $\pm 6^\circ$ or $\pm 12^\circ$.

The response of the test wing was measured at frequencies between 10.5 and 23 rad/sec which emcompassed the first bending mode. Figure 3 illustrates the effectiveness of the vane-dashpot system in attenuating the wing bending response. In the vicinity of and above the bending mode frequency, the system reduces the perturbed motion by nearly a factor of three. The factor reduces to 1.4 at the lowest frequency tested.

Substantial attenuation above the bending mode frequency also is realized with just the mass-dashpot system activated. The damper provides the phase shift required to activate the flap and nullify some of the gust induced load. It is ineffective at very low frequencies because the stiffness of the system prohibits motion of the mass with respect to the wing, and at very high frequencies because the damper induces a similar condition.

The flutter speed test made use of a six-inch wide board placed normal to the free stream ahead of the wing to provide more turbulence. The test could not be extended to the actual flutter speed for fear of destroying the wing. However, responses at lower speeds clearly indicated the flutter speed would be higher than that of the unmodified wing. In particular, much less torsional bending was observed with the vane system operating than without.

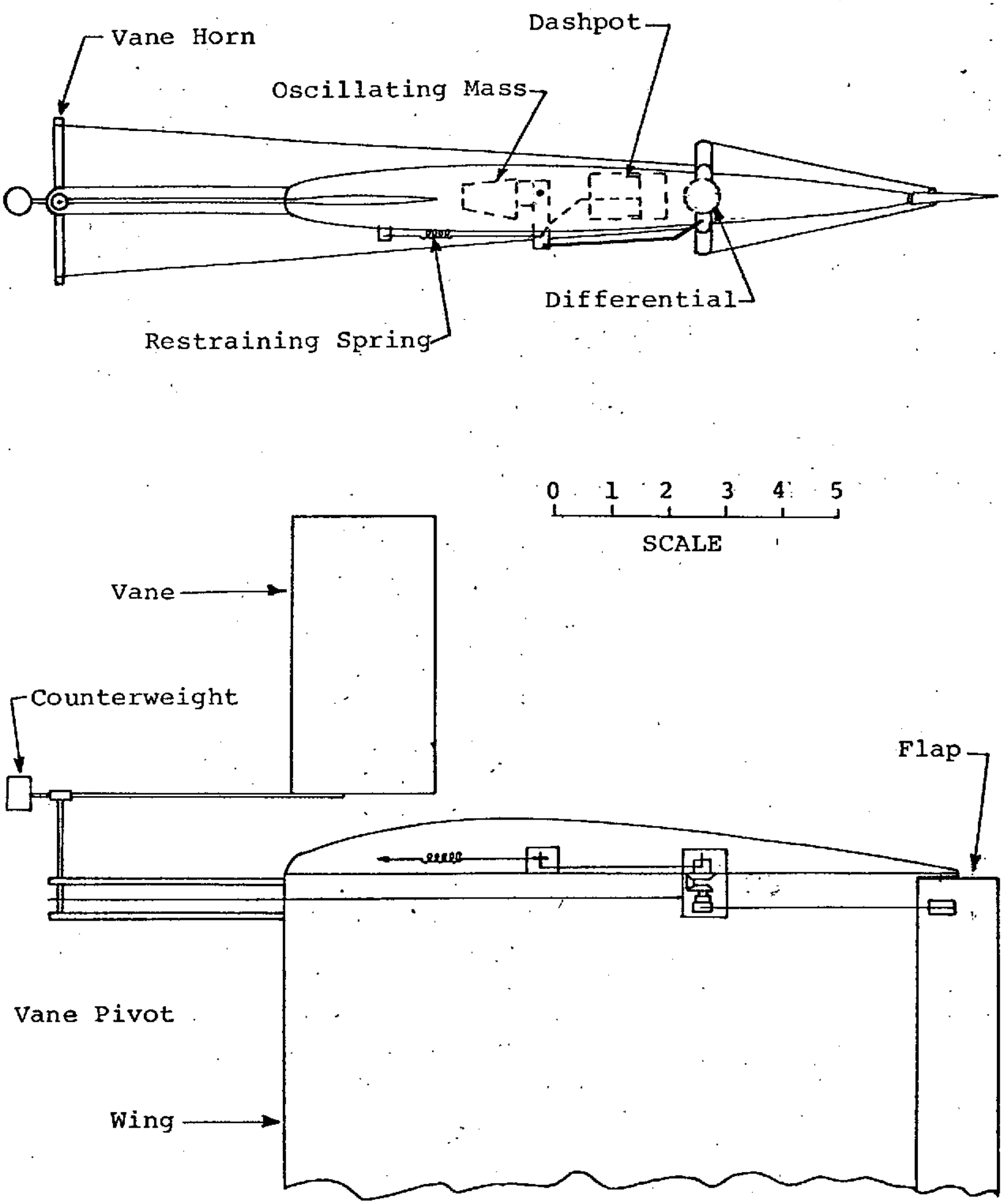

Figure 1. Sketch of Load Alleviation System

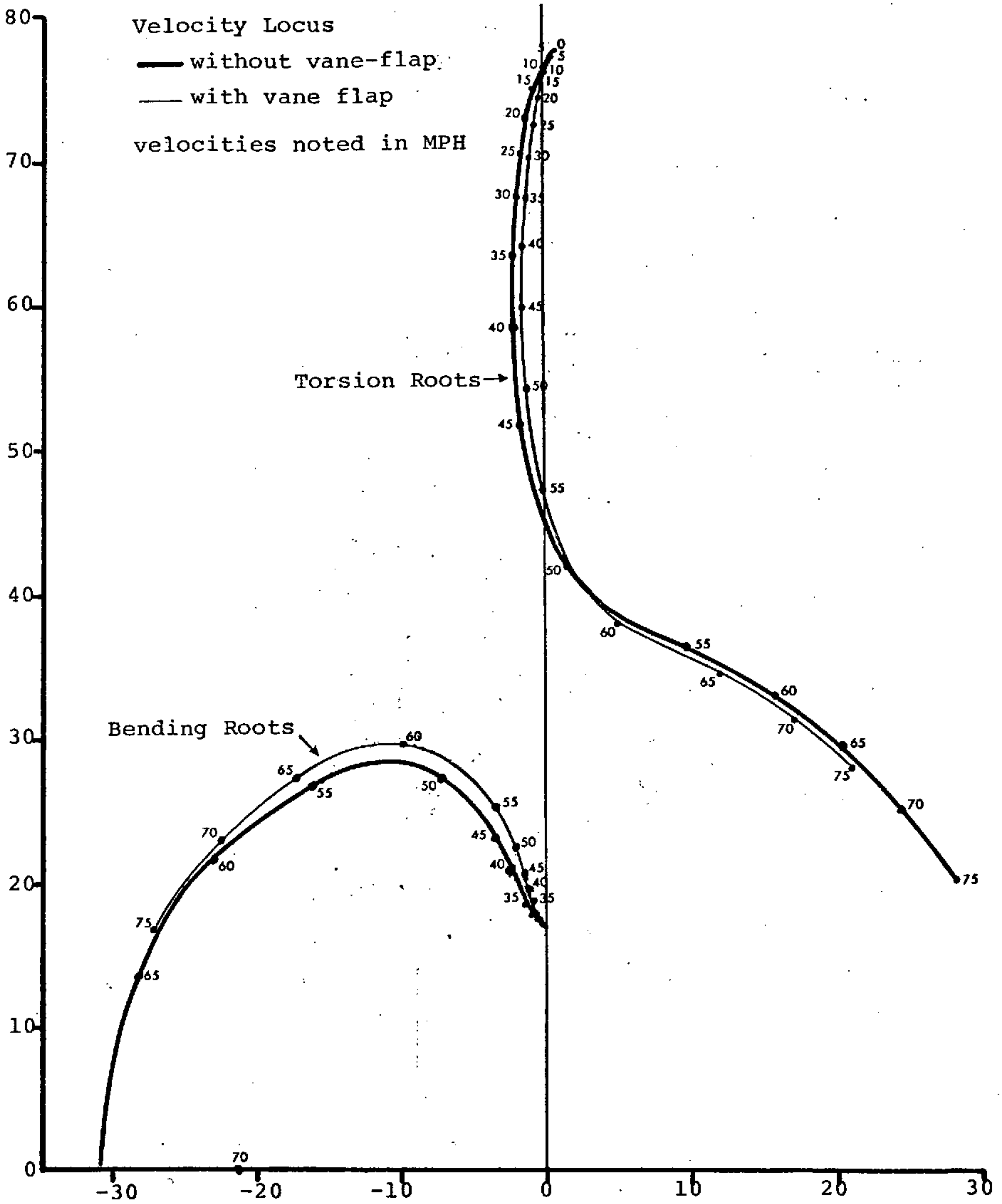

Figure 2. Test Wing Root Locus

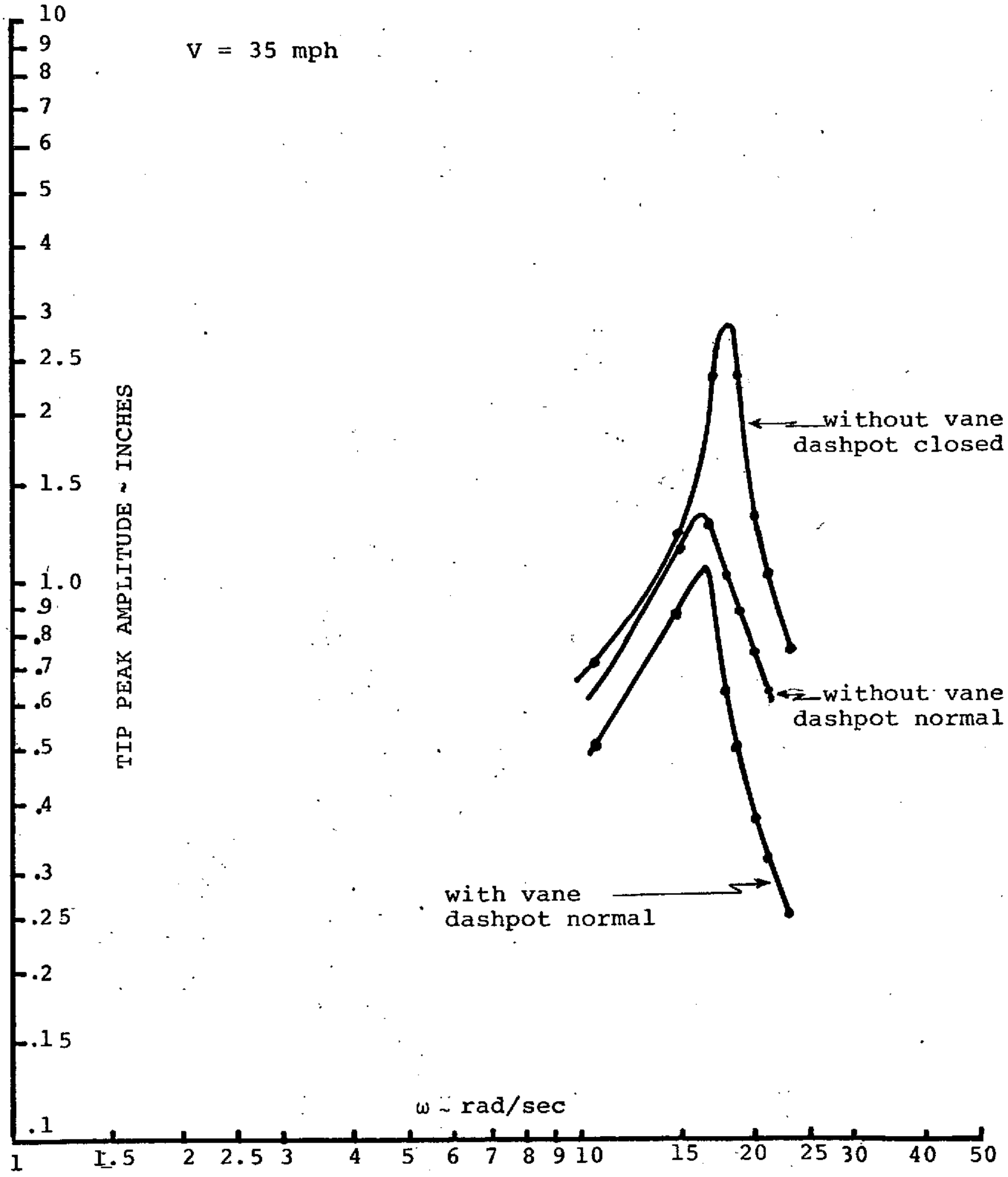

Figure 3. Wingtip Frequency Responses