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16. Abstract

The predicted dynamic stability of the XV-15 tilting proprotor aircraft in cruise flight is updated, using a reduced increase in the pitch-gimbal coupling with collective, and a higher nominal control system stiffness. The major influence of the pitch-lag coupling of the XV-15 gimballed, stiff-inplane rotor on the aircraft stability is shown. The influence of the blade pitch dynamics is found to be contained primarily in the quasistatic pitch-lag and pitch-gimbal coupling, although the complete dynamics should be retained in the analysis for an accurate quantitative calculation of the stability boundary.

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THE INFLUENCE OF PITCH-LAG COUPLING ON THE PREDICTED AEROELASTIC STABILITY OF THE XV-15 TILTING PROPROTOR AIRCRAFT

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SUMMARY

The predicted dynamic stability of the XV-15 tilting proprotor aircraft in cruise flight is updated, using a reduced increase in the pitch-gimbal coupling with collective, and a higher nominal control system stiffness. The major influence of the pitch-lag coupling of the XV-15 gimballed, stiff-inplane rotor on the aircraft stability is shown. The influence of the blade pitch dynamics is found to be contained primarily in the quasistatic pitch-lag and pitch-gimbal coupling, although the complete dynamics should be retained in the analysis for an accurate quantitative calculation of the stability boundary.

INTRODUCTION

The NASA/Army XV-15 is a research aircraft intended to demonstrate the feasibility of the tilting proprotor configuration. A principal objective of the aircraft flight test program is to determine the aeroelastic characteristics of the aircraft. The predicted dynamic characteristics of the XV-15 tilting proprotor aircraft were documented in reference 1, based on a rotorcraft aeroelastic analysis which is described in reference 2. The present report updates the dynamic stability predictions, and discusses the role of the rotor pitch-lag coupling in the stability of this aircraft.

ANALYTICAL MODEL

The dynamic stability of the XV-15 aircraft is calculated as a function of forward speed in airplane or cruise mode flight, with the

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pylon tilt angle $\alpha_p = 0^o$. The rotor speed is 458 rpm, and the flap setting is zero for airplane mode. The operating condition is trimmed level flight at a gross weight of 5900 kg and mid CG position, at sea level and 3800 m altitude.

The following degrees of freedom are used for the motion of the gimballed rotor: gimbal pitch and yaw, two elastic bending modes per blade, one rigid pitch mode per blade, and the rotor speed perturbation. The aircraft motion is described by the three rigid body degrees of freedom (pitch, longitudinal velocity, and vertical velocity for the symmetric dynamics; or roll, yaw, and lateral velocity for the anti-symmetric dynamics); and four airframe elastic modes -- fundamental wing vertical bending, chordwise bending, torsion, and pylon yaw. The engine and transmission dynamics are modelled, including the rotor speed governor (for symmetric motions) and the inter-connect shaft (for anti-symmetric motions). The calculated trim conditions and the airframe natural frequencies are given in reference 1. The critical aeroelastic modes are wing vertical bending (q_1), wing chordwise bending (q_2), and wing torsion (p) for both symmetric and anti-symmetric motions.

UPDATED STABILITY PREDICTION

Since the work of reference 1, two changes have been made in the input parameters describing the XV-15 aircraft for the aeroelastic analysis. The calculations of reference 1 used a rigid pitch natural frequency of $\omega_\theta = 4.8$/rev for the cyclic control system, and 5.2/rev for the collective control system. The current nominal value of the control system stiffness is 18900 N-m/rad, which gives a larger pitch natural frequency of $\omega_\theta = 5.4$/rev for the blade torsion inertia used. The pitch-gimbal coupling varies with collective pitch according to:

$$K_{P_G} = \frac{(K_{P_G})_{\text{pitch horn level}}}{\cos(\theta_{75} + \phi_{PH})}$$

(see reference 2), where $(K_{P_G})_{\text{pitch horn level}} = \tan \delta_3$. The XV-15 rotor has $\delta_3 = -15^o$ when the pitch horn is level. Reference 1 assumed that the pitch horn was level when the collective pitch at 75% radius was zero ($\phi_{PH} = 0$). It has been established that the XV-15 rotor actually has the pitch horn level when the collective pitch is 20.5^o ($\phi_{PH} = -20.5^o$). Thus the new value of pitch-gimbal coupling is smaller at high collective (high speed).

Figures 1 to 3 show the predicted dynamic stability of the critical symmetric and anti-symmetric aeroelastic modes of the XV-15 in cruise flight at sea level. The damping ratio ζ is shown as a function of the aircraft speed. Figure 1 reproduces the results of reference 1, using $\omega_\theta = 4.8$/rev and the old δ_3 values (see figure 13 of reference 1). Figure 2 shows the effect of the new δ_3 values on the stability, and figure 3 shows the effect of increasing the control system stiffness to $\omega_\theta = 5.4$/rev as well. Figures 4 to 6 present the corresponding stability predictions for flight at 3800 m altitude (figure 4 duplicates figure 18 of reference 1).

The magnitude of the pitch-gimbal coupling increases with speed, as the rotor collective pitch increases. With the pitch horn level at $\Theta_{75} = 20.5^o$ rather than at $\Theta_{75} = 0$, the new values of δ_3 at high speed are smaller in magnitude than the old values used in reference 1. The result is an increase in the predicted stability boundary, by about 10 knots at sea level (compare figures 1 and 2) and by about 25 knots at 3800 m (compare figures 4 and 5). The reduced air density results in an increased stability boundary with altitude. So at 3800 m the trim collective pitch at the stability boundary is larger than at the sea level boundary, and then the effect of the reduced δ_3 is larger at 3800 m altitude. The increased control system stiffness is stabilizing because it reduces the rotor pitch-lag coupling. The result of using the nominal control system stiffness of $\omega_\theta = 5.4$/rev is about a 15 knot increase in the stability boundary both at sea level and at altitude.

The current predictions of the aeroelastic stability of the XV-15 tilting proprotor aircraft are presented in figures 3 and 6. Both the reduced pitch-gimbal coupling magnitude at high collective and the increased nominal control system stiffness are stabilizing (c.f. figures 1 and 4). The predicted stability boundaries are now 320 knots at sea level, and 375 knots at 3800 m altitute.

PITCH-LAG COUPLING INFLUENCE

Reference 3, considering a proprotor and cantilever wing system, found that the pitch-lag coupling has a major impact on the dynamic stability. The XV-15 has a gimballed, stiff-inplane rotor with no lag hinge, for which there are significant moments about the pitch axis due to lag deflections of the blade. Figure 7 shows the pitch-lag, pitch-cone, and pitch-gimbal coupling calculated for the XV-15 rotor. The pitch-lag coupling is positive for lag back/pitch down; the pitch-cone and pitch-gimbal coupling are positive for flap up/pitch down. The total effective coupling was obtained by directly examining the equation of motion for the blade pitch degree of freedom. The ratio of the coefficient of the lag degree of freedom in this equation to the coefficient of the pitch degree of freedom gave the pitch/lag coupling, and similarly for the pitch-cone and pitch-gimbal coupling. It should be noted that the lag and coning blade modes used in this analysis have a cantilever root boundary condition; the gimbal tilt and shaft rotation are described by separate degrees of freedom (see reference 2). The bending modes are normalized to unit total deflection at the tip. The total effective coupling includes the kinematic coupling due to the control system geometry, which is also shown in figure 7. The kinematic pitch-gimbal coupling is just the δ_3 angle, which increases with collective as discussed above. There is a kinematic pitch-cone coupling due to the displacement and slope change at the pitch bearing during the coning mode. The kinematic pitch-lag coupling is negligible. The kinematic pitch-cone and pitch-lag coupling were calculated using a model of the blade root and control system geometry described in reference 2.

Figure 8 shows the predicted dynamic stability without the rotor blade pitch dynamics, but with the total effective coupling given in figure 7 input as if it were all simply kinematic coupling. Clearly this model retains the basic physical characteristics of the aeroelastic system (compare figures 3 and 8), although the predicted stability boundary is too high by about 15 knots now. Reference 3 showed that the effect of the blade pitch dynamics is essentially all quasistatic, involving only the spring terms in the pitch equations of motion. The present result shows further than the coupling of the pitch with the blade bending and gimbal degrees of freedom is of primary importance, although the coupling with the other degrees of freedom does change the quantitative results. Figure 9 presents the dynamic stability calculated for a control system of infinite stiffness, which eliminates all the pitch-bending coupling except for the kinematic terms. Comparing figures 3 and 9 shows the great importance of the pitch-lag coupling to the proprotor stability with the aircraft in flight, as was found in reference 3 for the proprotor on a cantilever wing.

Figures 10 and 11 present the stability calculated with the kinematic pitch-cone and pitch-lag coupling set to zero, for $\omega_\theta = 5.4$/rev and $\omega_\theta = \infty$ respectively. Comparing with figures 3 and 9, it is concluded that the kinematic pitch-bending coupling (primarily pitch-cone in this case) has little influence on the dynamics.

INFLUENCE OF RIGID BODY MODES

Figure 12 shows the XV-15 aeroelastic stability calculated with the rigid body degrees of freedom dropped from the set of equations of motion. The airframe elastic modes are still for the aircraft in free flight. Comparing figures 2 and 12, it is concluded that the stability boundary can be calculated satisfactorily without the aircraft rigid body motions, which are principally involved in the low frequency flight dynamics modes.

EFFECT OF LIFT DIVERGENCE

All the preceding results have used for the rotor blade aerodynamics a lift-curve slope which is corrected for compressibility effects by using the Prandtl-Glauert factor: $c_{l_\alpha} = a/(1 - M^2)^{\frac{1}{2}}$, where M is the section Mach number and a = 5.7 is assumed for the incompressible section lift curve-slope. At high Mach numbers, lift divergence reduces the lift-curve slope substantially. To examine the effect of lift divergence, the following approximation was used for the lift-curve slope above a section Mach number of M_{div}:

$$c_{l_\alpha} = a \frac{1 - M}{\sqrt{1 - M_{div}^2} \quad (1 - M_{div})}$$

The airfoil data for the XV-15 rotor blade indicate a lift divergence Mach number of $M_{div} = 0.68$. Using $M_{div} = 0.68$, no change was found in the aeroelastic stability boundary calculated at sea level, since at 320 knots the helical tip Mach number is only $M = 0.73$. The lift-curve slope determines the magnitude of the aerodynamic forces involved in tilting proprotor dynamics however, so if $M > M_{tip}$ over a significant portion of the rotor disk there will definitely be an influence on the stability. Figure 13 shows the damping calculated for an altitude of 3800 m using $M_{div} = 0.68$ (c.f. figure 6). The stability boundary is now at 420 knots (where the helical tip Mach number is $M_{div} = 0.87$). The lift-curve slope is reduced by lift divergence, so this compressibility effect has a favorable influence on the stability.

CONCLUDING REMARKS

This report has updated the predictions of the XV-15 tilting proprotor aircraft dynamic stability in cruise flight, with now a reduced pitch-gimbal coupling increase with collective and a higher nominal control system stiffness than used for reference 1. Both of these changes to the aircraft description are mildly stabilizing. The effect of lift divergence on the blade lift-curve slope has also been included, which is stabilizing when the helical tip Mach number is sufficiently far above the divergence Mach number. The currently predicted stability boundary is 320 knots at sea level and 420 knots at 3800 m altitude. The major effect of the pitch-lag coupling of the XV-15 gimballed, stiff-inplane rotor on the stability has been shown. The effect of the kinematic pitch-bending coupling is small, but eliminating the pitch-lag coupling by assuming an infinite control system stiffness greatly increases the stability boundary. The effect of the blade pitch dynamics is contained primarily in the quasistatic pitch-lag and pitch-gimbal coupling, but the other couplings present in the pitch equation of motion do influence the stability boundary. Thus for an accurate quantitative prediction of the boundary the complete pitch dynamics should be retained in the analysis.

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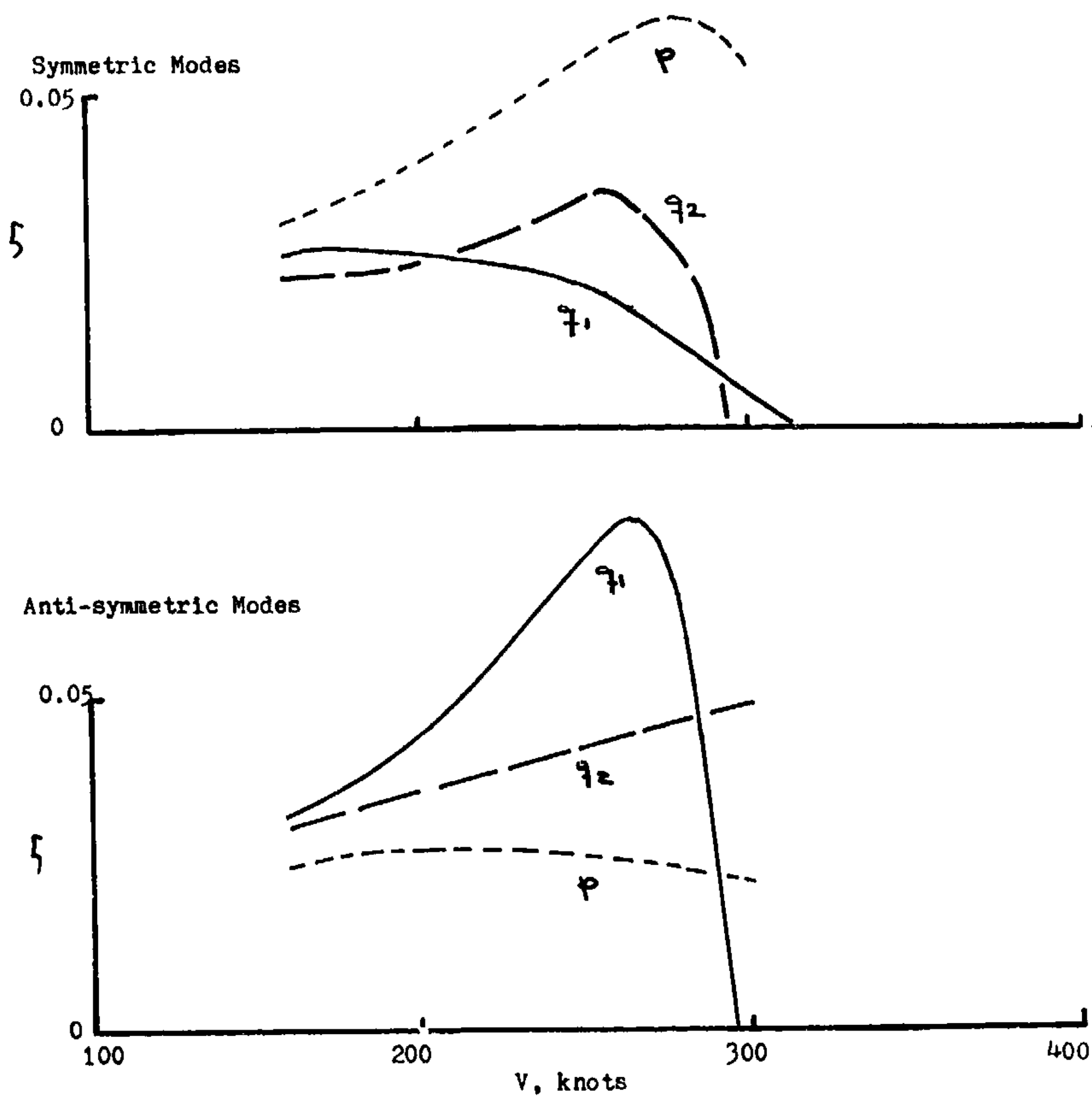


Figure 1 XV-15 aircraft aeroelastic stability in cruise flight at sea level: $\omega_\theta = 4.8/\text{rev}$ and old δ_3 variation.

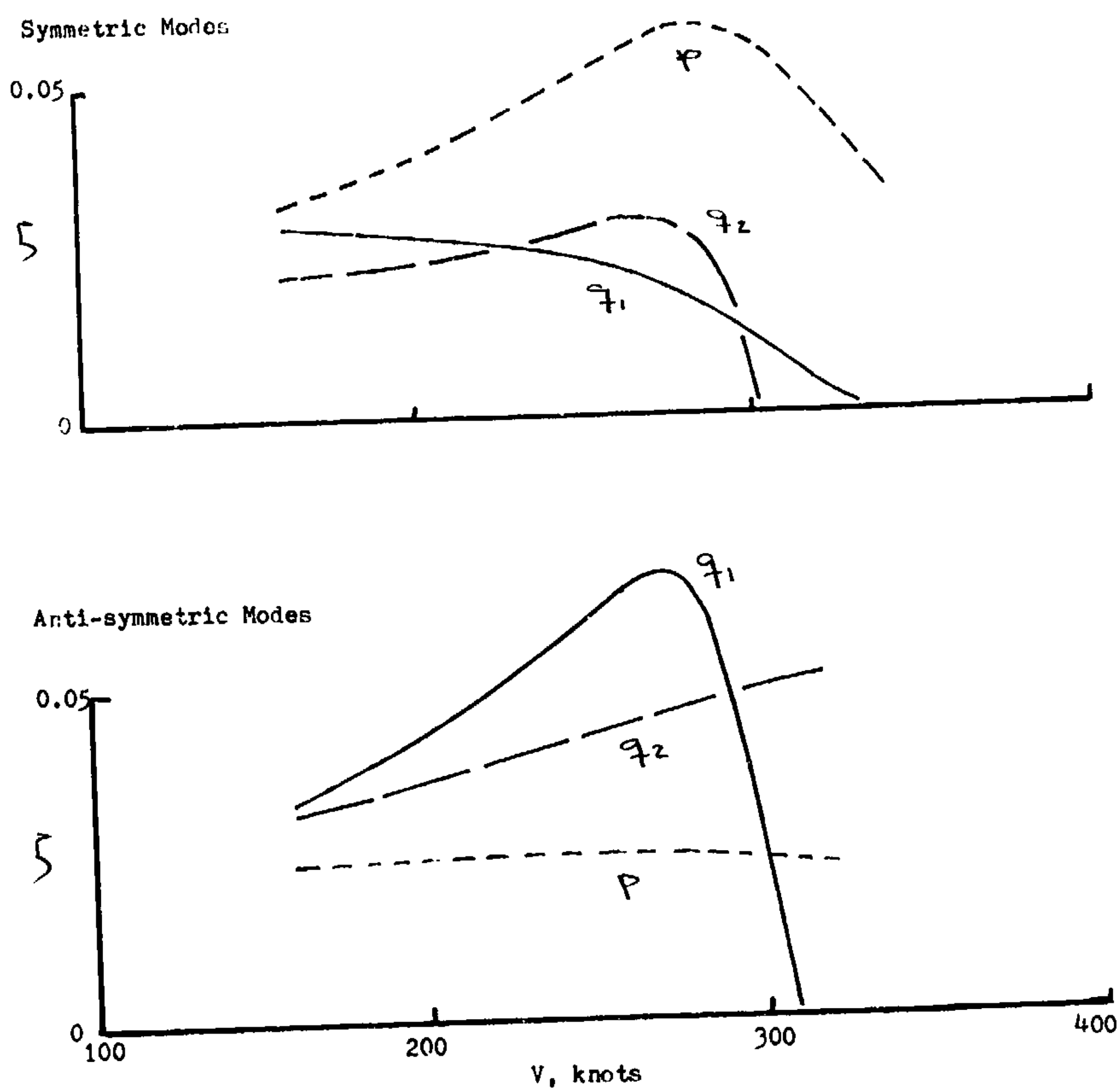


Figure 2 XV-15 aircraft aeroelastic stability in cruise flight at sea level: $\omega_\theta = 4.8$/rev and new δ_3 variation.

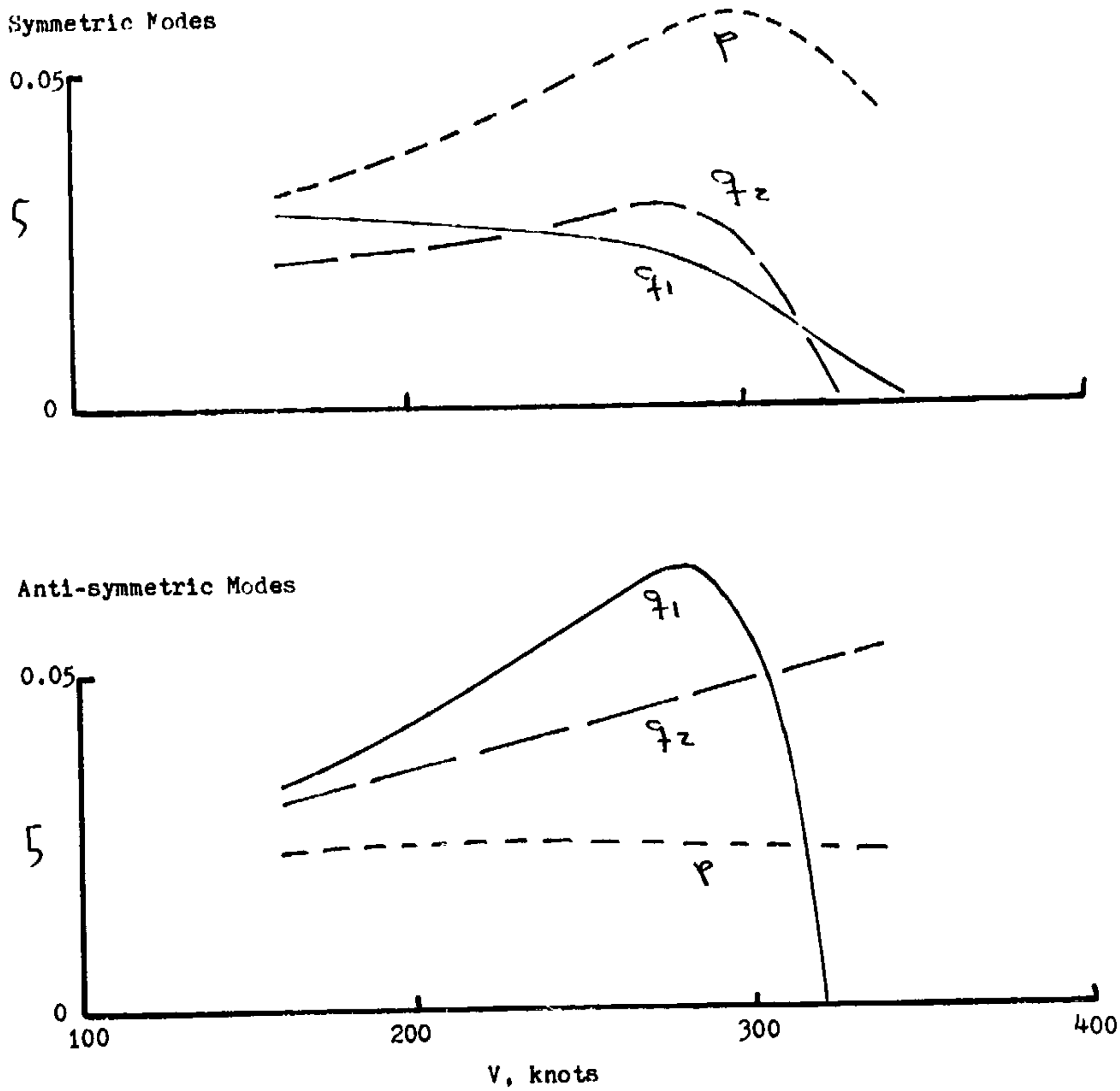


Figure 3 XV-15 aircraft aeroelastic stability in cruise flight at sea level: ω_θ = 5.4/rev and new δ_3 variation.

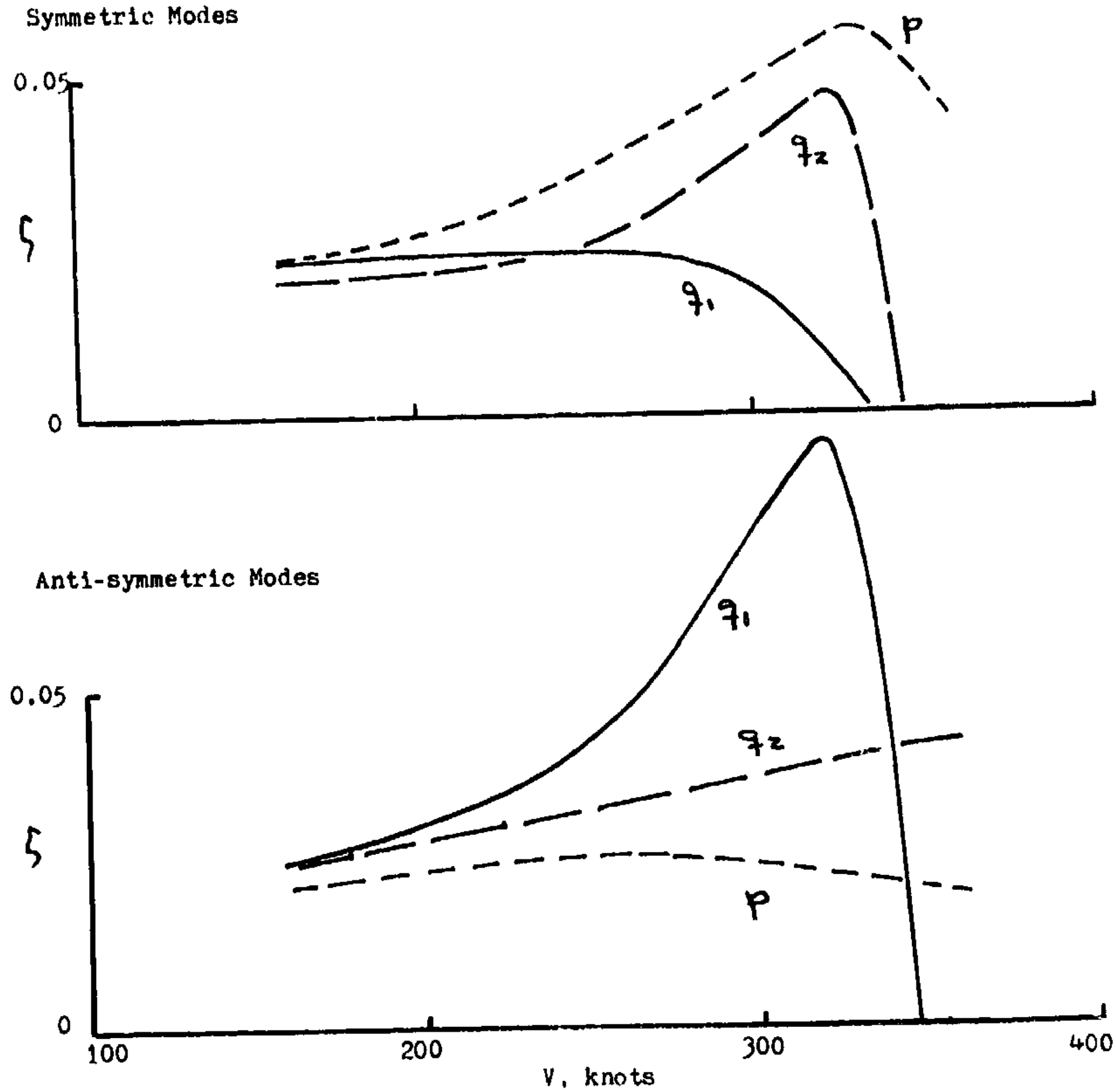
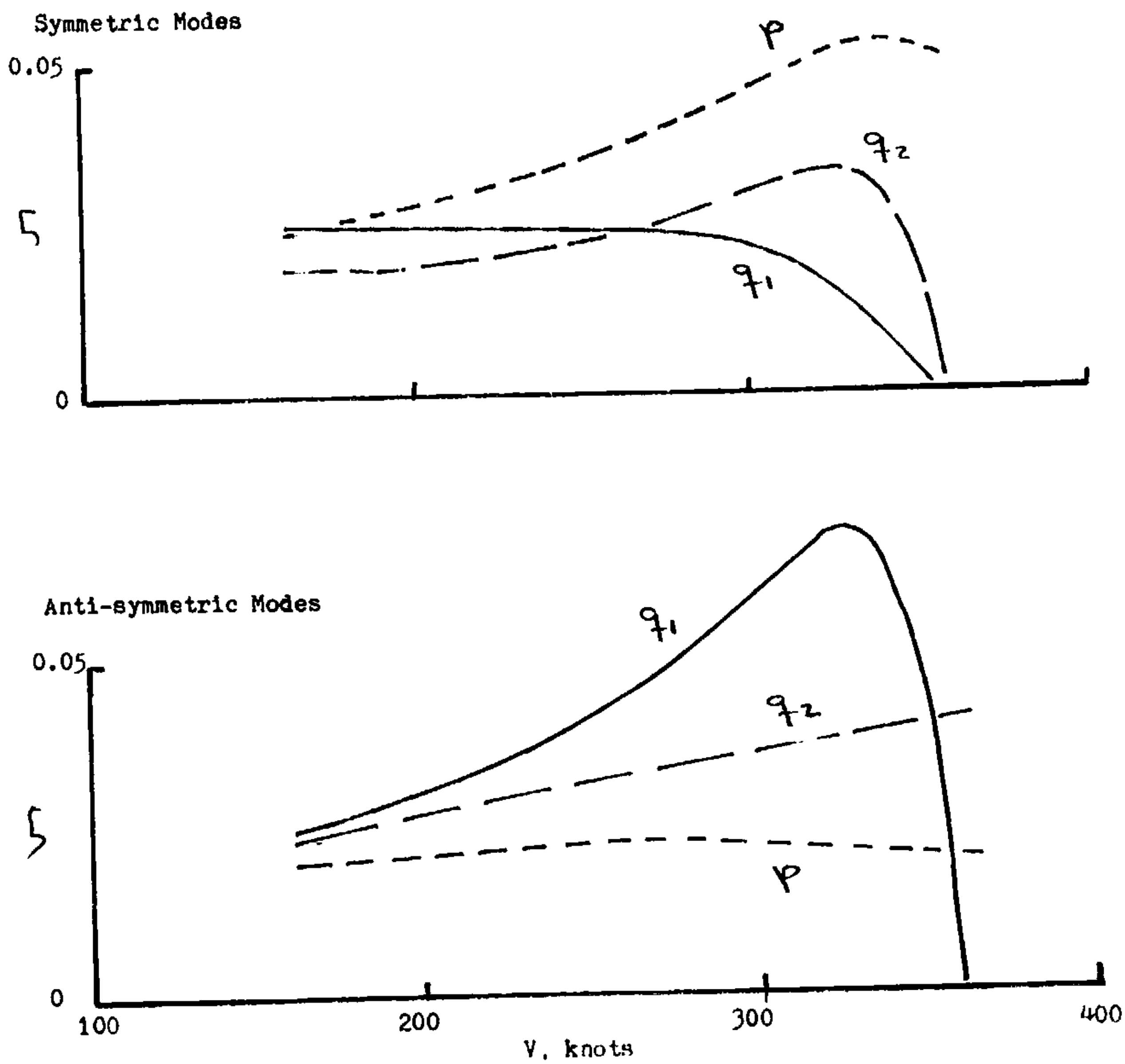


Figure 4 XV-15 aircraft aeroelastic stability in cruise flight at 3800 m altitude: ω_β = 4.8/rev and old δ_3 variation.



<u>Figure 5</u> XV-15 aircraft aeroelastic stability in cruise flight at 3800 m altitude: ω_θ = 4.8/rev and new δ_3 variation.

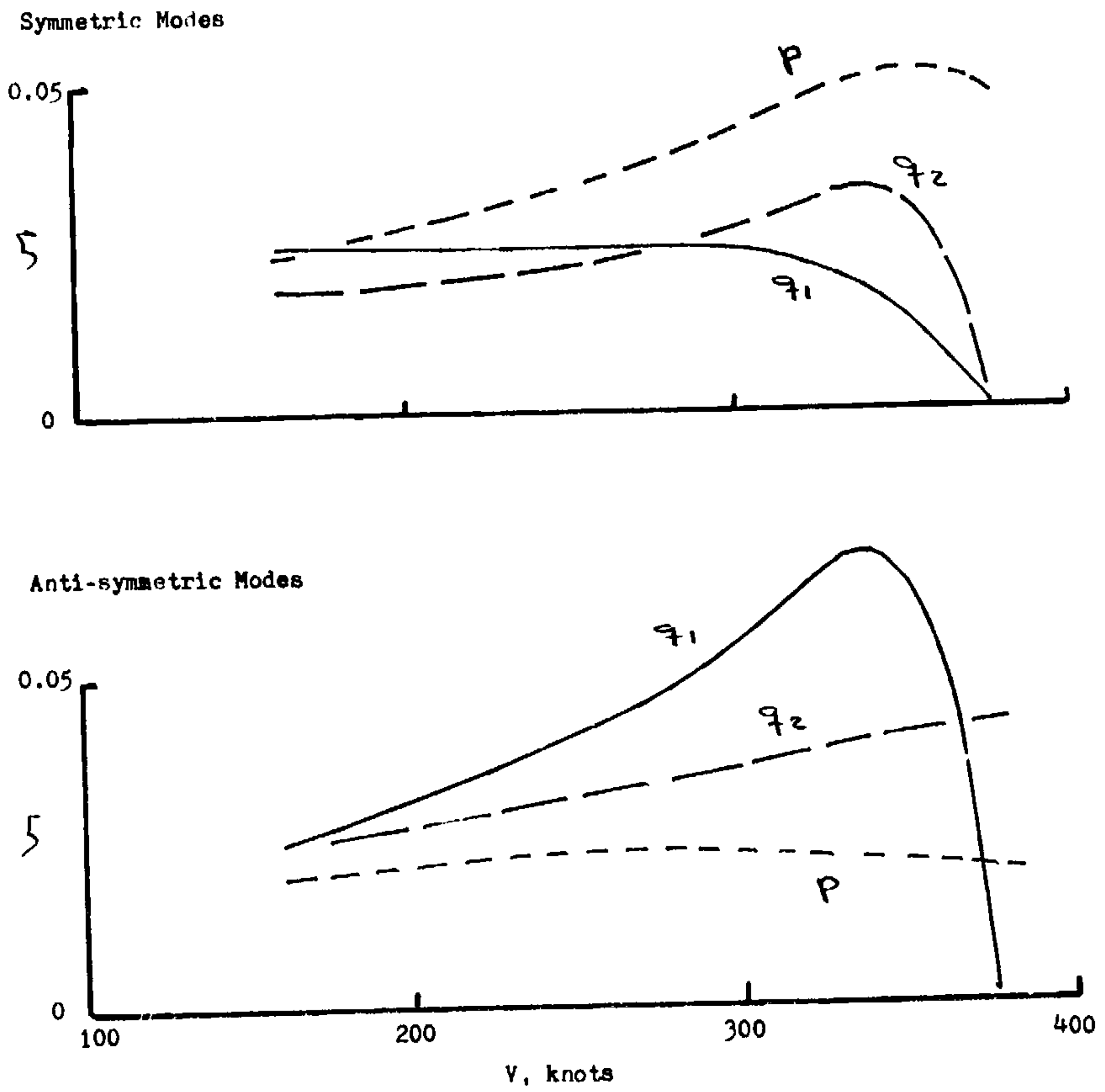


Figure 6 XV-15 aircraft aeroelastic stability in cruise flight at 3800 m altitude: $\omega_\theta = 5.4$/rev and new δ_3 variation.

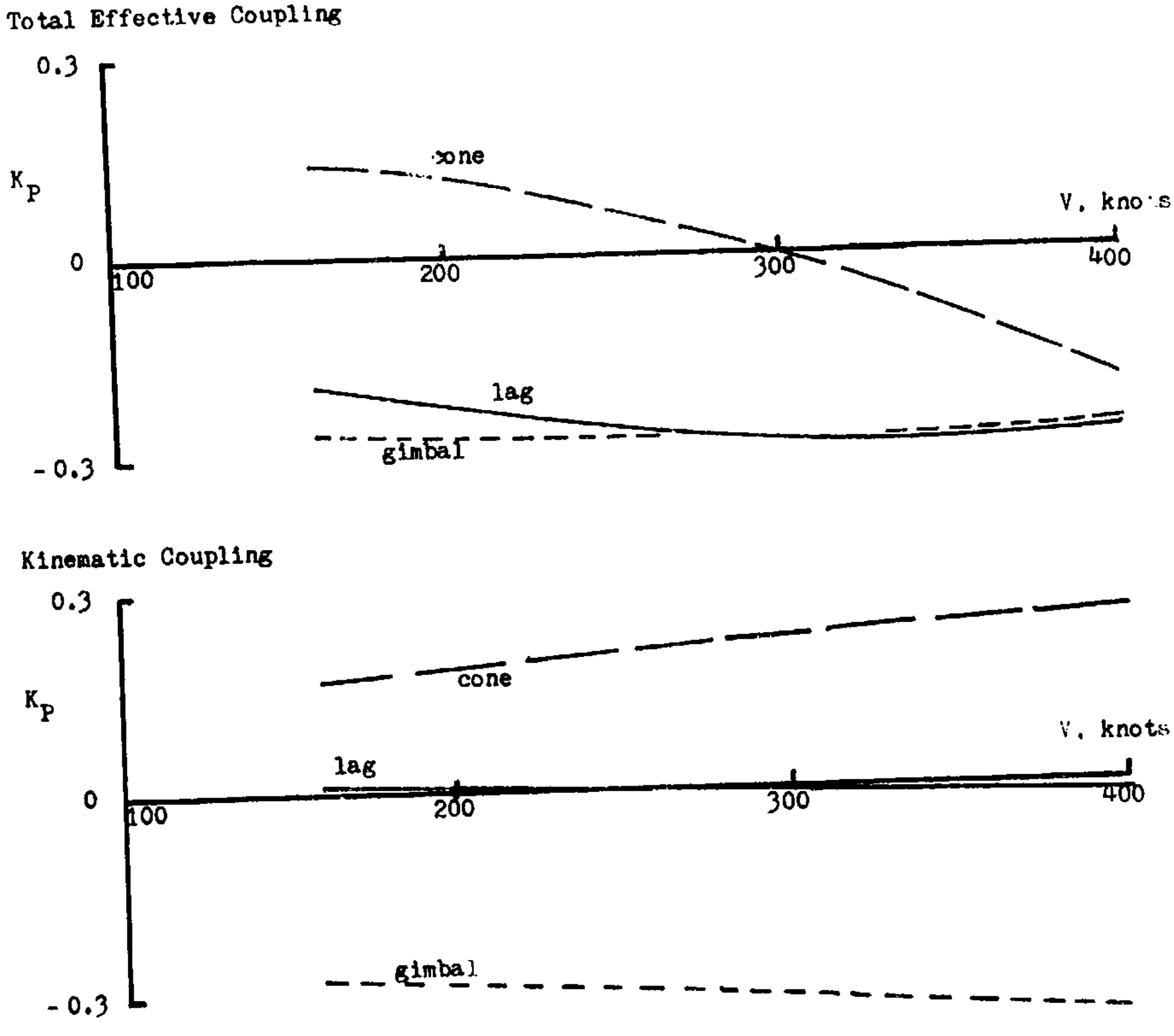


Figure 7 Pitch-bending and pitch-gimbal coupling of XV-15 aircraft in cruise flight at sea level (ω_B = 5.4/rev and new δ_3).

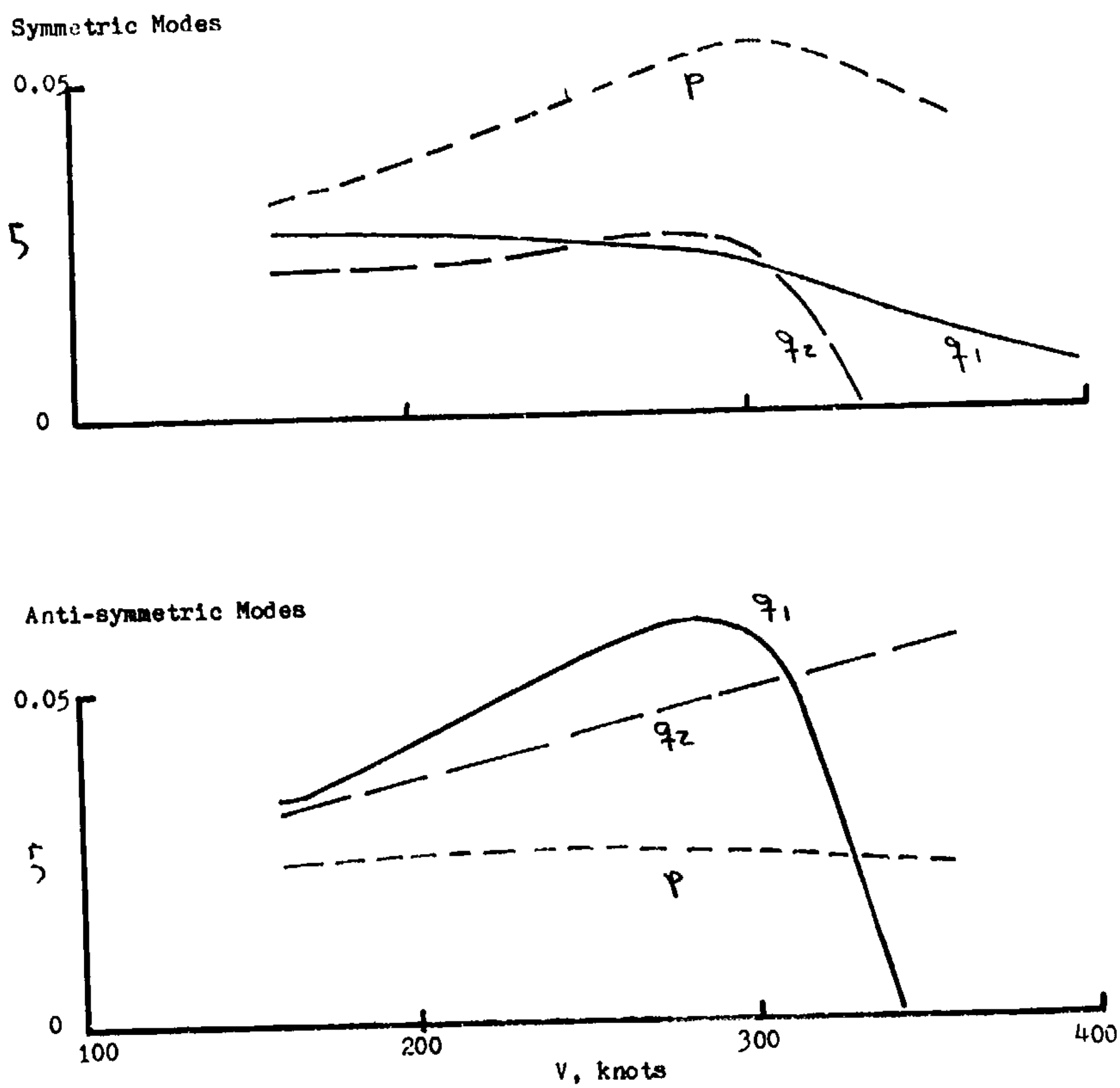


Figure 8 XV-15 aircraft aeroelastic stability in cruise flight at sea level: no torsion dynamics, total effective pitch-bending and pitch-gimbal coupling input (based on $\omega_\theta = 5.4$/rev and new δ_3).

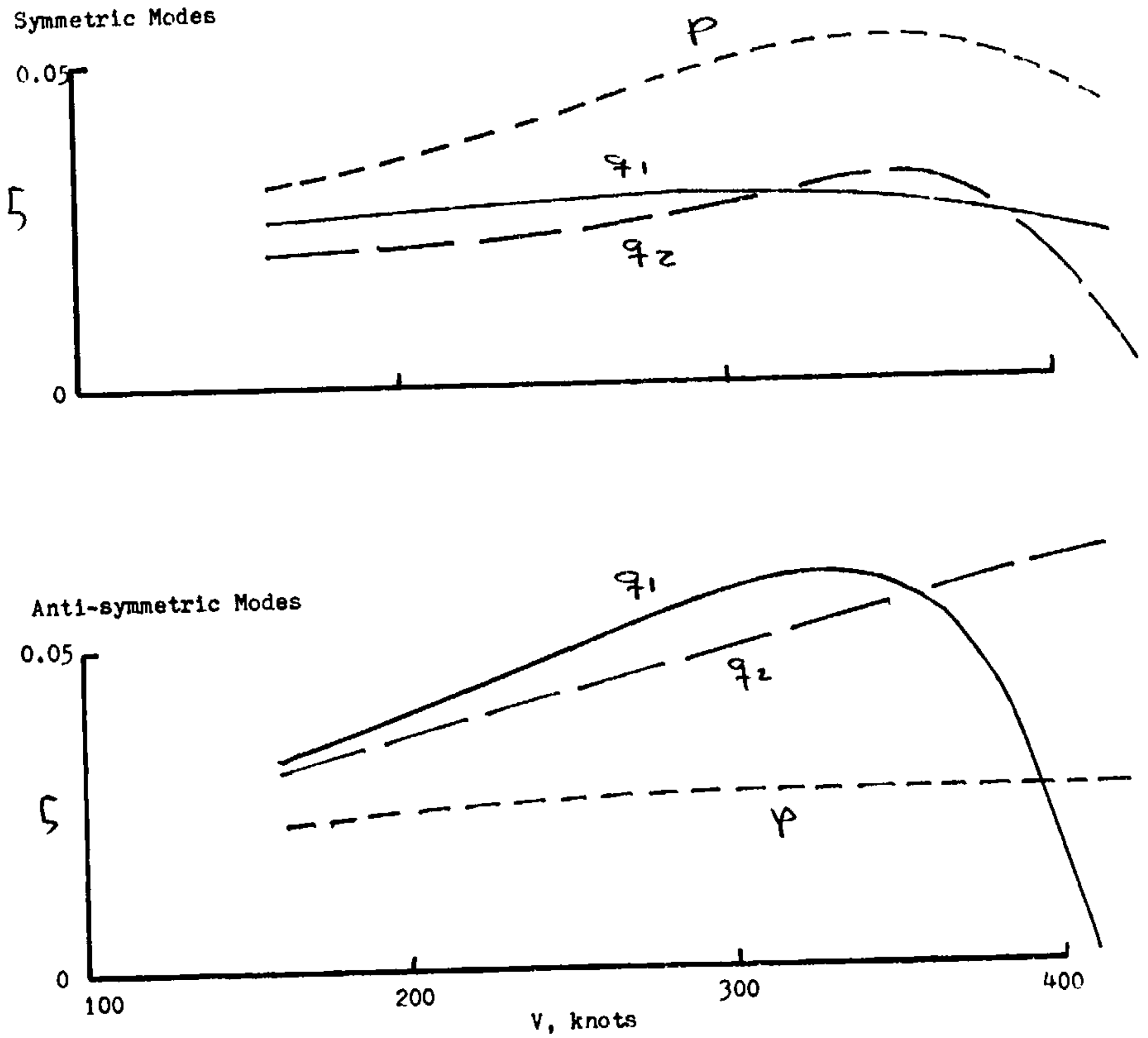


Figure 9 XV-15 aircraft aeroelastic stability in cruise flight at sea level: no blade pitch dynamics, kinematic pitch-bending and pitch-gimbal coupling only ($\omega_\theta = \infty$ and new δ_3).

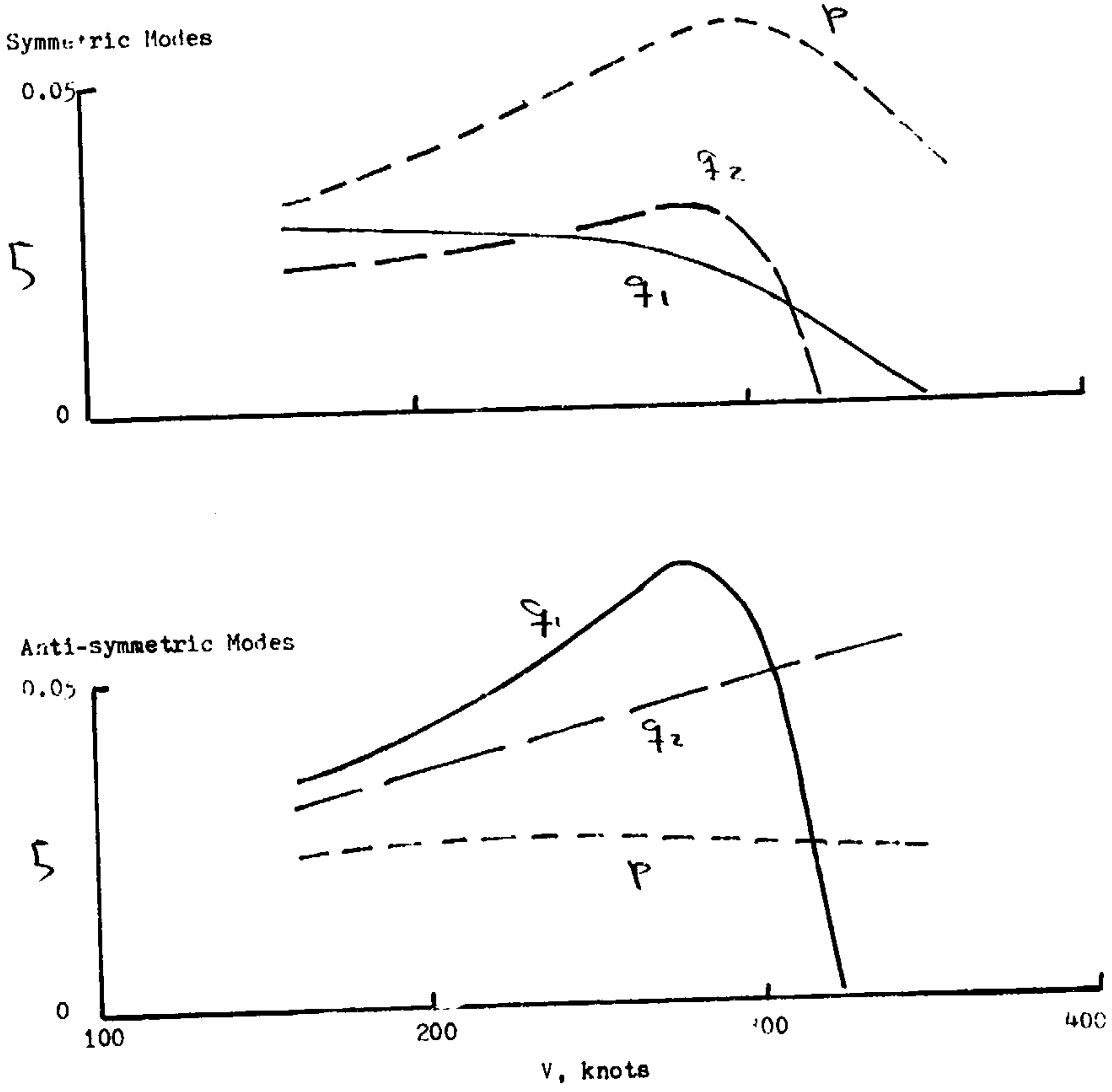


Figure 10 XV-15 aircraft aeroelastic stability in cruise flight at sea level. ω_θ = 5.4/rev, new δ.. and no kinematic pitch-bending coupling.

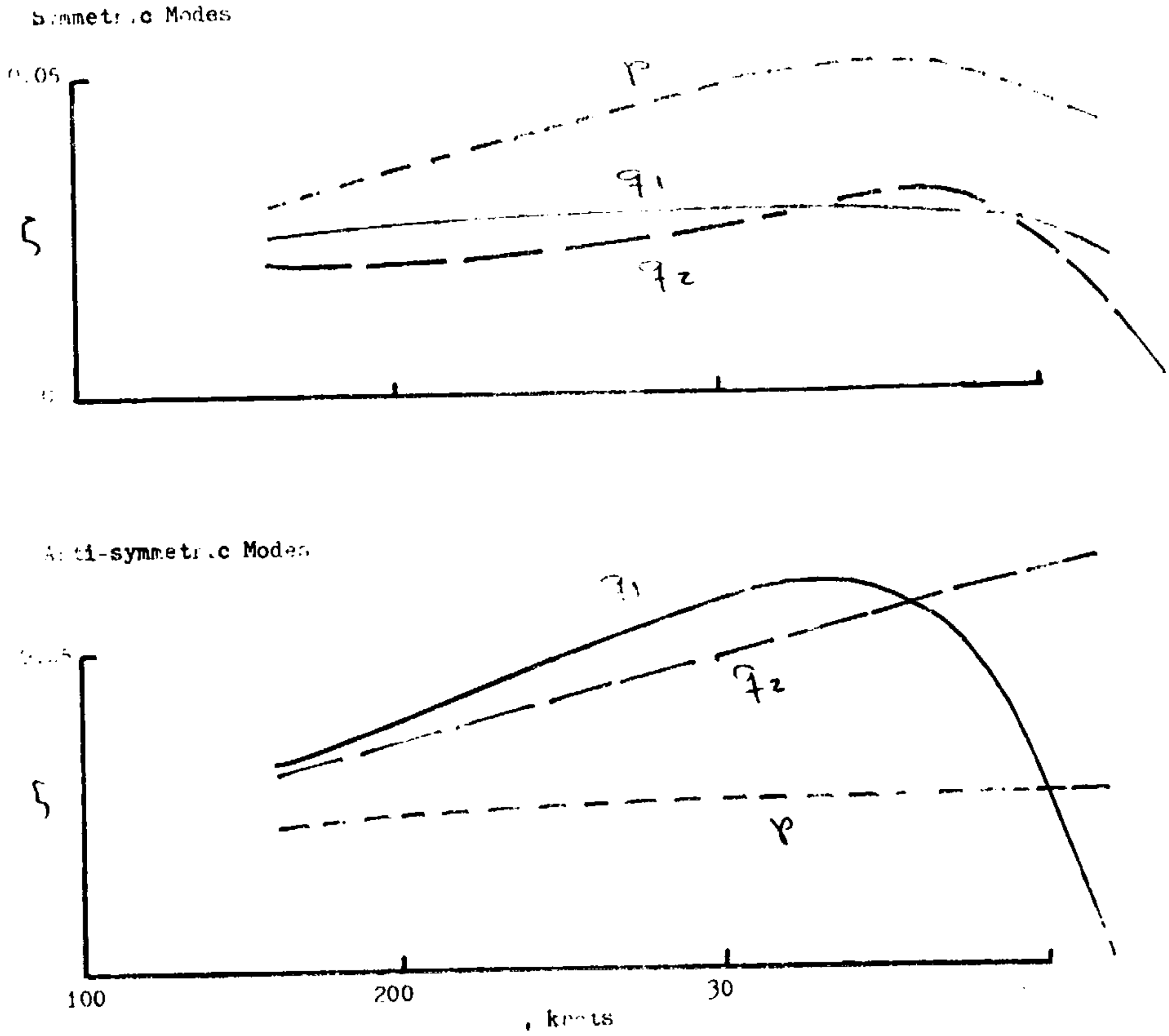
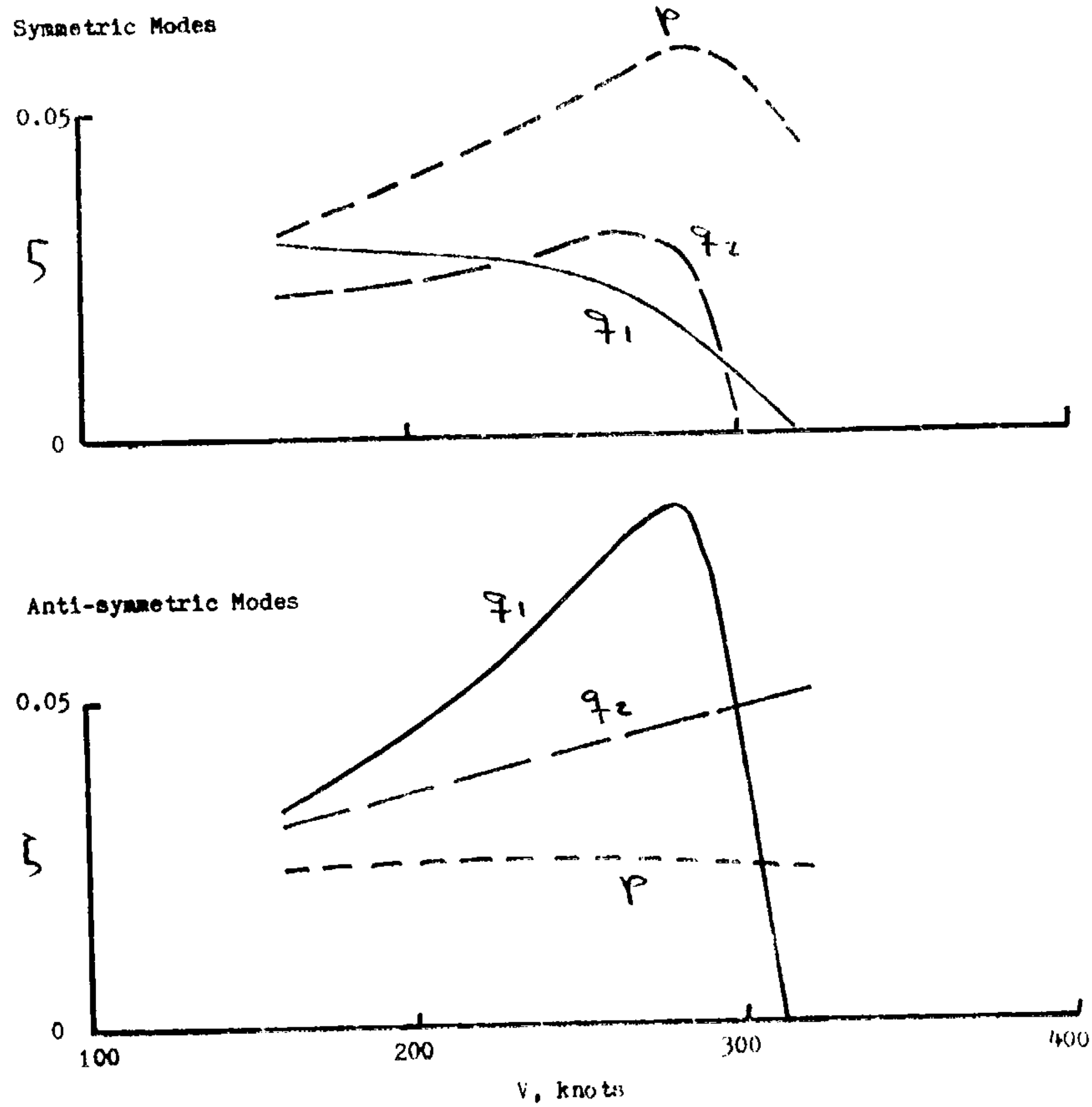
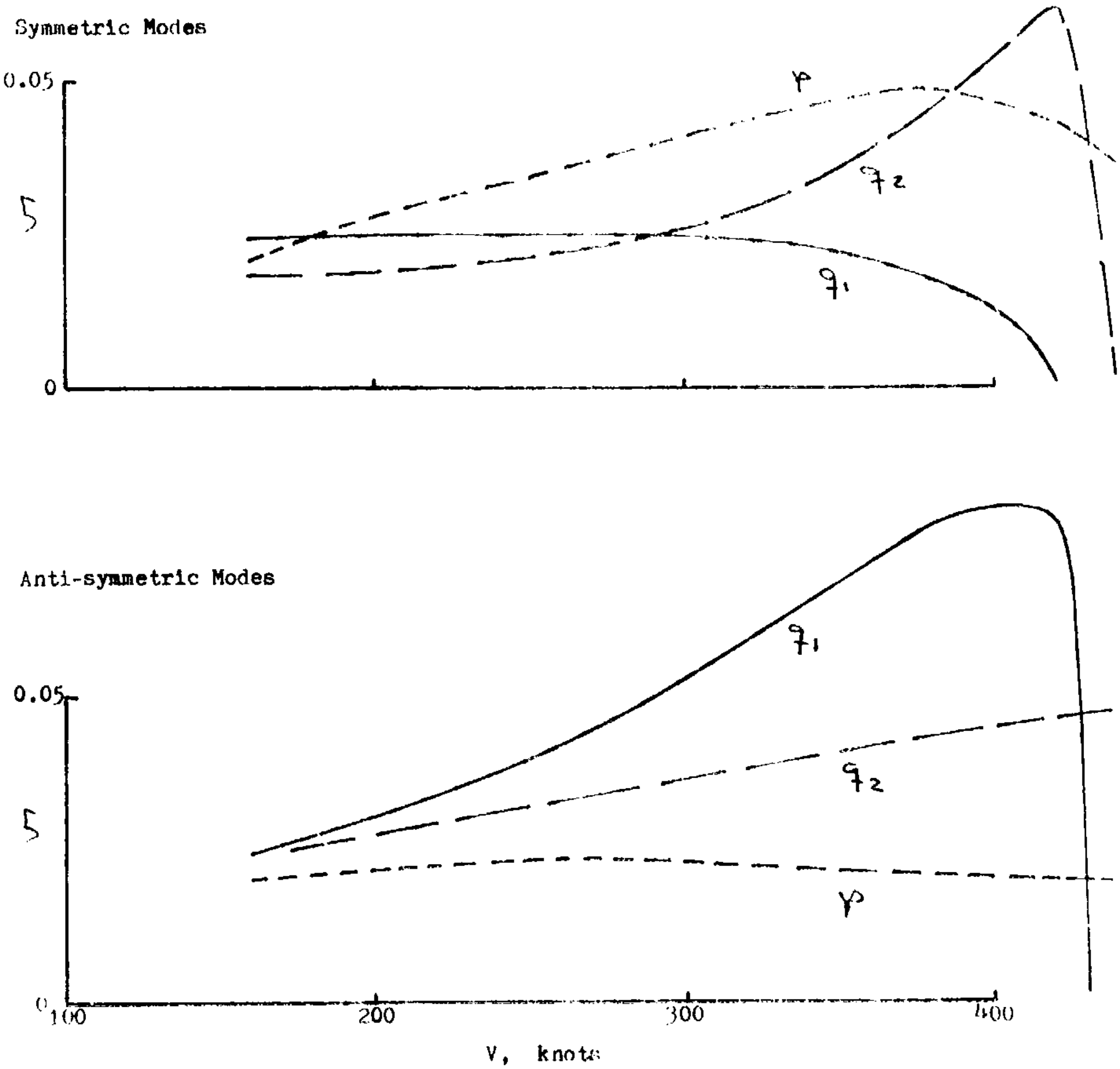


Figure 11 XV-15 aircraft aeroelastic stability in cruise flight at sea level: no blade pitch dynamics and kinematic pitch-gimbal coupling only ($\omega_{\theta} = \infty$, new δ_3, and no kinematic pitch-bending coupling).



<u>Figure 12</u> XV-15 aircraft aeroelastic stability in cruise flight at sea level: ω_β = 4.8/rev, new δ_3, and no rigid body motions.



<u>Figure 13</u> XV-15 aircraft aeroelastic stability in cruise flight at 3800 m altitude: lift divergence Mach number M_{div} = .69 (ω_θ = 5.4/rev and new δ_3).