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Decoupler Pylon: A Simple, Effective Wing/Store Flutter Suppressor

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As an alternative to alleviating wing/store flutter by conventional passive methods or by more advanced active control methods, a quasi-passive concept referred to as the decoupler pylon is investigated which combines desirable features of both methods. Passive soft-spring/damper elements are used to decouple wing modes from store pitch modes, and a low-power control system maintains store alignment under changing mean loads. It is shown by analysis and wind tunnel tests that the decoupler pylon provides substantial increase in flutter speed and makes flutter virtually insensitive to inertia and center-of-gravity location of the store.

Nomenclature

b	= wing semichord
e	= store pivot location measured from leading edge of wing
g_θ	= damping of store pitch mode
I_s	= mass moment of inertia of store about pivot
M	= wing mass
M_s	= store mass
q	= flutter dynamic pressure of the wing with store
q_w	= flutter dynamic pressure of the wing without store (clean wing)
r_s	= store radius of gyration about pivot
x_s	= store center of gravity (c.g.) location measured from store pivot, positive aft
y	= spanwise location of store measured from wing root
l	= wing span
ω_f	= flutter frequency
ω_{h_l}	= fundamental wing bending frequency with rigidly mounted store
ω_{α_l}	= fundamental wing torsion frequency
ω_θ	= uncoupled store pitch frequency

Introduction

CURRENT fighter/attack aircraft are required to carry a large variety of external stores mounted at various locations on the wing (Fig. 1). Each store station must accommodate an array of store configurations, some whose mass and inertia properties change during flight. Thus, on a single aircraft, there are literally thousands of possible store loading combinations.

Because the attachment of stores to an aircraft wing has led to substantial reductions in flutter speeds, extensive analysis, wind tunnel testing, and flight flutter testing are required to assure safety from flutter.[1-3] For flutter-critical store configurations, either the flutter speed must be raised by some means or a flutter placard placed on the aircraft operating envelope.

The flutter speed can be raised by conventional passive methods or by more advanced methods involving active control technology. Some examples of passive methods are: adding mass ballast, changing stiffness of the wing or the store pylon, and relocating the wing/store attachment point. Passive schemes of this kind are generally tailored for a specific store configuration and are not readily changed to accommodate the necessary broad range of store mass and inertial combinations.

Active flutter suppression concepts have been the subject of considerable research in recent years.[4-8] Compared with passive methods, active control of flutter has the advantage of possible weight savings plus versatility to accommodate a variety of store combinations by merely changing the control law. With active flutter suppression, the onset of flutter is sensed by transducers on the structure and, with appropriate feedback control laws, used to produce forces that oppose

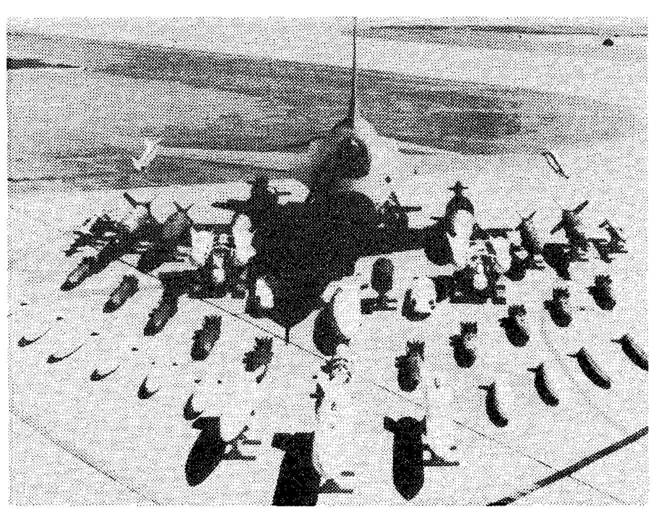

Fig. 1 Wing stores carried by fighter/attack aircraft.

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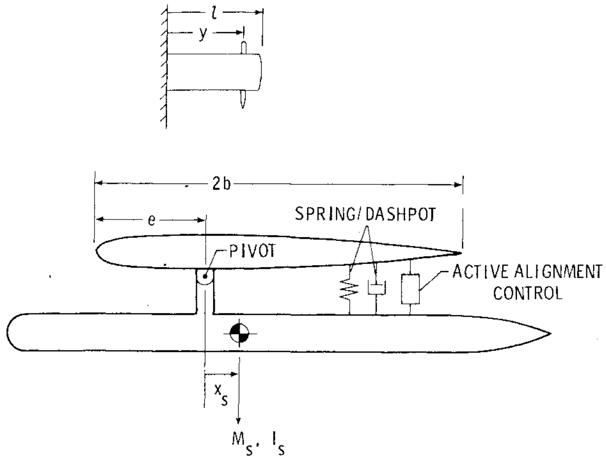

Fig. 2 Decoupler pylon system.

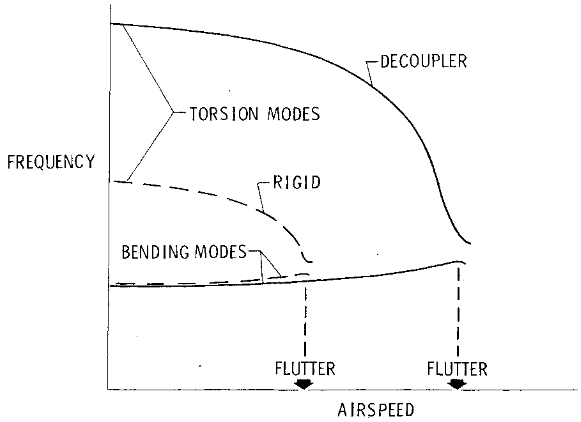

Fig. 3 Decoupler pylon increases frequency separation of flutter-critical modes.

flutter. In most active flutter suppression schemes, aerodynamic control surfaces are actuated in a manner to counteract the aerodynamic forces that produce flutter. A major difficulty in implementing this approach comes from the need for accurate knowledge of unsteady aerodynamic forces produced by the control surfaces, particularly in the transonic speed range where theoretical predictions are least reliable and flutter concerns usually most critical. Reliability of active control systems is another important concern.

A particular active flutter suppression concept investigated by Triplett et al.[6] uses hydraulic actuators as the load-carrying tie between wing and store. Through feedback control, the actuators nullify dynamic loads but transmit steady loads to the wing. By dynamically decoupling the wing/store system in this way, the flutter mechanism and speed revert to that of the bare wing. Unfortunately, this potentially promising scheme for wing/store flutter control was found to be impractical due to excessive hydraulic flow rates required by the actuators.

The concept presented herein involves combining desirable features of both active and passive flutter suppression methods while at the same time avoiding some inherent disadvantages associated with either approach if used alone. The concept, called the decoupler pylon, features a store-suspension pylon which dynamically decouples the wing from pitch motions of the store. Passive soft-spring/damper elements are used to isolate the store in pitch at the flutter frequency while a low-power active control system maintains store alignment under changing mean loads such as maneuvers or drag loads. It is shown that this isolation provides a marked increase in flutter speed and makes flutter virtually insensitive to variations of store inertia and center of gravity location.

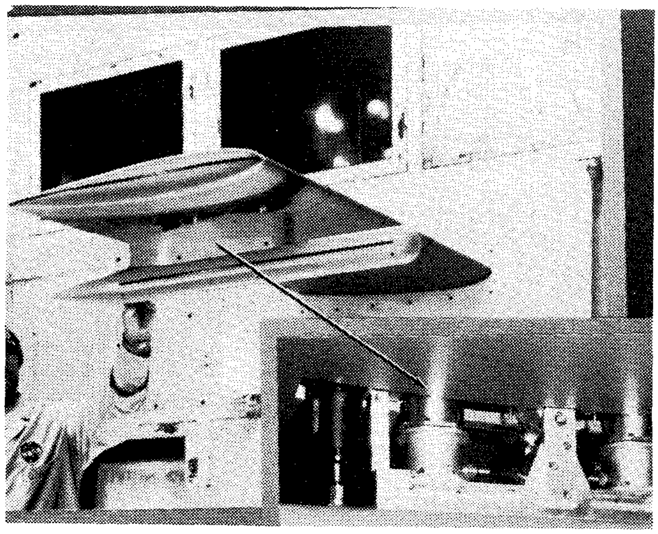

Fig. 4 Wing/store flutter model with decoupler pylon.

In this report the effectiveness of the decoupler pylon is demonstrated by analysis and wind tunnel model studies, and the results of parametric variations of some important flutter parameters are presented.

Decoupler Pylon Concept

A schematic illustration of the decoupler pylon system studied herein is shown in Fig. 2. The store is pivoted near the wing elastic axis. Frequency and damping of the store pitch mode are controlled by passive spring/dashpot elements. To avoid large static deflections normally associated with low-frequency suspension systems, a low-power servo control system is used to maintain alignment of the store relative to the wing under conditions of varying load.

The basis for decoupling wing modes from the store pitch mode as a means to increase flutter speed may be discussed with reference to Fig. 3. Wing bending-torsion flutter involves coupling of at least two natural vibration modes, one or more of which contain torsional deformations of the wing. In Fig. 3 are shown analytically predicted frequencies of two wing modes which couple as flutter is approached. The dashed pair of curves represent a rigidly attached store; the solid pair represent a decoupler-pylon mounted store. In both cases flutter occurs when the bending and torsion frequencies come close together. Since the decoupler pylon isolates the wing from inertia moments associated with store pitch, the wing torsion frequency with the decoupled store is substantially higher than that for the wing with the store rigidly attached (being about the same as for the bare wing). The bending frequency, however, is less than the bare wing bending frequency in both cases. Thus, as illustrated in Fig. 3, the decoupler pylon increases the frequency separation between the flutter-critical modes, and, as a consequence, the flutter speed is increased.

System Studied

General

Analyses and wind tunnel experiments were conducted to isolate and show the influence of various parameters affecting wing/store flutter. The parameters investigated (see Table 1 and Fig. 2) are: $\omega_\theta/\omega_{h_1}$, ratio of uncoupled store pitch frequency to fundamental bending frequency of the wing with store rigidly attached; x_s, horizontal distance between store center of gravity and pitch axis; r_s, store radius of gyration about the pivot; y, spanwise location of store on wing; e,

Table 1 Wind tunnel model configurations and flutter characteristics

Store configuration (• ballast weight)	x_s/b	$(r_s/b)^2$	$\omega_\theta/\omega_{h_l}$	$\omega_{\alpha_l}/\omega_{h_l}$	q/q_w Experiment	q/q_w Theory
1	−0.010	0.416	Rigid	1.29	0.61	0.57
			1.56	1.11	0.29	0.36
			1.04	1.34	2.98[b]	4.30
			0.54	2.59	1.89	1.96
2	0.325	0.577	Rigid	1.45	0.49	0.39
			0.44	2.29	2.92	2.32
3	−0.413	0.692	0.89	...[a]	2.32	1.96
4	−0.010	0.684	Rigid	1.15	0.23	0.17
			0.42	2.63	2.32	1.98
5 Wing without store	...	...	...	2.1	...	1.0

[a]Not measured. [b]No flutter.

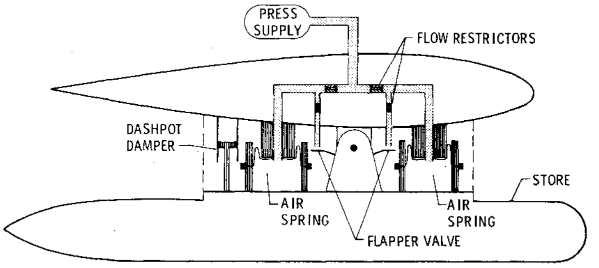

Fig. 5 Experimental decoupler pylon model.

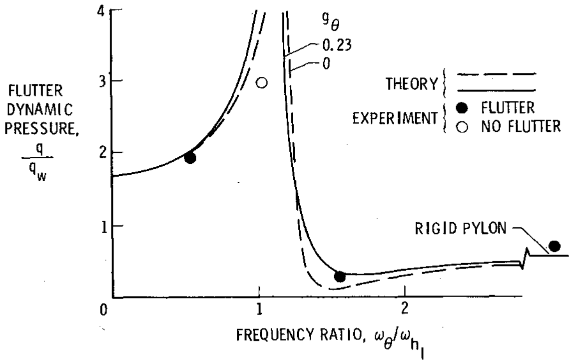

Fig. 6 Effect of store pitch frequency.

chordwise distance from the wing leading edge to the pivot axis; M_s/M, mass of store relative to mass of wing; and g_θ, pitch damping of the store.

Wind Tunnel Model

The model experiments were conducted in the Langley Transonic Dynamics Tunnel at low subsonic speeds at atmospheric pressure. The model is shown mounted in the wind tunnel test section in Fig. 4. It consists of a rectangular, aspect ratio-5 wing that is cantilevered at the root and carries a single store pivoted near the wing elastic axis. The wing structure is made of a constant cross-section aluminum spar onto which are attached lightweight balsa shells having the shape of a 12% thick symmetrical airfoil section. A splitter plate at the wing root separates the wing from the boundary layer of the test section wall. The store, with mass of 64% of the wing mass, attaches to the wing at spanwise station $y/l = 0.815$. The store pitch axis and wing elastic axis are both located at the 30% chord station. Two movable masses housed within the store provide a means for varying the inertia and c.g. location.

Experimental Decoupler Pylon Model

As a simple means of mechanizing the decoupler pylon for these wind tunnel studies, an all-pneumatic system was devised. Pneumatic springs have an advantage over mechanical springs in that low stiffness can be maintained without the large static deflections usually associated with low-frequency suspension systems. This feature is possible because the gas in the spring can be compressed to the pressure required to counteract steady external loads while retaining low stiffness necessary for vibration isolation. A photograph of the experimental model is shown in Fig. 4, and a schematic diagram in Fig. 5. The air springs are connected between the wing and the store on either side of the pivot axis. Pitch stiffness is governed by the average pressure in the air springs and pitch alignment by the pressure difference. This pressure difference is achieved by flapper-type valves which allow excess pressure to vent from the air springs. Thus, when the store pitches due to a change in external load (drag), the vent on the side of the compressed spring is sealed by the flapper valve, causing a pressure buildup in that spring; whereas, the vent on the side of the extended spring opens, allowing pressure to escape. This pressure difference provides the feedback mechanism needed for automatic alignment of the store. Also indicated in Fig. 5 is a dashpot damper which was used to avoid an instability that is possible with such a feedback control system. A comprehensive treatment of the stability of pneumatic isolators with automatic centering control is given in Ref. 9.

Adverse coupling between the store alignment and wing/store flutter modes or the aircraft dynamic stability modes is a possibility that should be examined. In the present studies, however, such coupling was of no consequence since the time constant of the alignment system was much greater than the period of the flutter mode, and aircraft dynamic stability modes were not simulated in the wind tunnel.

Analytical Model

The analytical flutter model considered was that of a uniform cantilevered wing with a pivoted, sprung mass attached at arbitrary spanwise and chordwise locations. The equations for flutter were developed in terms of uncoupled vibration modes. Specifically, eight degrees of freedom were considered: four uncoupled uniform beam bending modes, three uncoupled uniform beam torsion modes, and store pitch. Unsteady aerodynamic forces on the wing were represented by two-dimensional incompressible flow theory, and aerodynamic forces on the store were neglected. The decoupler pylon was modeled as a simple linear spring since, as stated earlier, there was negligible coupling between flutter modes and the store alignment control system.

Flutter Studies

General

Flutter characteristics of the wing/store system as determined from wind tunnel tests and analysis are presented and discussed in the following sections of this paper. In Figs. 6-11, the onset of flutter, as a function of various parameters, is

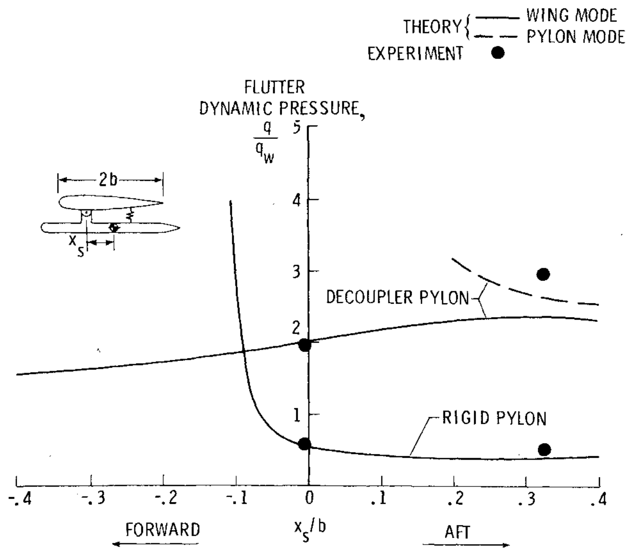

Fig. 7 Effect of store c.g. location.

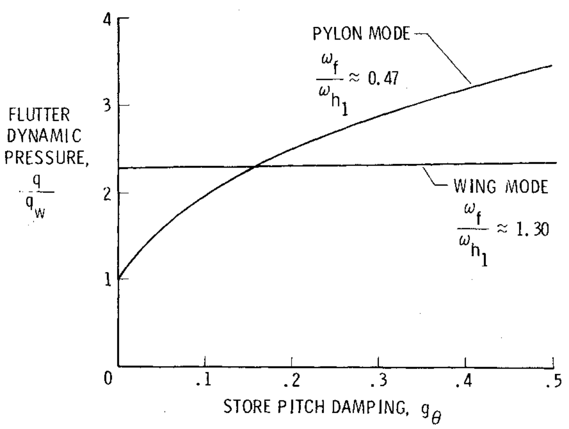

Fig. 8 Effect of store pitch damping (configuration 2).

presented as the ratio q/q_w, where q is the flutter dynamic pressure of the wing/store system and q_w the flutter dynamic pressure of the clean wing. To minimize the risk of model damage, flutter onset conditions were estimated by a subcritical flutter testing technique called the peak-hold spectrum method.[4]

Experimental flutter data were obtained for a total of four combinations of store inertia and c.g. location, using various levels of pitch spring stiffness. The model parameters that were varied, together with the measured and predicted flutter dynamic pressure for each configuration, are presented in Table 1.

Influence of Various Parameters on Wing/Store Flutter

Store Pitch Frequency

One of the basic parameters in this study is the uncoupled store pitch frequency. Shown in Fig. 6 is the variation of flutter dynamic pressure ratio q/q_w with store pitch/wing bending frequency ratio $\omega_\theta/\omega_{h_l}$ for store configuration 1 (see Table 1). This plot may be discussed in terms of three regions of pylon stiffness: stiff ($\omega_\theta/\omega_{h_l} \leq 1.5$), tuned ($0.7 < \omega_\theta/\omega_{h_l} < 1.5$), and soft ($\omega_\theta/\omega_{h_l} \leq 0.7$). In the "stiff" region, which is representative of current design practice, it is seen that flutter always occurs at a dynamic pressure below that for the clean wing, i.e., $q/q_w < 1$ (the rigid pylon case being about 60% of the clean wing flutter dynamic pressure). From trends shown in Fig. 6, it might appear desirable to select a pylon stiffness corresponding to the "tuned pylon" region because there flutter speed is highest. Flutter speed, however, is not the only factor to be considered. An equally important consideration is the sensitivity of flutter to changes in store inertia and c.g. location. Whereas in the "tuned pylon" region it can be shown that flutter is sensitive to store inertia and c.g. location, in the "soft" (decoupler pylon) region these parameters have little influence on flutter and the flutter speed remains well above that for the wing with no store at all.

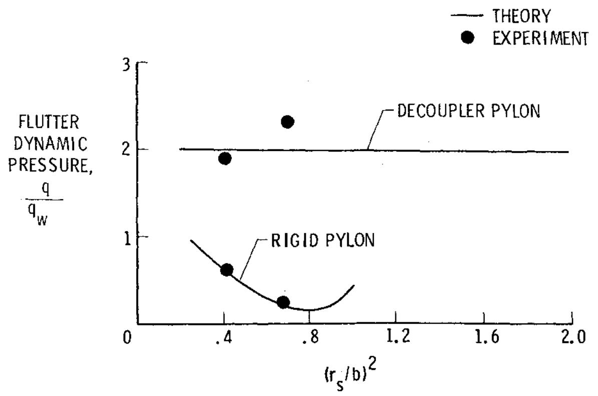

Fig. 9 Effect of store radius of gyration.

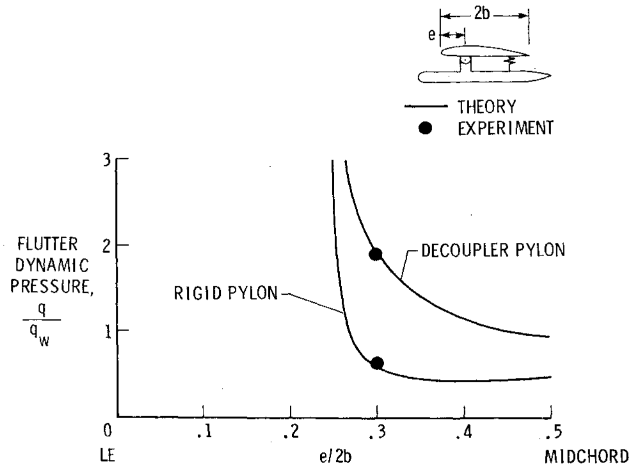

Fig. 10 Effect of store pivot location.

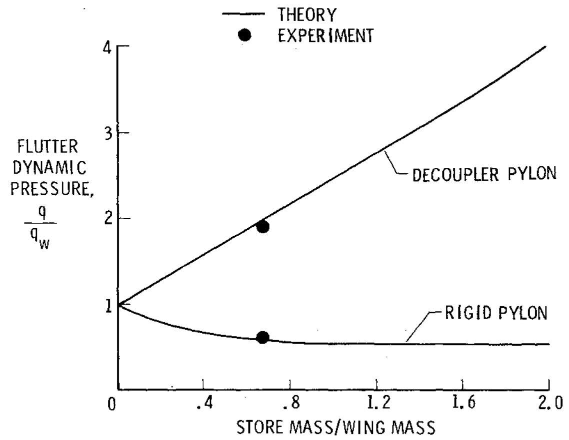

Fig. 11 Effect of store mass.

The remainder of this study will deal with the soft pylon case. Specifically, in all subsequent cases where other parameters are varied, the pylon stiffness is held constant at the value corresponding to the experimental point at $\omega_\theta/\omega_{h_l}=0.54$ in Fig. 6 and Table 1.

Center-of-Gravity Location

To study the effects of store c.g. location x_s/b the position of ballast in the store was varied, keeping the store mass and pylon stiffness constant. Measured and predicted flutter boundaries for the rigid-mounted store and the decoupler-pylon mounted store are presented in Fig. 7.

For the decoupler-pylon case, analysis predicted two flutter modes: a wing mode, which involved coupling between wing bending and wing torsion modes, and a pylon mode, which occurred for aft c.g. locations only at approximately the frequency of store pitch. Only wing-mode flutter was observed in the wind tunnel experiments. Over the rather broad range of store c.g. travel presented in Fig. 7, the flutter dynamic pressure for the decoupler pylon was always at least 1.5 times greater than that for the wing without store. For the rigid pylon case with the c.g. aft, flutter occurs at a dynamic pressure about one-half that for the clean wing case, but, when the c.g. is moved forward of $x_s/b=-0.1$, flutter no longer exists.

As stated before, the analytically predicted pylon flutter mode for aft c.g. locations was not observed in the wind tunnel model studies. The reason may have been due to structural damping of the store pitch mode. Analytical results shown in Fig. 8 indicate that store pitch damping has a strong stabilizing influence on flutter of the pylon mode but does not affect wing flutter. The store pitch damping measured on the model was approximately $g_\theta=0.23$.

Radius of Gyration

The store radius of gyration about the pivot was varied by changing the separation distance between two ballast weights in the model store (see Table 1). Results for this case are presented in Fig. 9. Again the decoupler pylon increases the flutter dynamic pressure and flutter becomes insensitive to variations in store radius of gyration. This insensitivity to variations in store c.g. and inertia properties can greatly simplify and reduce analysis and testing required to flutter-clear aircraft that must carry a large variety of store configurations.

Pivot Location

Analytical prediction of flutter trends as a function of the chordwise location of the store point pivot, $e/2b$, are presented in Fig. 10. Since changing the pivot location is equivalent to changing the chordwise location of a mass attached to the wing, similar trends are shown for both the rigid pylon and the decoupler pylon. In fact, the rigid pylon case in Fig. 10 is basically the same as that presented in Fig. 7. The difference between the two flutter boundaries in Fig. 10 can be attributed to differences in the effective store pitch inertia experienced by the wing in the two cases. The decoupler pylon case has a lower effective inertia and a higher flutter dynamic pressure than the rigid pylon case.

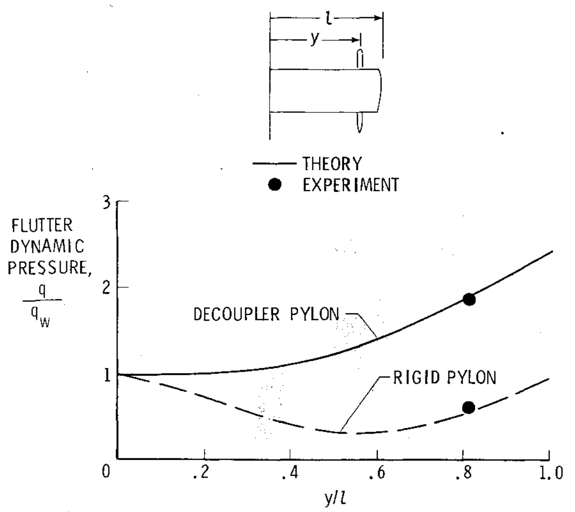

Fig. 12 Effect of spanwise store location.

Store Mass

The effect of varying store mass relative to wing mass was also studied analytically, and the results for store configuration 1 are shown in Fig. 11. Note that with increasing store mass the flutter dynamic pressure for the rigid pylon is reduced, becoming constant at about one-half the clean-wing value. On the other hand, trends predicted for the decoupler pylon show that the addition of store mass has a strong favorable influence on flutter. For example, a store with twice the mass of the wing raises the bare-wing flutter dynamic pressure by a factor of 4.

Spanwise Store Location

As in the two preceding examples, analysis alone was used to predict the effect of change in another parameter which was not varied in the experiments, namely spanwise store location y/l for configuration 1. Results presented in Fig. 12 show that flutter speed is degraded for all spanwise locations of the rigid pylon, the worst being at $y/l=0.6$. In contrast, the flutter speed for the decoupler pylon increases continuously as the store is moved toward the wing tip.

Other Considerations

Points not addressed in the present study but which could become important considerations in flight applications of the decoupler pylon concept are: pylon strength; static divergence; transient loads and response such as gusts, maneuvers, and weapons release; and dynamic coupling between the low-frequency pylon mode and airplane flight control system.

Apart from wings/store flutter alleviation, the decoupler pylon might also alleviate problems in other areas. For example, the soft pylon suspension system would act to isolate the store from shock and vibration loads and the automatic alignment control could be used to compensate for weapon aiming errors due to aeroelastic twist of the wing in high-g maneuvers.

Conclusions

A simple and effective concept for suppressing wing/store flutter by means of a store suspension system that decouples wing modes from the effects of store pitch inertia is investigated. A cantilevered rectangular wing with a single store was used as a basis for exploratory wind tunnel and analytical studies. Basic conclusions from the study are:

1) For all cases studied the flutter speed of the wing with the decoupler-pylon-mounted store was higher than the flutter speed of the wing without a store.

2) In addition to increasing the flutter speed, the decoupler pylon made flutter relatively insensitive to inertia and c.g. location of the store. This feature can greatly simplify and reduce the analysis and testing required to flutter-clear aircraft that must carry a large variety of stores.

3) Wing/store decoupling and the attendant flutter speed increase occurred when the uncoupled store pitch frequency was less than approximately 0.7 times the fundamental bending frequency of the wing with the store rigidly attached.

4) Flutter trends predicted using incompressible two-dimensional aerodynamic theory generally agreed well with those observed in the wind tunnel model experiments.

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