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Evaluation of Methods for Prediction and Prevention of Wing/Store Flutter

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In response to the need to reduce costs and improve safety for flutter evaluation of aircraft carrying external stores, the Flight Dynamics Laboratory has sponsored several efforts in the technical areas of unsteady aerodynamics, flutter prediction, and active flutter suppression. This paper discusses each of these three areas as they relate to wing/store flutter and presents specific examples from analyses and tests. NLR, the Netherlands, measured aerodynamic data in the wind tunnel at subsonic, transonic, and supersonic speeds on a fighter wing with tip mounted launcher and store and also with underwing pylon and store. Store flutter calculations were performed using both calculated and measured aerodynamics to determine the influence of store aerodynamics on the flutter characteristics.

Nomenclature

C	= local chord length
C_m	= sectional pitching moment coefficient
C_r	= root chord length
C_z	= sectional normal force coefficient
f	= frequency of oscillation
M	= freestream Mach number
q	= dynamic pressure
q/q_f	= nondimensional flutter dynamic pressure
S	= semispan
t	= time
V/V_{ref}	= nondimensional flutter velocity
α	= angle of attack
Δ	= change in a given quantity
η	= fraction of semispan
θ	= amplitude of oscillation
ρ	= fluid mass density
ω	= angular velocity $= 2\pi f$

Subscripts

qs	= quasisteady quantity
ref	= reference

Introduction

FIGHTER aircraft are commonly designed for a primary mission, such as air superiority, which may require few, if any, wing-mounted external stores. However, for increased effectiveness and versatility, many secondary missions evolve which are necessary and require the use of a wide variety of external stores. Thus many combinations of these external stores must be carried at various stations on the wings to achieve the complex, multirole missions required by the operational commands.

The carriage of external stores on the wings of fighter aircraft can in some cases result in significant reductions in the speed at which dangerous flutter instabilities would be encountered. All the various external store configurations must be evaluated for flutter safety to assure that the required 15% speed margins are met throughout the allowable flight envelope. Also, sufficient damping must be maintained in the important structural vibration modes.

To improve the accuracy and reduce the time and costs of flutter evaluations on the many store configurations carried by Air Force fighters, the Flight Dynamics Laboratory (FDL) has sponsored several programs in the technical areas of unsteady aerodynamics and flutter predictions. Also, the FDL has been sponsoring several efforts to explore the potential of active flutter suppression systems using feedback control techniques to provide the required stability and to avoid speed placards.

This paper reports on some of the FDL research related to wing/store flutter prediction and prevention. The research includes an unsteady aerodynamic measurement program for a representative fighter wing, with and without tip missile, and an underwing store with test data covering the Mach number range 0.6-1.35. Flutter analyses based on an FDL computer program specifically for use on aircraft with external stores are also described. Flutter trends using this computer program are presented for the wing with and without stores based on sectional force coefficients from wind-tunnel measurements and from theoretical calculations. A brief description is given of some FDL programs in active flutter suppression, and typical results are presented for wings with stores which indicate significant potential for improvement in flutter speeds.

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Wing/Store Aerodynamics

Aerodynamic forces on fighter wings with stores must be suitably determined if reliable flutter predictions are to be achieved. There are several aerodynamic theories which are available to predict the unsteady loading in the subsonic and supersonic speed ranges. However, numerical methods capable of dealing with transonic flow with large regions of separated flow and shock-wave/boundary-layer interactions have not yet been developed. To provide experimental data on wing/store aerodynamics for comparison with theories, and to establish trends for various store configurations, wind-tunnel tests in the Mach number range 0.6-1.35 were condicted by NLR of the Netherlands.[1] The NLR was sponsored by the U.S. Air Force (Flight Dynamics Laboratory and Air Force Armament Laboratory). These aerodynamic data provide the basis for the flutter trends calculated for this study and are discussed in subsequent sections.

Aerodynamic Test Data

The NLR aerodynamic data used in the flutter analyses of this paper were obtained on an F-5 wing model with and without an AIM-9J missile mounted on the wing tip (Fig. 1) and the same missile mounted on an underwing pylon/launcher (Fig. 2). Detailed locations of pressure taps on the wing are given in Ref. 1. These tests were run with each of the store arrangements in varying stages of buildup to evaluate interference effects.

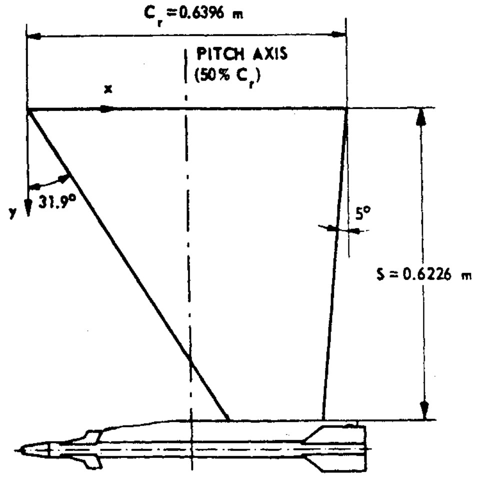

Fig. 1 Wing model with tip store/launcher.

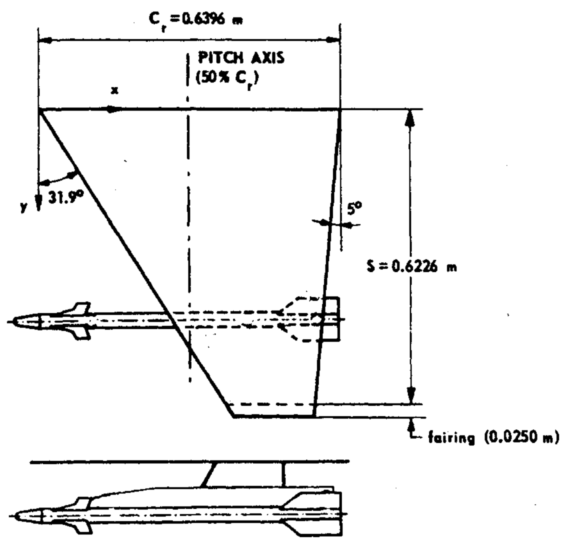

Fig. 2 Wing model with underwing store/pylon/launcher.

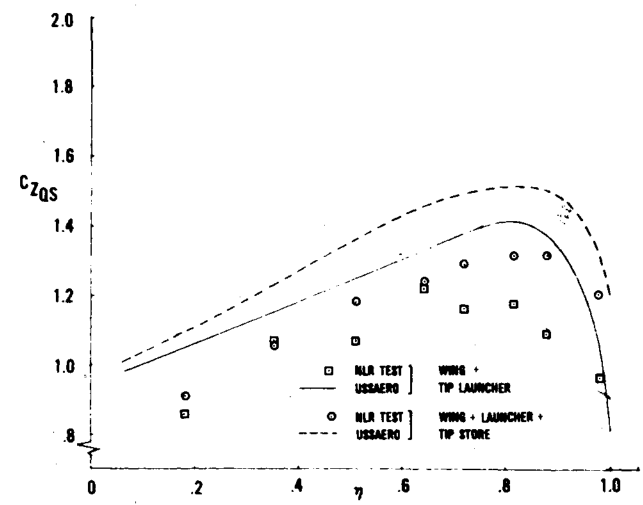

Fig. 3 Sectional normal force vs semispan, $M=0.60$.

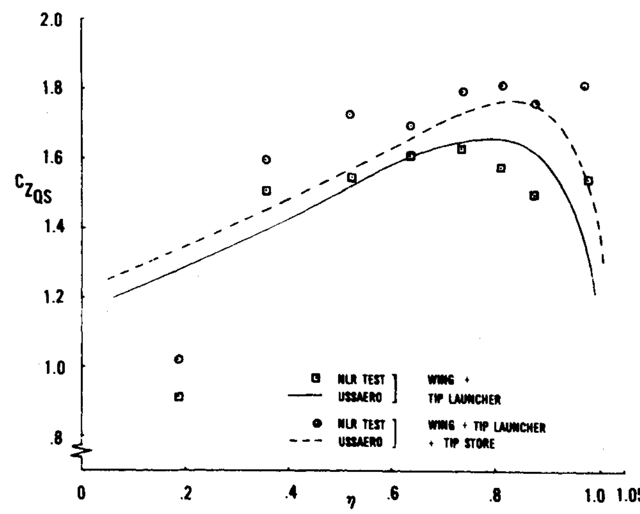

Fig. 4 Sectional normal force vs semispan, $M=0.90$.

Steady and unsteady pressure measurements were taken at $\alpha=0$, 0.5, and -0.5 deg over the Mach range 0.6-1.35. Unsteady motion of the model was the result of harmonic oscillation about the 50% root chord axis with frequencies of up to 40 Hz. The NLR measuring system employing tubes and scanivalves is also described in Ref. 1. Sectional loads were computed from the pressure distribution by chordwise integration. Strain gage balances were used to measure the steady and unsteady loads acting on the tip store and pylon store. For the tip store and pylon store, lift and pitching moments were obtained. For the pylon store, side force and yawing moment were also obtained.

Quasisteady approximations to the spanwise distribution of the unsteady aerodynamic coefficients are presented in this paper to show the effects of store loadings and Mach number. These quasisteady coefficients and center-of-pressure data were used in modified strip theory flutter analyses described in later sections.

The NLR definition of the sectional quasisteady normal force and pitching moment for the wing are as follows:

Sectional normal force

$$Z_{qs} = \pi q C C_{z_{qs}} \theta e^{i\omega t}$$

$$C_{z_{qs}} = \frac{1}{\pi}\frac{\Delta C_z}{\Delta\alpha} = \frac{C_z(\alpha_0+\Delta\alpha_1) - C_z(\alpha_0-\Delta\alpha_2)}{\Delta\alpha_1+\Delta\alpha_2}$$

Sectional pitching moment (positive nose-down)

$$M_{qs} = (\pi/2) q C^2 C_{m_{qs}} \theta e^{i\omega t}$$

$$C_{m_{qs}} = \frac{2}{\pi}\frac{\Delta C_m}{\Delta\alpha} = \frac{2}{\pi}\frac{C_m(\alpha_0+\Delta\alpha_1) - C_m(\alpha_0-\Delta\alpha_2)}{\Delta\alpha_1+\Delta\alpha_2}$$

Aerodynamic Analytical Methods

For comparison with the experimental aerodynamic measurements, analyses were made using an aerodynamic paneling method developed by Woodward.[2-4] In this method a lifting surface is divided into a number of aerodynamic panels, each containing distributions of sources and vortices. A surface source distribution can represent a fuselage or external store. Wing thickness is represented by a linearly varying source distribution in which the strength is equated to the chordwise slope of the wing thickness. Camber, twist, and lifting effects are represented by a linearly varying vortex distribution where the strength is determined to satisfy tangential flow at panel control points. An iterative procedure is employed in solving the boundary value problem. In the analysis, the surface slope is described and singularity strengths are determined by inverting the matrix of aerodynamic influence coefficients. With the strengths of the aerodynamic singularities known, the velocity components at a given point may then be determined. Pressures, forces, and moments are calculated by numerical integration.

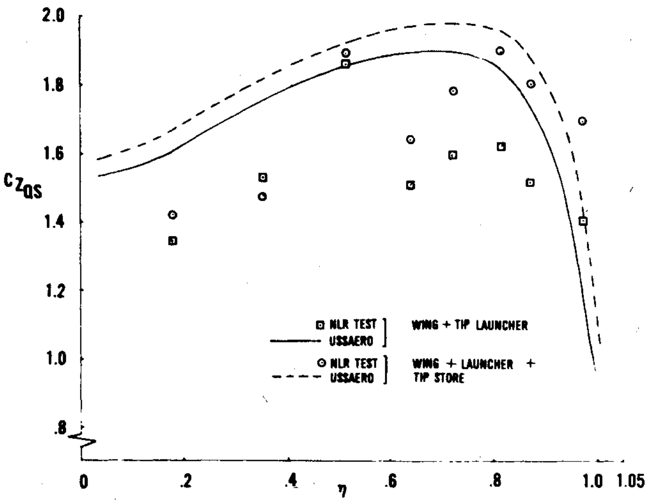

Fig. 5 Sectional normal force vs semispan, $M = 1.10$.

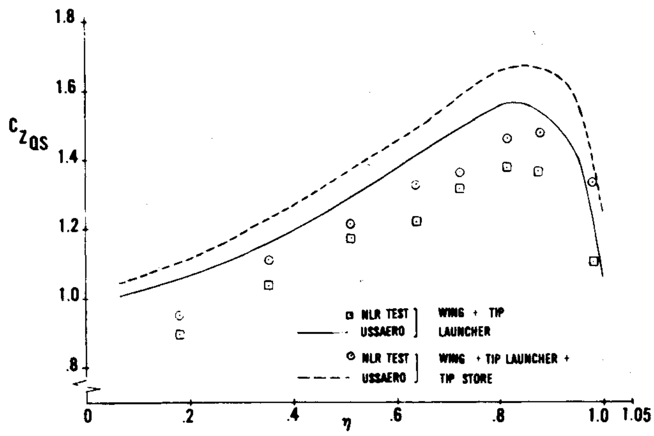

Fig. 6 Sectional normal force vs semispan, $M = 1.35$.

The well-known, subsonic, three-dimensional, compressible, unsteady aerodynamic theory known as doublet lattice was also used for some limited-check cases in performing flutter analyses in the subsequent sections. The doublet-lattice theory is described in Ref. 5.

Only limited, quasisteady aerodynamic wind-tunnel data used in the flutter analyses and calculations with the Woodward method are presented in this paper. Comparisons of calculations with NLR data,[1] using the doublet-lattice aerodynamic method, are presented in Ref. 6. As shown in Ref. 6, the doublet lattice correlates very well with the subsonic unsteady test data.

Aerodynamic Results: Tip Store

The quasisteady normal force for $M = 0.6$, 0.9, 1.1, and 1.35 used in the flutter analyses are presented in Figs. 3,4,5, and 6, respectively. Each plot shows the test data[1] and the analytical results for the wing with the tip launcher and the wing with launcher plus complete tip store. The analysis and test data show that the addition of the tip store increases the loading on the outboard sections of the wing. As expected at $M = 0.6$, the linear theory overpredicts the loads (Fig. 3). The interference effects of the tip store are reasonably well predicted.

As the Mach number is increased from 0.6 to 0.9, the flow becomes transonic, the loads (Fig. 4) increase, and the linear theory no longer overpredicts the loads. The experimental loads on the inboard section of the wing are low, which may be due to an interference effect from the boundary layer on the wind-tunnel wall. At both $M = 0.9$ and 1.1 (Fig. 5), the

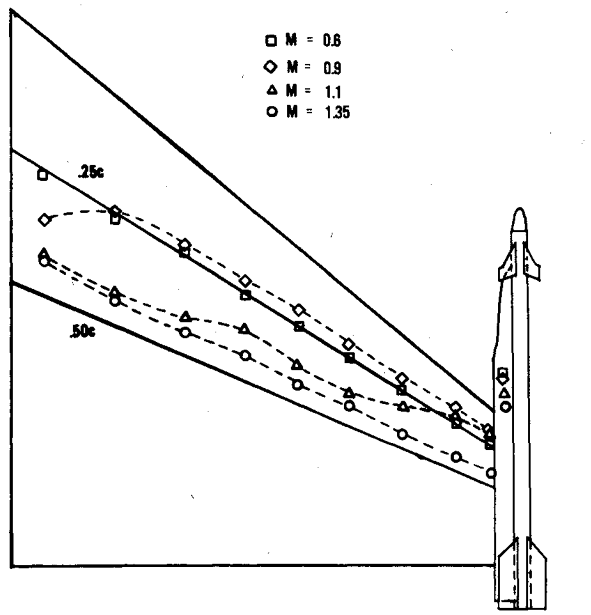

Fig. 7 Experimental center-of-pressure location, wing/tip store.

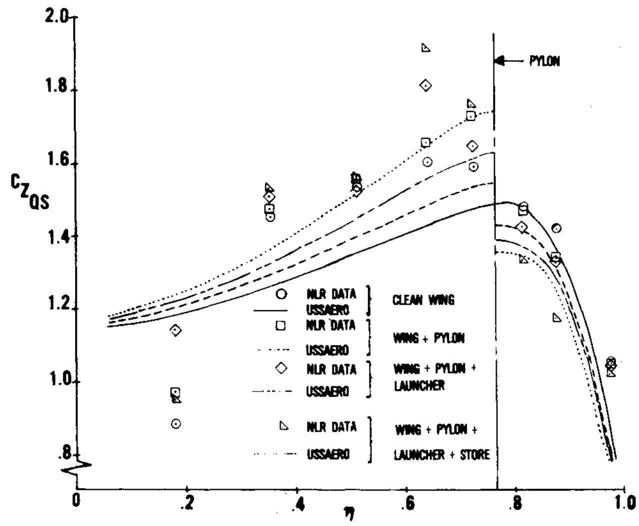

Fig. 8 Sectional normal force vs semispan, $M = 0.9$.

overall loads are about the same and the interference effects from the store seem to influence the normal force over the entire wing. The decrease in the experimental loads at the 64% semispan station is unresolved. This decrease may be due to insufficient spanwise taps to accurately resolve spanwise variation of sectional normal force. Comparison of the test results and the numerical results at $M = 0.9$ and 1.1 show appreciable differences.

Figure 6 presents a comparison of the experimental and analytical sectional normal force for $M = 1.35$. Numerical calculations and experimental data showed similar interference effects in spanwise variation of load.

Figure 7 shows the experimental center of pressure location for $M = 0.6$, 0.9, 1.1, and 1.35 for the wing/tip store configuration. At $M = 0.6$, the center of pressure is very near the quarter chord, as would be expected for subsonic flow. As the Mach number is increased to 0.9 and the flow becomes transonic, the center of pressure moves slightly forward of the quarter chord. At $M = 1.1$, the center of pressure has moved aft of the quarter chord for all semispan stations except the two outboard sections. At $M = 1.35$, the center of pressure has moved aft near the 50% chord which is typical of supersonic flow.

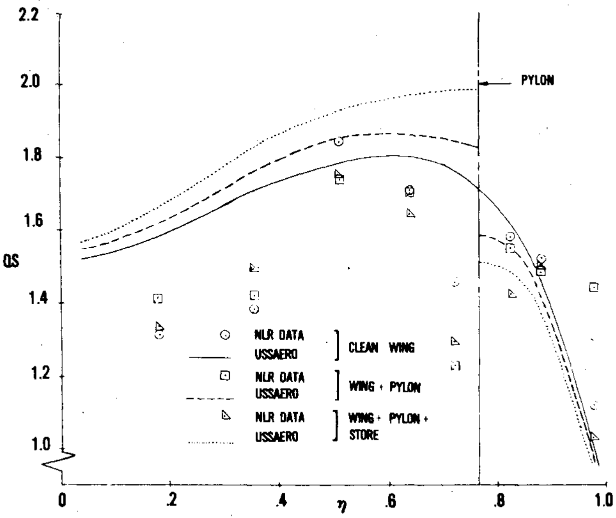

Fig. 9 Sectional normal force vs semispan, $M=1.1$.

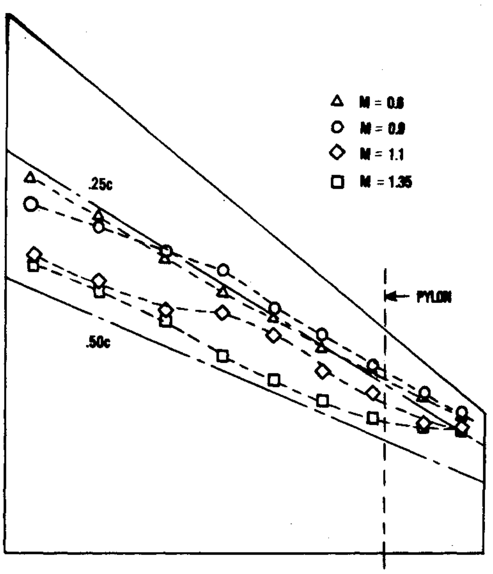

Fig. 10 Experimental center-of-pressure location, underwing store.

Aerodynamic Results: Wing with Underwing Store

The quasisteady aerodynamic normal force for $M=0.9$ and 1.1 are presented in Figs. 8 and 9, respectively. The plots present both the test data[1] and the analytical results for the clean wing and the wing with underwing store. Interference effects arising from the pylon produce a discontinuity in the loading across the pylon. The loading is higher inboard of the pylon and lower outboard of the pylon as compared with the loads on the clean wing.

Figure 8 shows the variation in loads as the underwing store configuration is systematically built up from the clean wing to the wing plus pylon, launcher, and store. As the Mach number increases from 0.6 to 0.9 (Fig. 8), the flow becomes transonic, the loads increase, and the theory is generally unconservative. There appears to be an interference effect due to the wind-tunnel wall which reduces the experimental loads on the inboard section of the wing.

Figure 9 presents the normal force distribution for $M=1.1$. There are significant differences between the test results and the analytical results. The decrease in the experimental loads at the 72% semispan station is unresolved but may be due to insufficient spanwise pressure taps, as discussed previously. This decrease is present for the clean wing, wing with pylon, and the wing with underwing store.

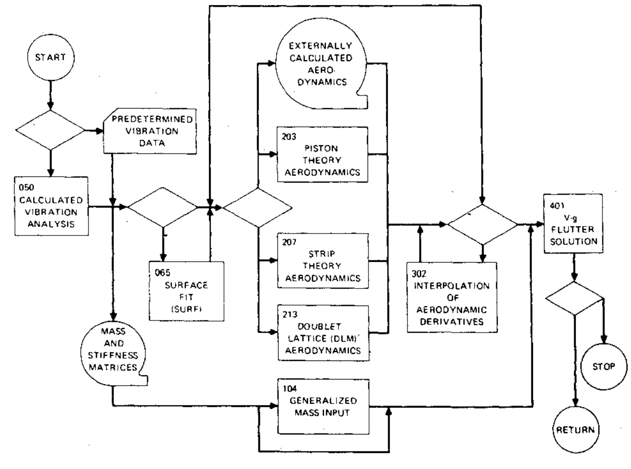

Fig. 11 FACES flutter routine.

Figure 10 presents the experimental center-of-pressure locations at $M=0.6$, 0.9, 1.1, and 1.35 for the wing with underwing store. For $M=0.6$, the center of pressure is very near the quarter chord, as expected for subsonic flow. As the Mach number is increased to 0.9, the center of pressure moves forward of the quarter chord. At $M=1.1$, the center of pressure is generally aft of the quarter chord except for the two outboard sections. As would be expected for supersonic flow, the center of pressure at $M=1.35$ is near the midchord, except it is forward of the midchord for the two outboard sections.

Flutter Analysis

Rapid Flutter Analysis Procedure, FACES

The FACES computer program[7-10] was used for the flutter analyses. It was developed especially for simplified and efficient aircraft/external store flutter analyses. As shown in Fig. 11, the FACES computer program is in modular form and requires very simple, straightforward input data. Versions of the program are available for both CDC and IBM computer equipment.

The unsteady aerodynamic theory options available in FACES include the doublet-lattice, strip theory, modified strip theory, and supersonic piston theory. For subsonic, compressible flow, the doublet-lattice method[5] is generally considered to be the best available unsteady aerodynamic theory. The unsteady airloads on external stores can be represented in doublet lattice by either lifting surface panels or by a constant cross-section cylinder based on the method of images. The method of images would be expected to provide the most accurate lifting surface/body/interference effects.

Strip theory assumes that the sectional lift-curve slope C_{L_α} is 2π, with the aerodynamic center (a.c.) at the quarter chord, in accordance with two-dimensional, incompressible flow theory. Although strip theory analyses are very fast, the two-dimensional theory usually overestimates the aerodynamic forces on three-dimensional surfaces and thus generally provides conservative flutter speed predictions.

To retain the rapid, efficient capability of the strip theory approach and also improve the accuracy, available measured or analytical values for steady-state C_{L_α} and a.c. can be used in a FACES option called modified strip theory. In the present study the C_{L_α} and a.c. used in modified strip theory were obtained from the experimental data[1] described previously.

Flutter calculation in this study, using the doublet-lattice method, involved the following FACES modules from Fig. 11:

1) predetermined vibration data;
2) surface fit (used to calculate polynomials for the

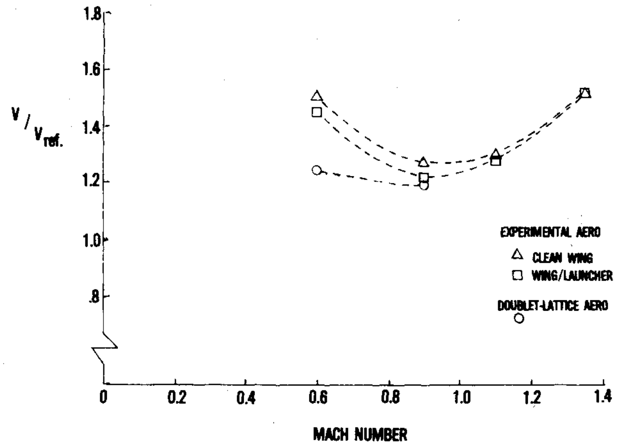

Fig. 12 Flutter trends vs Mach number, wing with tip launcher.

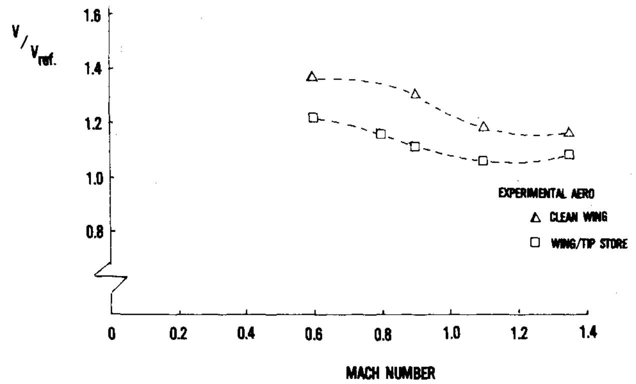

Fig. 13 Flutter trends vs Mach number, wing with tip store.

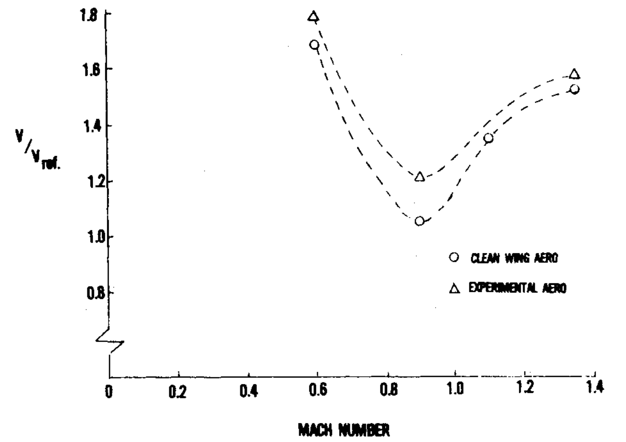

Fig. 14 Flutter trends vs Mach number, wing with underwing store.

doublet-lattice method), module 065;

3) generalized mass input, module 104;

4) doublet-lattice aerodynamic method, module 213;

5) interpolation of aerodynamic derivatives (used for interpolation to reduce expensive computations with the doublet-lattice method), module 302;

6) flutter solution, module 401.

For flutter calculations using strip or modified strip theory, modules 065, 213, and 302 are replaced by module 207 (Fig. 11).

Calculated Flutter Results

Results for flutter calculations using the FACES method with various aerodynamic representations are shown in Figs. 12-14. These flutter calculations were based on available calculated modal data for a fighter aircraft and consisted of generalized mass, deflections, and frequencies. Two rigid body and six elastic modes were used in the FACES analyses.

Flutter of Wing with Launcher

Figure 12 shows the calculated trend of nondimensional flutter velocity vs Mach number for the wing with tip launcher (no store). This flutter trend with Mach number, based on the previously described experimental aerodynamics, shows a 17% decrease in velocity from Mach 0.6 to 0.9 followed by a 20% increase from Mach 0.9 to 1.35. Clean wing measured aerodynamics were also used with the same vibration modes to evaluate the aerodynamic effect of the tip launcher. Using measured sectional lift coefficients and centers of pressure for the clean wing, the calculated flutter trend, also shown in Fig. 12, was somewhat similar to the trend based on the wing/launcher aerodynamics. At Mach 0.6, the flutter velocity using clean wing aerodynamics was only 2% higher than the value for the wing/launcher aerodynamics; at $M=0.9$, 5% higher; and at Mach 1.1 and 1.35 the velocities were about the same.

Figure 12 also presents calculations using doublet-lattice aerodynamic theory for the wing with tip launcher. For this study, the launcher and tip missile were represented as flat lifting surface panels in the doublet-lattice analysis. At Mach 0.6, the doublet-lattice theory gave a flutter velocity 15% lower than the value using experimental aerodynamics, while at Mach 0.9 the flutter values predicted were almost identical.

For the wing with launcher, the flutter trends vs Mach number are consistent with the overall aerodynamic data. The center of pressure is farthest forward at Mach 0.9, while Fig. 4 shows that the normal force is highest. Both of these parameters account for the observed low flutter velocity at Mach 0.9. At supersonic speeds, the center of pressure moves aft while the normal force decreases, both of which contribute to the observed increase in flutter speed.

Flutter of Wing with Tip Launcher plus Tip Store

Figure 13 presents the trend of nondimensional flutter velocity vs Mach number for the wing with tip launcher plus tip store. For this configuration, the trend with Mach number is flatter than was shown in Fig. 12 for the wing with tip launcher. With the addition of the tip store, the flutter velocity decreased from Mach 0.6 to a minimum at Mach 1.1 by 14%, and increased at Mach 1.35 by only 2%. Figure 13 shows that the calculated flutter velocity using clean wing aerodynamics compared to the velocity using tip store aerodynamics is 10% higher at $M=0.6$, 19% higher at $M=0.9$, and 7% higher at $M=1.35$. The difference between calculated flutter velocity using clean wing aerodynamics and tip store aerodynamics (Fig. 13) is considerably larger than the difference between clean wing aerodynamics and tip launcher aerodynamics (Fig. 12). Thus the tip launcher aerodynamics had a slightly detrimental effect on flutter and addition of the tip store aerodynamics had a larger detrimental effect.

Flutter of Wing with Underwing Store

Figure 14 presents the nondimensional flutter velocity vs Mach number for the wing with underwing store. As observed for the wing with tip launcher, the lowest flutter velocity occurred at $M=0.9$. However, the decrease in flutter velocity was greater, being 33% from Mach 0.6-0.9 and then increasing 31% from Mach 0.9-1.35. This variation is somewhat larger than is normally expected for such lifting surfaces. Since a similar variation is observed for this configuration with clean wing aerodynamics, the large variation is not due to the aerodynamic effect of the underwing pylon and store but is caused by the complex interaction of vibration characteristics and the aerodynamic forces. The flutter velocities predicted using clean wing aerodynamics were 10-15% lower than those based on the experimental aerodynamics for the wing with underwing store. The higher flutter speed with underwing store aerodynamics apparently results from the decreased aerodynamic loading on the wing outboard of the underwing pylon and store. Thus, in this case, the underwing pylon and store aerodynamics had a beneficial effect on the flutter speed as compared to clean wing aerodynamics.

Wing/Store Flutter Suppression

Flutter suppression with active control is another option to the standard passive techniques (e.g., increased stiffness, mass balance, or speed restriction) for the prevention of flutter on fighter-attack aircraft. This section discusses Air Force programs in the area of wing/store flutter suppression and reviews current and future programs.

Background and Completed Efforts—Flutter Suppression

Beginning in 1971, the Flight Dynamics Laboratory sponsored a feasibility study[11] to evaluate the potential of active flutter suppression systems for military aircraft that are performance-limited owing to flutter. The objective of this study was to establish the aircraft surfaces or configurations, flutter modes, and flight conditions, where active flutter suppression can show an advantage over conventional techniques for flutter prevention. Active control of wing/external store flutter was determined to be the most promising application. A follow-on effort focused on a preliminary design study of a wing/store flutter suppression system to provide a comprehensive analytical evaluation of integrating the system into a representative fighter-attack aircraft. This effort is reported in Ref. 12.

In 1974, an FDL program[13] was conducted to improve aeroelastic modeling technology by including miniaturized active controls. In this program, a one-thirtieth scale B-52 model was modified to represent the Control Configured Vehicle (CCV) B-52 flight test aircraft with an active flutter suppression system. The wind-tunnel tests and the CCV flight tests demonstrated increased damping (improved flutter speeds) when the active system was in operation.

From 1976-1980, Northrop Corporation designed a wind-tunnel model with active controls and conducted a series of wind-tunnel test demonstrations of the concept.[14,15] In addition to Northrop's control laws, foreign investigators (United Kingdom, France, West Germany, and Israel) provided alternative control laws for testing. The wind-tunnel model was a semispan representation of a lightweight fighter. Partial-span leading- and trailing-edge control surfaces were used as the active flutter suppression surfaces. The external store consisted of an AIM-7S on an outboard pylon. This wing/store combination provided a fairly violent flutter mode at about 6.3 Hz.

Figure 15 presents the wind-tunnel test results as a plot of damping vs dynamic pressure for the passive case, a control law using the trailing-edge surface, a control law using the leading-edge surface, and a control law using both the leading- and trailing-edge control surfaces. The goal was a 30% improvement in velocity. The trailing-edge control law provided approximately 22% improvement in speed. In this case, the flutter mode was well damped; however, the bending mode became unstable with increased speed. Subsequent analyses of an improved trailing-edge control law have shown that the trailing-edge surface could exceed the goal. Both the leading-edge control law and the two-surface control law exceeded the goal.

A study[16] was conducted in 1978 to determine the feasibility of employing active controls to suppress wing/store flutter of the F-16. The results of the study show that a flutter suppression system with the existing flaperon as the active control surface can be used to significantly increase the flutter speed of the F-16 with wing mounted external stores. General Dynamics modified and tested an F-16 flutter model with active flaperons. The results of the study and wind-tunnel tests (January 1979) of the F-16 flutter model with active flaperons are presented in Ref. 17. For one of these store configurations, antisymmetric flutter (8.6 Hz) was encountered at $M=0.59$. With the flutter suppression system operating, an increase in flutter dynamic pressure of approximately 100%, was obtained. Figure 16 illustrates these results.

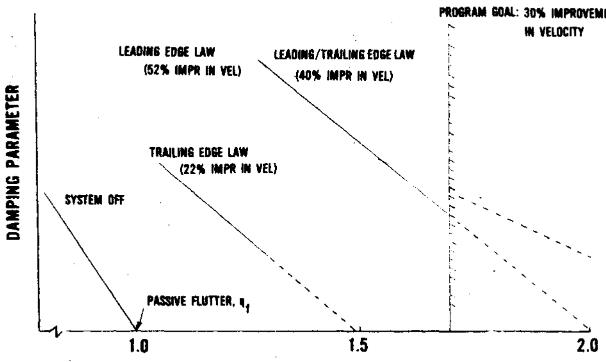

Fig. 15 Wind-tunnel test results, $M=0.8$, FDL model.

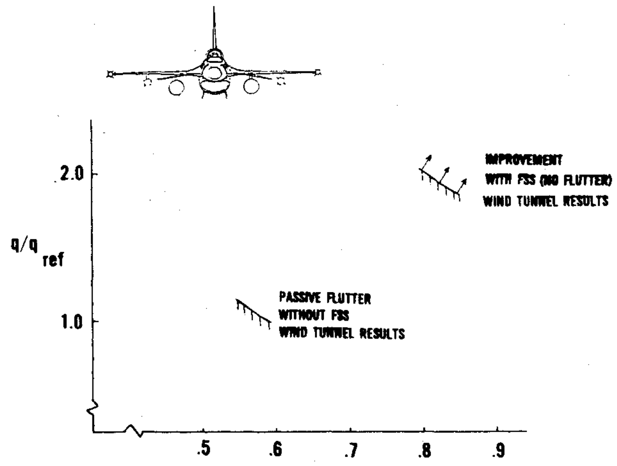

Fig. 16 F-16 flutter suppression results.

An adaptive control study for wing/store flutter was conducted and is presented in Ref. 18. Some of these adaptive concepts will be tested on a wind-tunnel model in March 1982.

Under a joint USAF/FMOD (German Federal Ministry of Defense) program, an F-4F aircraft with external stores was used to investigate active flutter suppression.[19] The existing outboard aileron was used as the active surface. Using optimal control theory, MBB found a control law that minimized the control surface motion and provided the required stability. The selected flutter case involved the coupling of the first wing bending mode with the first wing torsion/store pitch mode near 5 Hz. One of the difficulties encountered was the nonlinear behavior of this wing/store combination, which resulted in a limited amplitude flutter at approximately 610 knots. With the active flutter suppression system operating, the aircraft was flown to approximately 645 knots. The flutter mode was well damped. The final tests were completed in October 1980 and the technical report should be available by July 1982.

Current and Future Programs—Flutter Suppression

This section discusses FDL's ongoing and future efforts to demonstrate the active flutter suppression technology. Two wind-tunnel test programs are underway. Additional wind-tunnel tests will be conducted in the NASA Langley 16-ft Transonic Dynamics Tunnel (TDT) using the available F-16 flutter suppression model.

Since this is a full-span, free-flying model, the tunnel gust vanes will be used to determine the effects of turbulence on the control system performance and to evaluate gust alleviation with the active system on. Symmetric and asymmetric store loadings will be evaluated, both symmetric and antisymmetric flutter modes will be included, and the sensitivity of failed control systems (e.g., one side inoperative) will be evaluated. The tests were completed in October 1981.

Digital adaptive control of wing/store flutter are being investigated in the wind tunnel using the semispan model of Refs. 14 and 15. In the November 1981 test, digital control laws were evaluated. In the April 1982 tests, adaptive flutter suppression schemes will be investigated. Inflight changes in the store loadings will be made to evaluate the effects of transients on the system stability and adaptability.

Concluding Remarks

Flutter trends for three different fighter wing/store configurations were calculated using the FACES flutter analysis procedure. Use was made of available modal vibration data and measured aerodynamic data. The predicted Mach number trends gave minimum flutter speeds at transonic and low supersonic speeds, as would be expected from the trend of measured center-of-pressure and lift-curve slope data. Although the aerodynamics on the tip launcher had a somewhat detrimental effect on flutter, the aerodynamics on the tip store had a much larger detrimental effect. For the underwing store, the aerodynamics effects were beneficial for flutter, since the pylon had the effect of decreasing the aerodynamic loading on the outer portion of the wing.

Although use of measured modal and aerodynamic data in flutter calculations would be expected to provide improved accuracy in flutter evaluation over theoretical aerodynamics, it is recommmended that such calculations be correlated with actual flutter data for verification. Such data were not available for this study. There is still a need to develop better unsteady aerodynamics methods particularly in the transonic and low supersonic region where the lowest flutter velocity is likely to occur.

Flutter suppression with active controls shows promise of preventing wing/store flutter on fighter-attack aircraft. A flight test demonstration of wing/store flutter suppression on a modern U.S. fighter is needed to further evaluate the digital/adaptive concepts in the real environment with flight hardware.

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