AIAA 81-0604R

Effect of Store Aerodynamics on Wing/Store Flutter

C.D. Turner*
North Carolina State University, Raleigh, N.C.

Owing to the high cost of doing flutter analysis for aircraft carrying large numbers and types of stores, it is not economically feasible to include store aerodynamics when there will be little change in the flutter results. But store aerodynamics should be included if it will change the results of the flutter analysis. This study represents the first systematic analytical study of the effect of store aerodynamics on wing/store flutter. A large number of wing/store single carriage configurations and parameters were included in the study; multivariate analysis techniques were used for the first time to analyze wing/store configurations, modal data, and flutter results. The results of the multivariate analysis indicate that it may not be possible to develop general guidelines, but it is possible to develop specific guidelines for use with a particular aircraft.

Nomenclature

A_B = store body area projected in horizontal plane
A_{F1} = store fin area projected in horizontal plane
A_{F2} = store canard area projected in horizontal plane
A_S = total store area $= A_B + A_{F1} + A_{F2}$
A_W = wing area
$\bar{C}$ = reference chord of wing
C_S = chord of wing at store location
H_W = distance from wing to top of store, defined in Fig. 2
L_{S1} = length of store
L_{S2} = distance from E.A. to store nose, defined in Fig. 2
L_{S3} = distance from E.A. to store canard, defined in Fig. 2
L_{S4} = distance from E.A. to store fin, defined in Fig. 2
L_{W1} = distance from aircraft centerline to wing tip, defined in Fig. 2
L_{W2} = distance from aircraft centerline to store, defined in Fig. 2
N = number of configurations used in multivariate analysis
r = radius of store, defined in Fig. 2
r_{ij} = correlation coefficients, defined in Eq. 3
V = velocity
V_C = clean wing flutter velocity
V_F = wing/store flutter velocity with no store aerodynamics
V_{FA} = wing/store flutter velocity with store aerodynamics
W_S = weight of store
W_W = weight of wing
X = independent variable in factor analysis
$\bar{X}$ = mean value
x_{ij} = variation from the mean
α_i = angular pitch of store at store center of gravity for mode i
δ_i = displacement of E.A. at store location, mode i
η = number of parameters used in analysis
κ = reduced frequency
λ = transient decay rate coefficient
ω_F = wing/store flutter frequency, no store aerodynamics
ω_{FA} = wing/store flutter frequency with store aerodynamics
ω_i = natural frequency for wing/store, mode i

Presented as Paper 81-0604 at the AIAA Dynamics Specialists Conference, Atlanta, Ga., April 9-10, 1981; submitted April 24, 1981; revision received Sept. 25, 1981.

*Assistant Professor. Member AIAA.

I. Introduction

WHEN large external bodies or stores, such as engine nacelles, fuel tanks, or pods, are added to the wing of an aircraft, the dynamic characteristics of the aircraft will be changed. In particular, the flutter speed of the aircraft may be adversely affected because of the inertia, elastic, and aerodynamic coupling between the wing and its stores. It has been possible for the last several years to account for the wing/store aerodynamic coupling in flutter analysis. Even so, store aerodynamics are usually not included in a standard flutter analysis, except for a few cases of tip pods and tip missiles on fighter aircraft and engine nacelles on the larger transport aircraft. This situation is the result of both economic considerations and the hopeful assumption that store aerodynamics have little effect on the calculated flutter speeds.

In the case of wing/store flutter analysis, the economics of including the store aerodynamics must be considered, together with other technical aspects of the flutter analysis. The computation of the unsteady aerodynamic coefficients for the aircraft is the single-most costly item in any flutter analysis. Owing to the variety of stores that can be carried on a typical modern tactical fighter, the total number of possible aircraft/store configurations is in the thousands. On military aircraft, the effect of unsteady aerodynamics is computed for both the clean wing and the wing with tip missiles. Using these two aerodynamic configurations, the flutter analysis is done on between 300 and 400 selected wing/store configurations. If wing/store aerodynamics were also considered for each of these configurations, the cost of the analysis would increase by several orders of magnitude. In many cases, this increased cost is not justified because store aerodynamics usually has a small effect on the flutter speed. However, there are a few important instances where neglecting store aerodynamics will lead to the overestimation of the flutter speed. Determining when the store aerodynamics should be included in the flutter analysis is a major problem.

Early wind-tunnel tests left the impression that store aerodynamics were not needed to accurately compute flutter. However, several instances of wing/store flutter during flight flutter tests changed this. From these flight flutter tests and subsequent wind-tunnel tests, general "rules" have evolved as to when store aerodynamics should be included in the flutter analysis. These rules are not only based on limited data but sometimes conflict. Some experimental efforts have determined the effect of including the store on the wing of an aircraft with various shapes, but no real effort has been made to isolate the effect of the store aerodynamics on the wing/store flutter problem.

To determine the effect of store aerodynamics on wing/store flutter a data base had to be generated. This data base is limited to single carriage of each store type and does not include transonic flow effects.

To aid in studying the effects of store aerodynamics on wing/store flutter, a nonlinear multivariate analysis (factor analysis) was made of the data base. The factor analysis used a set of candidate parameters that were selected from flight test, wind-tunnel test, and analytical results. The factor analysis was used to determine if it is possible to show any correlation between the parameters and the wing/store flutter speed, thus making it possible to develop guidelines as to when to include store aerodynamics in the wing/store flutter analysis.

II. Background

The need to consider such items as inertia, elastic, and aerodynamic coupling between the wing and a store or a nacelle is extremely important considering the rapid increase in speed of fighter and multiengine aircraft. In the early 1940s, analytical flutter techniques were restricted to analysis of the wing and control surfaces. Thus the primary means of studying the effects of a store on wing/store flutter was through the use of wind-tunnel flutter models. By 1950 analytical techniques allowed the inclusion of the inertia effect of stores on wing/store flutter. Both wind-tunnel tests and flight tests were still needed to account for the total effect of the store on wing/store flutter. At this time, it was recognized that the store aerodynamics must be included in the wing/store flutter analysis for some configurations if one was to obtain results that matched the flight test. By the late 1960s it became technically possible to include all the possible effects of a store in the wing/store flutter analysis. However, even today, store aerodynamics are included only for wing/store flutter analysis for stores located on the wing tip. The good agreement usually obtained during the wind-tunnel flutter tests and flight tests of various other store configurations usually supports this practice. Today researchers are looking for active and passive ways to reduce the effects of stores on wing/store flutter, but even in these efforts the effect of store aerodynamics is usually ignored for underwing stores because of the complexity of the analysis.

It is useful to summarize the various investigations that have led to the present research. Goland and Luke[1] did an analytical study on the effect of the chordwise positions of a tip mass on wing flutter. A mass located aft of the elastic axis was observed to lower the flutter speed. Runyan and Sewall[2] conducted an experimental study of wing flutter in which the chordwise and spanwise positions of several different lumped masses on an unswept wing were varied. In general, they found that masses located forward of the elastic axis gave higher flutter speeds than those located aft of the elastic axis, except at the wing tip, where results were mixed. For all chordwise locations of each mass, as the mass was moved outboard from the root, there was an initial decrease followed by an increase in flutter speed with span position. Masses located forward of the wing elastic axis caused a minimum flutter speed at about 25% span, while masses located aft of the elastic axis caused a minimum flutter speed at about 50% span. In each instance where the mass was added forward of the elastic axis, there was a region along the span where the wing/mass flutter speed would exceed the clean wing flutter speed. Sewall and Woolston[3] did an experimental study of wing flutter that varied both the inertia and aerodynamic characteristics of the lumped mass. For the wing model used in this study, it was determined that the flutter speed was relatively unaffected by changes in aerodynamic shape. Andropoulos, Chee, and Targoff[4] studied, experimentally, the effect that two lumped masses have on wing flutter. Included in this study was the effect of the nacelle aerodynamics. To obtain a satisfactory comparison between theory and experiment, it was concluded that nacelle aerodynamics must be included in the analysis. It was also recommended that tip tanks be included among those cases where store aerodynamics are important. Gayman[5] conducted an experimental and theoretical investigation into the antisymmetric flutter of the Northrop Scorpion F-89. He attempted to cross-correlate the results obtained from six wing tip pods tested in the wind tunnel in terms of mass parameters. This effort was unsuccessful. It was felt that greater insight into the theoretical aspects of the problem was needed before a suitable correlation basis could be determined. The results of the study indicated that the effect of tip store aerodynamics must be included in the flutter analysis for wing/store configurations where the store center of gravity is on or near the wing elastic axis. Gayman concluded that the flutter speed would be less affected by store aerodynamics if a large store overbalance condition existed. Sewall, Herr, and Igoe[6] investigated an F-80 aircraft in which the inertial and geometric properties of the external stores were systematically varied. Their experimental investigation found that, when the volume of the tip tank increased, the flutter speed decreased. The addition of a horizontal fin to the smaller tip tank increased the flutter speed, while, for the larger tip tank, this addition decreased the flutter speed. Pollock and Cooley[7] recently analyzed a flight flutter test incident that occurred in July 1950 on an F-80 aircraft. For this test, the tip tanks were balanced with 85 lb of lead, located 59 in. aft of the wing elastic axis. This condition represented 13 gal of fuel in the aft end of the tank. For their study, flutter analysis was accomplished on three different aerodynamic configurations. The first was for the wing along, the second included the store body aerodynamics, and the third included the store body and fin aerodynamics. The first configuration gave flutter results that were 25% above the known flutter speed. The third gave flutter results that were within 1% of the known flutter speed, and the second configuration gave results that were about 10% below the known flutter speed. In this particular case, accurate representation of the store was found to be important. Cross and Albano[8] developed a perturbation technique for the rapid flutter clearance of aircraft carrying external stores. The technique allows for perturbations of the store mass and inertia data. For most cases, extreme accuracy was obtained for configurations involving moderate perturbations. The flutter program discussed in Ref. 8 can complete up to 1000 analyses/h and allows the screening of many configurations and the identification of problem areas. Van Nunen, Roos, and Meyer[9] have developed experimental techniques for measuring unsteady aerodynamics on wing/store configurations. These configurations include both tip wing and underwing stores. Data obtained in these tests are just now becoming available for the verification of existing computer programs. Hwang, Winther, and Mills[10] developed both analytical and experimental methods to demonstrate an active wing/store flutter suppression system on the Northrop YF-17 aircraft. Three configurations were studied, but no attempt was made in the analytical study to include the effect of store aerodynamics for the underwing stores. Reed, Foughner, and Runyan[11] have developed both analytical and experimental methods to demonstrate a simple, effective wing/store flutter suppressor known as a decoupler pylon. The effect of the store aerodynamics was not included in their flutter analysis. A comparison of the analytical and experimental data is given in the paper presented, with the variation between experimental and analytical results lying between 4 and 26% for the eight configurations tested.

The present study includes four different fighter aircraft and three basic stores. The four-model-data-base study required 364 computer runs to generate the 236 data points used in the final study.

Since it is possible to compute the effects of store aerodynamics on wing/store flutter for a given store, the next logical step would be to determine if it is possible to predict in general, on the basis of a given number of results, the effect of store aerodynamics on wing/store flutter. A technique of this type would be extremely useful in cases where a large number of store configurations are involved in the flutter analysis or in cases where a perturbation technique is applied for rapid flutter clearance of aircraft carrying external stores. The success of a prediction technique depends on the ability to select a set of parameters that best describes the effect of store aerodynamics on wing/store flutter. A review of past studies, together with the data base generated for the present study, has resulted in the selection of 23 candidate parameters.

III. Analytical Data Base

To determine the effects of store aerodynamics on wing/store flutter requires a data base that allows for the study of the effect of selected parameters on store aerodynamics. The required modal and flutter data needed for this specific type of data base was not available; therefore it was necessary to generate the data base analytically. The data base had to be developed with considerations for the scope of the task and for the effect it would have on the multivariate analysis. To keep the task manageable, four aircraft were selected. The F-5A/B[14] and the F-5E[12,13] were selected because they were similar, but still have variations in wing planform. In both cases, both the analytical and experimental data were available for checking the modal analysis and the flutter analysis. The F-17[10] was selected because of the availability of the wind-tunnel flutter test data. The F-80[7] was selected because it represented one of the first aircraft to have a known flutter problem that required the store aerodynamics to be included in the analysis to obtain a valid wing/store flutter prediction. Therefore wind-tunnel and flight test data were available for it. A wing planform view for each aircraft is given in Fig. 1.

A review of experimental and analytical flutter data indicate that the parameter groupings that are most likely to represent the effect of store aerodynamics on wing/store flutter are store motion, store location, store size, and store center-of-pressure location. Studies by Goland and Luke,[1] Runyan and Sewall,[2] and Gayman[5] indicate that store mass, chordwise, and spanwise position have an effect on the wing/store flutter speed. The first two studies did not include store aerodynamics, therefore the changes in flutter speed were due to changes in the natural frequencies and mode shapes of the wing itself. The last study included store aerodynamics so that the change in wing/store flutter speed was a combination of modal and aerodynamic effects. Later studies by Sewall, Herr, and Igoe[6] and Pollock and Cooley[7] indicate that accurate representation of the store center-of-pressure location is needed to obtain valid flutter results for some wing/store configurations. A set of 20 parameters was selected to represent store motion, store location, store size, and store center-of-pressure location. Three additional parameters were selected to represent the effect of store aerodynamics on the wing/store flutter speed. Store position is given by three parameters; store size is given by two parameters; and, instead of making the center of pressure one parameter, it was decided to include a set of geometric parameters that can be used to determine the center of pressure of the store. This allows the effects of the canards, fins, and body to be independently studied. These parameters are given in Fig. 2. A set of modal parameters was selected to describe the ratio of the natural frequencies and the relative displacement of the store (Fig. 2).

One additional area of concern was an apparent discontinuity in flutter speed due to mass variations as described by Gayman.[5] The discontinuity is due to a change in the flutter mechanism as various parameters are changed. In Gayman's study, the mass and center-of-gravity location were varied for a fuel tank. There was no discontinuity in the damping/velocity plots for various parameters, but there was a discontinuity in the flutter velocity vs mass properties. In an attempt to predict when the flutter mechanism will switch for various aerodynamic parameters, additional modal parameters have been included in the parameter set. These are ω_3/ω_1, δ_3, α_3 (see Fig. 2).

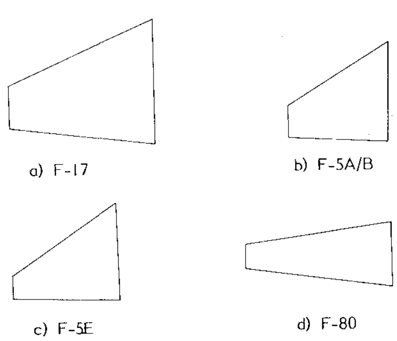

Fig. 1 Wing planforms.

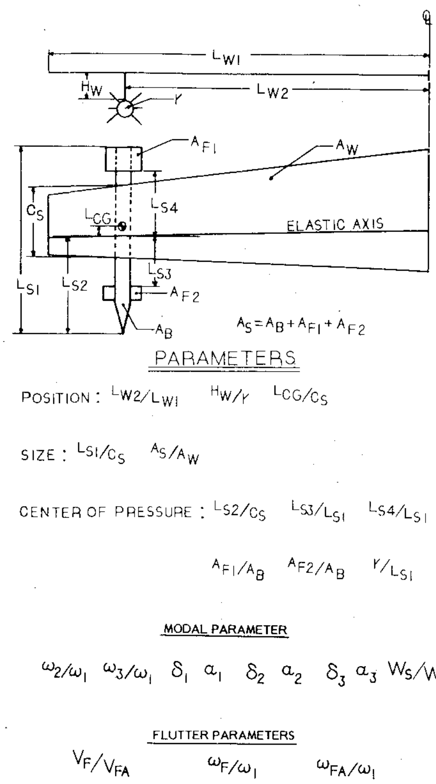

Fig. 2 Definition of parameters.

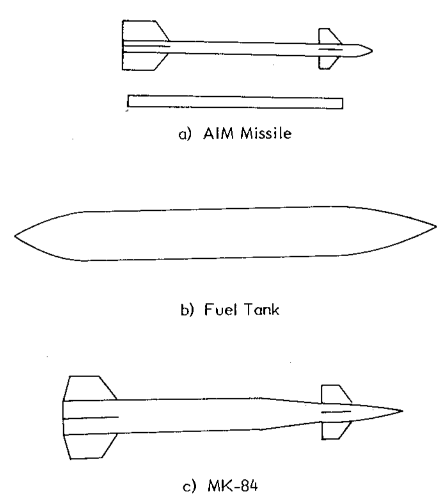

Fig. 3 Stores used in analyses.

For the multivariate analysis to yield useful results, each of the parameters must be adequately represented in the data base. With this in mind, three basic stores were selected with three different span positions being used with each store. The stores selected were the AIM missile[10,12-14] and launcher, the fuel tank,[14] and the MK-84[14] bomb (Fig. 3).

Each wing model consists of an elastic axis structural dynamics model restrained at the root by pitch and plunge springs while fixed in the *x,y* roll and yaw directions. The elastic axis models used for each aircraft are the same as the ones presented in Refs. 7, 10, and 12-14. In each case the structural model was checked against analytical and experimental natural frequencies and mode shapes given in these references. The nonplanar doublet lattice method, the method of images, and slender body theory as incorporated in MSC-50A NASTRAN[15-21] were used to model the wing/store configurations aerodynamically. The aerodynamic model of the F-17 with tip missile is presented in Fig. 4.

The addition of store aerodynamics to the wing/store flutter analysis can have one of three effects:

1) The aeroelastic instability begins as flutter without store aerodynamics, and the flutter mechanism is unchanged by store aerodynamics, but the flutter speed is changed.

2) The aeroelastic instability begins as flutter, but the flutter mechanism changes because the store aerodynamics causes different modes to couple together. This effect normally causes large variation in flutter speed.

3) The aeroelastic instability changes from flutter to divergence, a pseudostatic instability.

In the case of divergence, the addition of the store aerodynamics has increased the flutter speed beyond the wing divergence speed. This type of change occurred for 2% of the configurations studied. In each instance where this type of behavior was noted, the flutter velocity was first increased by the addition of the store and then increased beyond the wing divergence velocity by the addition of the store aerodynamics. These data were not included in the factor analysis since there was a change in the basic instability mode. This is a discontinuity in the data. For the remaining 98% of the configurations, the aeroelastic instability remained flutter, with 92% of the configurations displaying a continuous behavior in that the flutter mechanism was unchanged. However in 6% of the configurations, the flutter mechanism changed, with different modes causing the instability. This mode switching or discontinuous behavior was observed by Gayman,[5] and as noted previously, parameters were selected in an attempt to model this type of behavior. The velocity-damping curves for the F-5A/B with a forward mounted underwing tip missile, shown in Fig. 5, illustrates this type of behavior. When the aerodynamic center of pressure is moved forward by the addition of canards, the flutter mechanism changes from first bending to second bending/torsion with a lower flutter velocity. But in the majority of the configurations the flutter mechanism remained the same with only a shift in the flutter velocity, as shown for the F-5A/B with a forward mounted tip missile (Fig. 6). The ratio of the flutter velocity of the wing/store configurations vs the flutter velocity of the wing/store with store aerodynamics included is given for each configuration in Ref. 23.

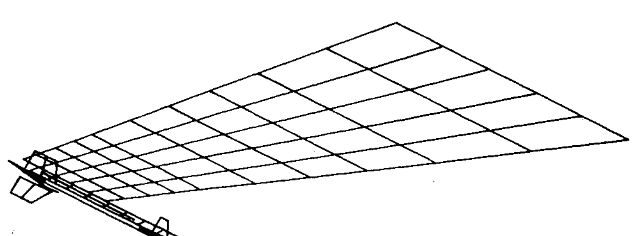

Fig. 4 F-17 with tip missile.

It is standard U.S. Air Force practice to use analysis to certify or "clear" stores for flight only after a sufficient amount of theoretical analysis, wind-tunnel test, and flight flutter test experience is obtained for a particular aircraft. The maximum allowable wing/store operation velocity of the aircraft is in most cases 85% of the wing/store analytical flutter velocity obtained using wing aerodynamics.

To present the effect of store aerodynamics on wing/store flutter taking into account the 15% margin, three arbitrary regions have been established. They are the following:

1) 0 to ±7% change in wing/store flutter speed;

2) ±7% to ±15% change in wing/store flutter speed;

3) ±15% or greater change in wing/store flutter speed.

In region 1, there is little need to include store aerodynamics in the wing/store flutter analysis since the change in speed is less than half of 15%. About 60% of the configurations fall within this region. Region 2 is considered

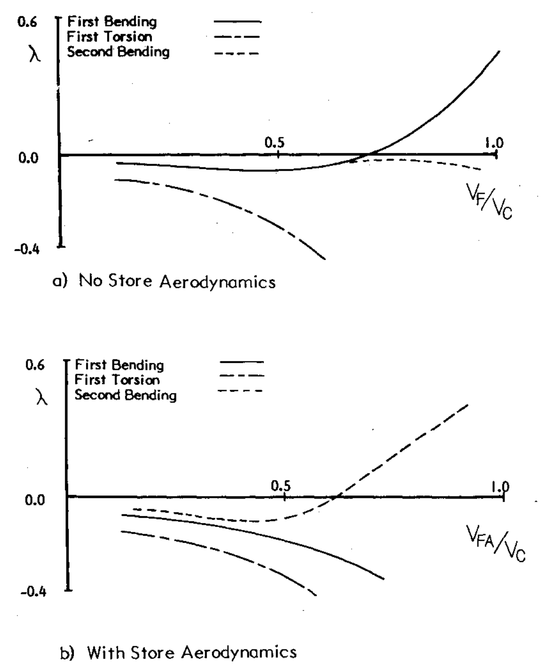

Fig. 5 F-5 A/B, damping vs velocity.

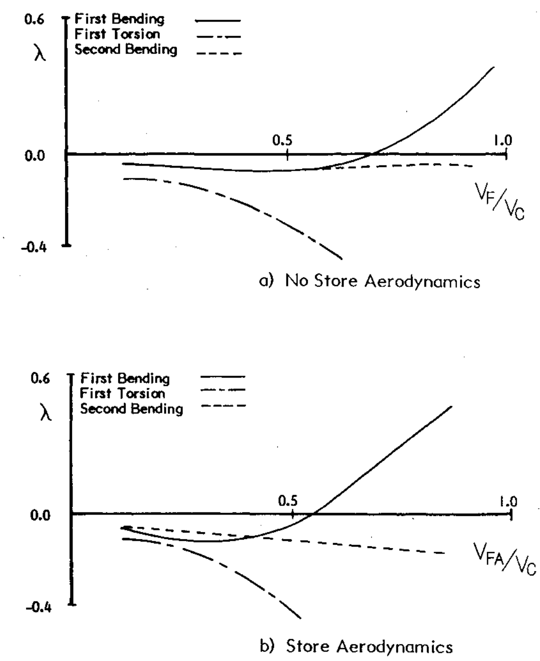

Fig. 6 F-5 A/B, damping vs velocity.

the crossover region. Therefore there is a need to carefully evaluate the requirements for aerodynamic modeling of the store. About 17% of the configurations fall within this region, with 70% of these configurations being nonconservative. Those configurations falling within region 3 would require the aerodynamic modeling of the store to obtain valid flutter results. About 23% of the configurations fall within this region, with 70% of these configurations being nonconservative. In summary, the data generated show that 18-30% of the total configurations studied would yield questionable flutter results if the store aerodynamics were not included in the flutter analysis. Assuming a well-behaved-type wing/store flutter problem, a few general observations concerning the effect of store aerodynamics on wing/store flutter could be made from examination of the data base itself. If the mechanism of flutter is second bending, which includes a significant amount of wing torsion motion (first torsion), then the location of the center of pressure of the store is a key parameter. In this particular case, the addition of fins to the store would increase the flutter velocity and the addition of canards to the store would decrease the flutter velocity. If the mechanism of flutter is primarily first wing bending motion, then the addition of either fins or canards would decrease the flutter velocity. The discontinuous type of flutter problem is encountered when there is a close relationship between first bending and first torsion/second bending. The addition of a fin or canard will shift the center of pressure enough to change the flutter mechanism with either a large increase or decrease in flutter velocity.

IV. Multivariate Analysis

A multivariate analysis was performed on the previously described data base using factor analysis[24,25] with selected parameters. Factor analysis seeks to explain observations in terms of a few important variables and to aid in making predictions concerning these observations. For these two reasons factor analysis was used to obtain information concerning the strength of the correlation among the various selected parameters, eigenvalues of the correlations matrix, and the relationship of the parameters for the various strengths of correlation, eigenvectors of the correlation matrix. Thus to be able to make predictions the correlation must be good between the wing/store flutter speed and a set of known parameters.

Having selected the parameters to be used in the factor analysis, the mean value for each of the selected parameters is determined.

$$\bar{X}_j = \sum_{i=1}^{N} \frac{X_{ji}}{N} \qquad j=1,2,\ldots,\eta \tag{1}$$

where η equals the parameters $\omega_2/\omega_1, \delta_1, \alpha_1$, etc.; and N are the observations, wing/store configurations to be included in the analysis.

The difference between each observation and the mean for each parameter is computed.

$$x_{ji} = X_{ji} - \bar{X}_j \qquad \begin{matrix} j=1,2,\ldots,\eta \\ i=1,2,\ldots,N \end{matrix} \tag{2}$$

The final step is the development of the correlation matrix. The coefficients of the matrix are given by

$$r_{jK} = \frac{\sum_{i=1}^{N} x_{ji} x_{Ki}}{\sqrt{\sum_{i=1}^{N} x_{ji}^2 \sum_{i=1}^{N} x_{Ki}^2}} \qquad j,K=1,2,..,\eta \tag{3}$$

The correlation matrix shows the strength of the relationship between any two parameters for a given number of wing/store configurations; the largest possible value is unity. To aid in determining the key relationships among the parameters, the eigenvalues of the correlation matrix are found. It is then assumed that the dimension of the solution space, the minimum number of parameters necessary to describe the data base, is equal to the number of principal components for which the eigenvalues are greater than unity. The eigenvectors of the eigenvalues which are greater than unity contain the parameter correlations. The larger the eigenvalue, the better the correlation is among the parameters represented in the eigenvector.

Owing to the nonlinear influence of system parameters on flutter velocity, a nonlinear factor analysis was also done on the data base to determine which of the parameters showed highly nonlinear behavior.

To accomplish this task, a series of factor analyses were made on the data base. The first set of analyses included all the aircraft, but looked at the various stores and store combinations. The eigenvalue/eigenvector of the correlation matrix was selected in which V_F/V_{FA} was a maximum. The wing/store configurations along with the eigenvalues are given in Table 1. As stated earlier, the closer the eigenvalue is to one, the weaker the correlation. For the eigenvalues in Table 1, the correlation is fairly weak, with the tip missile and underwing store configurations showing the strongest correlation. The results of this set of analyses would indicate that it is not possible to develop a good general method of determining the effect of store aerodynamics on wing/store flutter using the selected parameters. The next step was to do a series of factor analyses on each aircraft for all stores. Again, the eigenvalue/eigenvector of the correlation matrix was selected in which V_F/V_{FA} was a maximum. The results are given in Table 2 along with one of the earlier results from Table 1. For each of the specific aircraft, the correlation is very strong. These results indicate that it is possible to develop specific guidelines or a prediction technique for each type of aircraft.

To develop specific guidelines or a prediction technique, the eigenvector in which V_F/V_{FA} is a maximum would then be considered. An example of this for F-17 is given in Table 3. The key parameters are α_2, A_{F2}/A_B, L_{CG}/C_s, δ_2, $A\hat{S}/A_W$, ω_3/ω_1 as determined from the linear eigenvector. When both the linear and nonlinear eigenvectors are used, the key parameters are α_2, A_{F2}/A_B,L_{CG}/C_S, δ_2, A_S/A_W, ω_3/ω_1, H_W/γ, L_{S3}/L_{S1}. For this aircraft the analytical flutter mechanism is first wing torsion. Thus the effect that the store aerodynamics has on wing/store flutter is most closely related to the selected parameters that represent store pitch, store center-of-pressure movement, fore/aft location of store and

Table 1 Factor analysis of all aircraft for various configurations

Wing/store configurations	Eigenvalue for which V_F/V_{FA} is a maximum
Tip missile	2.61
Missile	1.64
Fuel tank	1.48
MK-84	1.48
Underwing stores	2.04
All stores	1.37

Table 2 Factor analysis for each aircraft, all stores

Aircraft type	Eigenvalue for which V_F/V_{FA} is a maximum
F-5A/B	11.77
F-5E	13.29
F-17	38.39
F-80	14.57
All aircraft	1.37

Table 3 Factor analysis results of wing model No. 1—all stores

Parameter	Linear eigenvector	Quadratic eigenvector	Cubic eigenvector
ω_2/ω_1	0.312	0.687	0.753[a]
ω_3/ω_1	−0.583	−0.776[a]	−0.767
δ_1	0.387	0.665[a]	0.646
α_1	−0.405	−0.620	0.763[a]
δ_2	−0.663[a]	−0.626	−0.542
α_2	0.812	0.994[a]	0.902
δ_3	−0.283	−0.488	−0.294
α_3	0.488	0.574[a]	0.393
W_S/W_W	−0.167	0.686	−0.830[a]
ω_F/ω_1	0.039	0.009	0.020
ω_{FA}/ω_1	0.066	−0.005	−0.062
L_{W2}/L_{W1}	−0.191	−0.065	0.068
A_S/A_W	−0.589	−0.379	−0.679[a]
L_{CG}/C_s	0.716[a]	0.294	−0.496
H_W/γ	0.578	0.849	0.939[a]
L_{S1}/C_S	−0.300	−0.617	−0.627[a]
L_{S2}/L_{S1}	0.174	−0.442	0.454
L_{S3}/L_{S1}	0.503	−0.781	−0.869[a]
L_{S4}/L_{S1}	0.292	−0.373	−0.439
A_{F1}/A_B	−0.133	−0.144	−0.0117
A_{F2}/A_B	0.812	0.948	0.974[a]
γ/L_{S1}	0.476	0.130	−0.642[a]

[a]Selected parameters.

store center of gravity, and overall store size. The selected parameters can now serve as a guide or be used in regression analysis to develop a technique for predicting when store aerodynamics should be included in wing/store flutter analysis for this specific aircraft.

V. Conclusion

This study was the first attempt to do a systematic analytical study of the effect of store aerodynamics on wing/store flutter. To determine this effect, flutter analyses were done on four aircraft with single carriage of three basic store types. In all, 308 configurations were analyzed with and without store aerodynamics. These configurations represented tip missiles, tip tanks, and underwing stores. Including store aerodynamics in the wing/store flutter analysis can have one of three effects:

1) The aeroelastic instability begins as flutter without store aerodynamics, and the flutter mechanism is unchanged by store aerodynamics, although the flutter speed changes (continuous behavior, 94% of the configurations).

2) The aeroelastic instability begins as flutter, but the flutter mechanism changes because the store aerodynamics causes different modes to couple together. This group normally will have large changes in flutter speed (discontinuous behavior, 4% of the configurations).

3) The aeroelastic instability changes from flutter to divergence, a pseudostatic instability (discontinuity in the data, 2% of the configurations). In the case of divergence, the addition of the store aerodynamics has increased the flutter speed beyond the wing divergence speed.

Three arbitrary regions have been established to present the effect of store aerodynamics on wing/store flutter taking into account the 15% margin normally used with military aircraft.

1) 0 to ±7% change in flutter speed. There is little need to include store aerodynamics in the flutter analysis since the change in speed is less than half of the 15%. About 60% of the configurations fall within this region.

2) ±7 to ±15% change in flutter speed. There is a need to carefully evaluate the requirements for aerodynamic modeling of the store. About 17% of the configurations fall within this region.

3) ±15% or greater change in flutter speed. To obtain valid flutter results the store aerodynamics must be included in the flutter analysis. About 23% of the configurations fall within this region.

About 75% of the configurations represented in regions 2 and 3 yielded nonconservative flutter results when store aerodynamics were not included in the analysis.

To aid in studying the effects of store aerodynamics on wing/store flutter, a factor analysis was made on the data base. Flight test results, wind-tunnel test results, and analytical results were used to determine a set of parameters to be used in the factor analysis. The parameters represented wing/store geometry, mass, modal, flutter, and aerodynamic configuration data. The factor analysis was used to determine if there was any correlation between the parameters and the wing/store flutter speed, thus aiding in developing guidelines to determine when store aerodynamics would have to be included in the wing/store flutter analysis to obtain valid flutter results. The results of the factor analysis indicate that it may not be possible to develop general guidelines, but it is possible to develop specific guidelines for use with a particular aircraft.

The results of this study are limited to those configurations which were used to generate the data base. Future efforts are needed to determine the effects on wing/store flutter including store aerodynamics for multiple carriage of stores. As wing/store flutter data become available for more configurations the data base can be updated and the multivariate analysis can be repeated.

References

[1]Goland, M. and Luke, Y.L., "The Flutter of a Uniform Wing with Tip Weights," *Journal of Applied Mechanics*, Vol. 15, No. 1, March 1948, pp. 13-20.

[2]Runyan, H.L. and Sewall, J.L., "Experimental Investigation of the Effects of Concentrated Weights on Flutter Characteristics of a Straight Cantilever Wing," NACA TN-1594, June 1948.

[3]Sewall, J.L. and Woolston, D.S., "Preliminary Experimental Investigation of Effects of Aerodynamic Shape of Concentrated Weights on Flutter of a Straight Cantilever Wing," NACA RM L9E17, July 1949.

[4]Andropoulos, T.C., Chee, C.F., and Targoff, W.P., "The Effect of Engine Location on the Antisymmetric Flutter Mode," AF Tech. Rept. 6353, Aug. 1951.

[5]Gayman, W.H., "An Investigation of the Effect of a Varying Tip-Weight Distribution on the Flutter Characteristics of a Straight Wing," *Journal of the Aeronautical Sciences*, Vol. 19, May 1952, pp. 289-302.

[6]Sewall, J.L., Herr, R.W., and Igoe, W.B., "Flutter Investigation of a True-Speed Dynamics Model with Various Tip-Tank Configurations," NACA RM L54119, March 1955.

[7]Pollock, S.J. and Cooley, D.E., "Evaluation of Prediction Methods for Aircraft/External Store Flutter Clearance," The Fourth Aircraft/Stores Compatibility Symposium, Fort Walton Beach, Fla., Oct. 1977.

[8]Cross, A.K. and Albano, E.A., "Computer Techniques for the Rapid Flutter Clearance of Aircraft Carrying External Stores, Part I Perturbation Theory and Application," Air Force Flight Dynamics Laboratory Rept. AFFDL-TR-72-114, Part I, Feb. 1973.

[9]Van Nunen, J.W.G., Roos, R., and Meyer, J.J., "Investigation of the Unsteady Airloads on Wing-Store Configurations in Subsonic Flow," The Fourth Aircraft/Stores Compatibility Symposium, Fort Walton Beach, Fla., Oct. 1977.

[10]Hwang, C., Winther, B.A., and Mills, G.R., "Demonstration of Active Wing/Store Flutter Suppression Systems," Air Force Flight Dynamics Laboratory Rept. AFFDL-TR-78-65, June 1978.

[11]Reed, W.H., Foughner, J.T., and Runyan, H.L., "Decoupler Pylon: A Simple, Effective Wing/Store Flutter Suppressor," AIAA/ASME/ASCE/AHS 20th Structures, Structural Dynamics, and Materials Conference, St. Louis, Mo., April 4-6, 1979.

[12]"Basic Weight and Stiffness Data for F-5E Modal Vibration Analysis," Northrop Corporation Rept. NOR 78-111, Aug. 1978.

[13]Arthurs, T.D., "Parametric Flutter Clearance of Wing Tip Missiles on the F-5 Series Aircraft," Aerospace Flutter and Dynamics Council, San Antonio, Texas, April 27, 1978.

[14]Clyburn, R.C., "Certification of AIM-9 Matrix on F-5A/B Aircraft CAN 1634 Flutter Analysis Report," Northrop Corporation Rept. NOR 78-112, Aug. 1978.

[15]MacNeal, R.H., ed., "MSC/NASTRAN Theoretical Manual," The MacNeal-Schwendler Corporation.

[16]McCormick, C.W., ed., "MCS/NASTRAN User's Manual," The MacNeal-Schwendler Corporation, May 1976.

[17]"MSC/NASTRAN Aeroelastic Supplement," The MacNeal-Schwendler Corporation.

[18]Wall, S.E., ed., "MSC/NASTRAN Programmer's Manual," The MacNeal-Schwendler Corporation.

[19]"The NASTRAN Theoretical Manual," NASA SP-221(04), 1978.

[20]"The NASTRAN User's Manual," NASA SP-222(04), 1978.

[21]"The NASTRAN Programmer's Manual," NASA SP-223(04), 1978.

[22]Rodden, W.P., Harder, R.L., and Bellinger, E.D., "Aeroelastic Addition to NASTRAN," NASA Contractor Rept. CR-3094, March 1979.

[23]Turner, C.D., "The Effect of Store Aerodynamics on Wing/Store Flutter," The Fifth Aircraft/Stores Compatibility Symposium, St. Louis, Mo., Sept. 9-11, 1980.

[24]Harman, H.H., *Modern Factor Analysis,* The University of Chicago Press, Chicago, 1976.

[25]Gregg, L.W. and Pearson, R.G., "Factor Analysis of Lightplane Accident Impact and Damage Variables," TREC-TR-61-122, Aug. 1961.