FLUTTER ANALYSIS OF F-16 AIRCRAFT UTILIZING TEST MODAL DATA

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Abstract

The Flutter analyses are performed for the KF-16 aircraft with brand new ALQ ECM pod. A flutter analysis method utilizing test modal data is proposed and validated using published F-16 modal data and flutter analysis results. Ground vibration test is performed for KF-16 stands on its landing gears. Attained modal data are transformed to free-free condition of KF-16 aircraft with ALQ-NEW pod and ALQ-119 pod respectively. As a result of comparison of flutter analyses, ALQ- NEW is cleared to be operated in the flight envelope authorized for existing ECM pods.

1. Introduction

The new ECM(Electronic Counter Measures) pod is designated to replace the existing ECM pod for carriage on the KF-16 aircraft in the ROKAF inventory. KF-16 is the Korean version of F-16. For this task, the aircraft configurations are to be cleared for flight, from flutter viewpoint. The required flight envelopes for the new store configurations are identical to the defined flight envelopes for the existing store configurations. The F-16 is sensitive, from the flutter viewpoint, to stores such as the ECM pods, and known flutter and LCO phenomena were observed for these stores. Therefore, the clearance of KF-16 with new ECM configurations required a more in-depth evaluation [1].

Since, we do not possess any analytical aero-elastic model of F-16, which includes a structural dynamics computational model, such as a Finite Element Method (FEM) model, the analyses were performed using a full modal approach. The structural dynamics of the aircraft is represented through its modal characteristics as measured during a set of GVT(Ground Vibration Tests) for the aircraft in several defined external stores configurations.

This paper introduces unconventional procedures for flutter clearance program which included performing Ground Vibration Tests [2] for the KF-16 in some chosen stores configurations and building an entire analytical database. Based on the experimental results, Flutter analyses were performed for the series of ECM Pods external store configurations for comparison. The analyses were performed using the linear flutter solvers available in MSC/NASTRAN aeroelastic module. Some modifications were implemented in order to enable the direct use of experimental data in MSC/NASTRAN aeroelastic module. However the analysis core remains the same. The modifications were checked against published results.

The modified version of the MSC/NASTRAN aeroelastic solver is used that enables using directly the modal characteristics measured during GVT, thus bypassing the need to calculate these characteristics using a FEM model. This hybrid approach is in fact more accurate, using experimental data, since it overpasses the existing discrepancies between GVT data and analytical data. The schematic diagram presents a chart diagram illustrating the computation procedure of flutter analysis with GVT modal data. However, the hybrid approach, using GVT data in the flutter analysis, is also more restrictive in the sense that only the relatively few cases of measured configurations could be analyzed. Modal characteristics of configurations of stores similar to the measured modes are also derived using the 'Added Generalized Mass approach'.

The incorporation of the capability to use GVT measured data into the MSC/NASTRAN solver was achieved using the MSC/NASTRAN DMAP programming language.

Flutter analyses were conducted for configurations for which the modes were measured during the GVT session for low subsonic; high subsonic and supersonic flight regime. The Doublet Lattice Method (DLM) was used for the subsonic analyses, and the Zona51 for the supersonic analyses. The results showed that the flutter calculated speeds for the newly developed store configurations were consistently higher than the corresponding calculated flutter speed for the existing store configurations.

The flutter analytical results for the KF-16 in flutter-critical stores configurations including newly developed ECM pods(namely, ALQ-NEW) showed that the configurations had consistently higher flutter speed than the correspondent existing store configurations.

2 Theoretical Backgrounds

2.1 Flutter analysis using test modal data

Generally, linear flutter analysis is performed using finite element method in the aeronautical industry at large. Here FEM model represents the structure and linear unsteady aerodynamics in the frequency domain is used to represent the aerodynamics of the aircraft. Several solvers could be used to solve the flutter equations in NASTRAN. The “P-K” or “KE” methods (reference [3]) are normally used for this purpose. The analyses are performed at different Mach numbers and altitudes in order to reconcile the calculated flutter speed with the altitude and Mach numbers used in the analysis.

The flutter analysis is performed in NASTRAN in the modal domain. Thus, the structural dynamics FEM model is used to calculate structural modes (eigenvalues and eigenvectors of the structure) and a transformation from the physical domain to the modal domain is done using these modes. The final aeroelastic analysis is then performed using N-degrees of freedom domain (DOF), where N is the number of modes taken. Then, the structural FEM model itself is no longer used in the aeroelastic solver module.

Since the calculation of the modes using a FEM model requires detailed information about the stiffness and mass distribution of the structure (which is not available for the KF-16 Aircraft) and alternative approach could be taken and bypassing the FEM analysis of the structure. This is a hybrid approach that uses directly measured modes from GVT. However, the hybrid approach, using GVT data in the flutter analysis, is also more restrictive in the sense that only the relatively few cases of measured configurations could be analyzed. Modal characteristics of configurations of stores similar to the measured modes are also derived using the ’Added Generalized Mass approach’. Figure 1 presents a chart diagram illustrating the computation procedure of flutter analysis with GVT modal data.

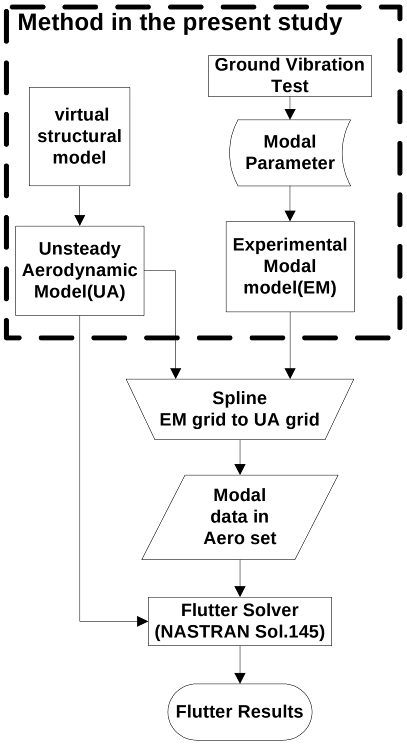


Fig 1. Schematic diagram for Flutter analysis using test modal data

The incorporation of the capability to use GVT measured data into the MSC/NASTRAN solver was achieved using the MSC/NASTRAN DMAP programming language. MSC/ NASTRAN is built in "modules" that are written for specific applications, those are the "rigid solutions" of the MSC/NASTRAN. Thus, "solution 103 - SEMODES" is a module that performs "structural dynamics modal analysis" and "solution 145 -SEFLUTTER" is a module that performs flutter modal analysis. We developed a DMAP to enable importing GVT data into NASTRAN/SEMODES and NASTRAN/ SEFLUTTER. Figure 2 shows the modified flutter analysis flow using the DMAP program.

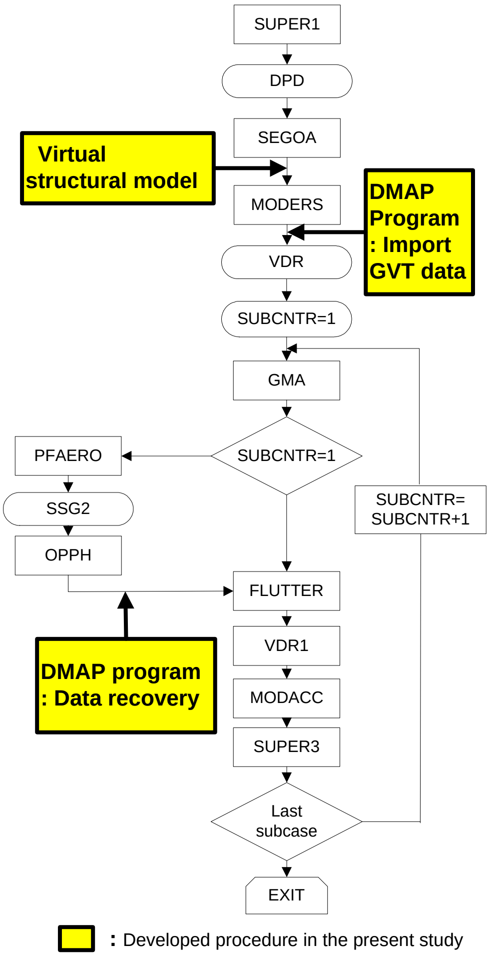
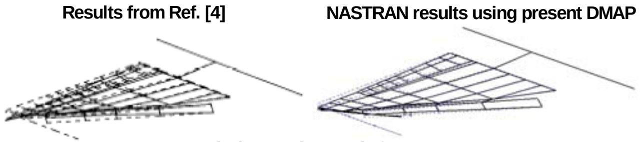


Fig 2. Modified procedure for MSC Flutter analysis

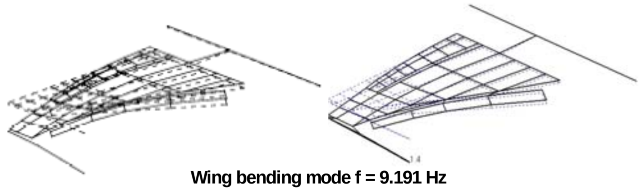
2.2 Verification of the developed program

The procedure presented above was used to import the tabulated data from reference [4] into NASTRAN and perform the flutter analysis. It is noted that here the tabulated data is considered GVT data (another name of GVT data could be – data external to the analytical run). The results of the NASTRAN analysis (using the DMAP programs presented above) were then compared with the results presented in reference [4].

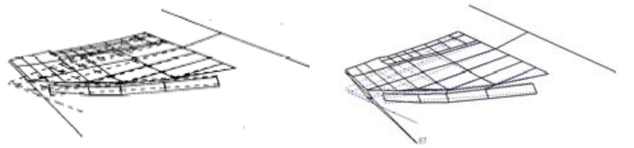
Figure 3 presents a pictorial comparison between the modes presented in Reference [4] and the modes resulted from NASTRAN runs. As it can be seen from figures 3, the modes were successfully imported into NASTRAN and could be showed as a result of SEMODES module solution of MSC/NASTRAN.



Forward wing torsion mode f = 10.246 Hz



Wing bending mode f = 9.191 Hz



Wing torsion mode f = 9.964 Hz

Fig 3. Comparison the results of F-16 normal mode analysis

Flutter analysis was performed for the modes imported into MSC/NASTRAN as described above. The unsteady aerodynamic model used in the analysis was built in MSC/NASTRAN, using the doublet lattice method (DLM), similar to reference [4]. The results for the first configuration ("Classical flutter configuration) are presented in a V-g,V-f plots in figures 4 and 5, for the reference[4] and results using present DMAP Program respectively. As it can be seen the results are almost identical. It is noted that the present hybrid approach was performed only with the few modes given in the reference [4] (3 modes for configuration 1 and only 2 modes for the second configuration).

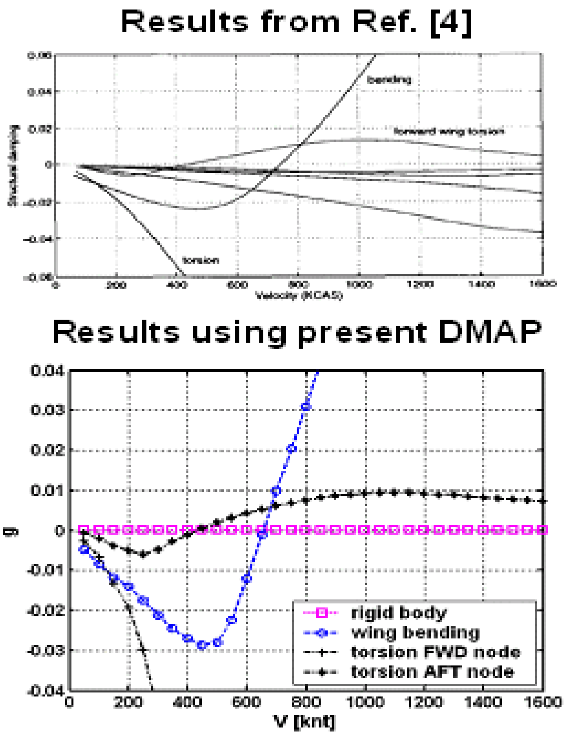


Fig 4. Comparison the results of F-16 flutter analysis (V-g plot)

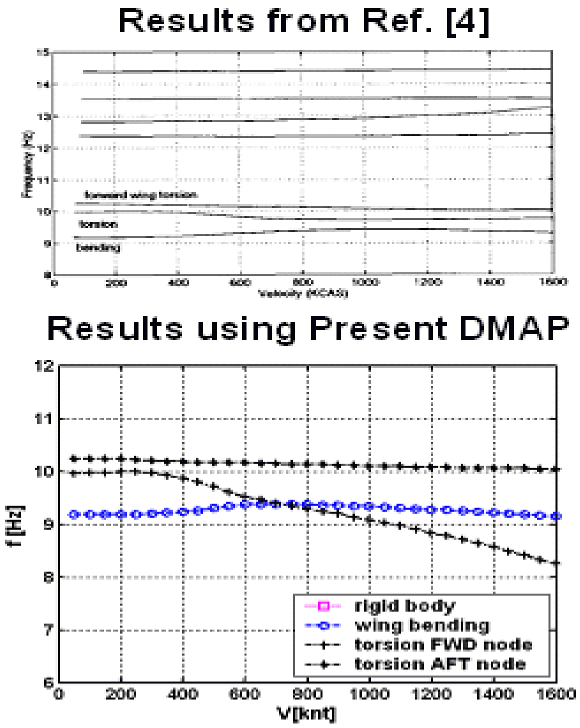


Fig 5. Comparison the results of F-16 flutter analysis (V-f plot)

Nevertheless, the results are similar to the ones presented in the paper where more modes were taken in the analysis. Nevertheless, the flutter mechanism here is predominantly bimodal and only few modes are required for the analysis.

The comparison with the reference [4] results was used to validate the new programs written in DMAP to enable to performed flutter analysis with imported data (instead of FEM results of structural dynamics analysis within MSC/NASTRAN).

2.3 Test modal data

The derivation of the free-free modes from the measured modes is performed using the ‘Added Generalized Stiffness’ technique.

Figure 6 illustrates the simplified model of the structure that is considered in this study. It is assumed that the structural system could be adequately represented as a structure connected to the ground by a set of two linear springs (a plunge spring and a roll spring). This system is denoted as structure #1.

Given the modal representation of system #1 from ground vibration tests results, it is required to evaluate the modal characteristics of the system that includes only Aircraft structure with free-free boundary conditions, without the plunge and roll springs. This is denoted as structure #2.

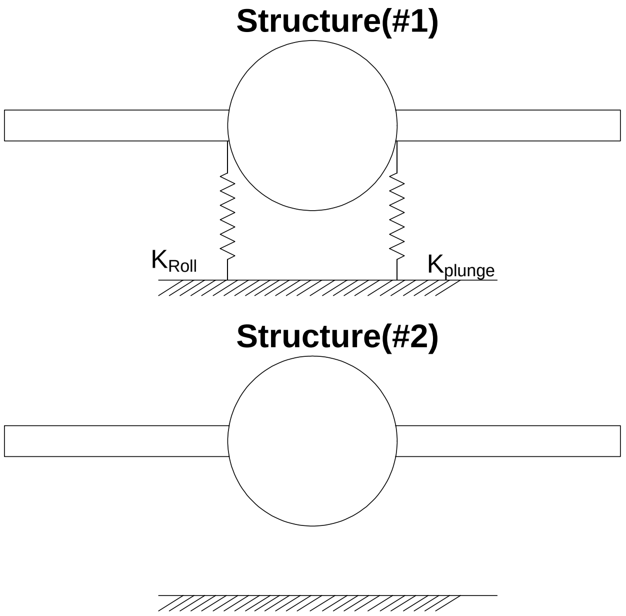


Fig 6. Embodiment of Free-Free condition

The equilibrium equation of the structural dynamics system of structure #1, including the set of grounded springs in plunge ($\tilde{K}_P$) and roll ($\tilde{K}_R$) could then be written as

$$\begin{pmatrix} M_A & 0 & 0 \\ 0 & M_R & 0 \\ 0 & 0 & M_P \end{pmatrix} \begin{Bmatrix} \ddot{X}_A \\ \ddot{X}_R \\ \ddot{X}_P \end{Bmatrix} + \begin{pmatrix} K_{AA} & K_{AR} & K_{AP} \\ K_{AR}{}^T & K_{RR}+\tilde{K}_R & 0 \\ K_{AP}{}^T & 0 & K_{PP}+\tilde{K}_P \end{pmatrix} \begin{Bmatrix} X_A \\ X_R \\ X_P \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \end{Bmatrix} \quad (1)$$

Pre-multiplying (1) by $\left[\phi_A{}^T \phi_R{}^T \phi_P{}^T \right]$ gives:

Where,

$[\phi_A]$: The eigenvector matrix of modes in the subset A (NA **μ** NL matrix).

$[\phi_R]$: The eigenvector matrix of modes in the subset R (NR **μ** NL matrix).

$[\phi_P]$: The eigenvector matrix of modes in the subset P (NP **μ** NL matrix).

NL : The number of modes.

NA : The number of D.O.F in the subset A.

NR : The number of D.O.F in the subset R.

NP : The number of D.O.F in the subset P.

$$\left([GK] + \phi_R^T \tilde{K}_R \phi_R + \phi_P^T \tilde{K}_P \phi_P \right) \zeta + [GM] \ddot{\zeta} = 0 \quad (2)$$

$[GK]$ is the 'generalized stiffness matrix' and it is defined as:

$$[GK] \equiv \left[\phi_A{}^T \phi_R{}^T \phi_P{}^T \right] \begin{pmatrix} K_{AA} & K_{AR} & K_{AP} \\ K_{AR}{}^T & K_{RR} & 0 \\ K_{AP}{}^T & 0 & K_{PP} \end{pmatrix} \begin{Bmatrix} \phi_A \\ \phi_R \\ \phi_P \end{Bmatrix} \quad (3)$$

$[GM]$ is the 'generalized mass matrix' and it is defined as:

$$[GM] \equiv \left[\phi_A{}^T \phi_R{}^T \phi_P{}^T \right] \begin{pmatrix} M_A & 0 & 0 \\ 0 & M_R & 0 \\ 0 & 0 & M_P \end{pmatrix} \begin{Bmatrix} \phi_A \\ \phi_R \\ \phi_P \end{Bmatrix} \quad (4)$$

In fact, Equations (3) and (4) show the generalized stiffness and generalized mass of the structure without the set of springs (free-free boundary conditions). Thus equation (2) could be written as,

$$\left([GK] + [\Delta GK] \right) \zeta + [GM] \ddot{\zeta} = 0 \quad (5)$$

Where the additional generalized stiffness due to the plunge and roll springs $\Delta GK \equiv \phi_R^T \tilde{K}_R \phi_R + \phi_P^T \tilde{K}_P \phi_P$, Solving the eigen-value equation (5), will yield the eigen-value matrix Ω_1

$$\left[\Omega_1{}^2 \right] = GM^{-1} \left(GK + \Delta GK \right) = GM^{-1} GK + GM^{-1} \Delta GK \quad (6)$$

Or alternatively, the generalized stiffness of the 'released structure' (without the set of springs) can be written as

$$GK = GM \Omega_1{}^2 - \Delta GK \quad (7)$$

The structural dynamics equation for the free-free condition $[GK]\varsigma + [GM]\ddot{\varsigma} = 0$ and substituting (7) gives

$$\left[GM \Omega_1{}^2 - \Delta GK \right] \varsigma + [GM] \ddot{\varsigma} = 0 \quad (8)$$

Solving the eigenvalue equation (8), will yield the eigenvalue matrix (thus the natural frequencies Ω_2) and the mode. It is noted that the eigenvalue matrix of the 'structure of free-free condition' could be written as a function of the clamped structure (through the spring set) and the contribution of the springs to the generalized stiffness

$$\left[\Omega_2{}^2 \right] = \left[\Omega_1{}^2 \right] - \left[GM^{-1} \Delta GK \right] \quad (9)$$

Table 1 shows a typical comparison of natural frequencies measured during the GVT and derived free-free modes.

Table 1. Results of GVT and derived of Free-Free modes

MODE		Freq. [Hz]		
		GVT	Derived(Free-Free)	
#	DESCRIPTION	Original	ALQ-NEW	ALQ-119
1	RBM - Plunge on LG	3.71	-	-
2	RBM - Roll on LG	3.81	-	-
3	Flexible Mode 1	7.22	7.06	7
4	Flexible Mode 2	10.27	9.98	9.95
5	Flexible Mode 3	10.56	10.28	9.79
6	Flexible Mode 4	11.2	10.37	10.11
7	Flexible Mode 5	12.31	11.75	11.57
8	Flexible Mode 6	13	12.74	12.63
9	Flexible Mode 7	14.22	14.14	13.4
10	Flexible Mode 8	14.32	14.26	14.01
11	Flexible Mode 9	14.79	14.48	13.01
12	Flexible Mode 10	15.51	15.33	14.76
13	Flexible Mode 11	17.88	16.97	16.62
14	Flexible Mode 12	17.05	17.74	17.73
15	Flexible Mode 13	18.37	18.25	18.11
16	Flexible Mode 14	18.88	18.38	17.92
17	Flexible Mode 15	19.84	18.47	16.4
18	Flexible Mode 16	20.73	18.48	18.11
19	Flexible Mode 17	21.17	19.7	18.84
20	Flexible Mode 18	23.57	22.79	22.65

2.4 Flutter analysis with measured and derived modes

Flutter analyses were conducted for configurations for which the modes were measured during the GVT, as well as for configurations for which the modes were derived using the 'Added generalized mass technique'. The flutter analyses were done at sea-level altitude (normally considered as critical conditions). The flutter analyses were done for 'derived modes' to account for free-free boundary condition. No Mach-match analyses were performed since the analyses are for comparison purpose.

V-f, V-g plots are used to display the flutter analyses results. The flutter analyses were performed for low subsonic, high subsonic and supersonic flight regime. The following Mach numbers: 0.3/0.6/0.9/1.2/1.5/1.8. The Doublet Lattice Method (DLM) was used for the subsonic regime, and the Zona51 for the supersonic regime. For the transonic flight regime, the linear flutter analysis is highly incorrect, and some form of interpolation should be done.

The aerodynamic model used for these analyses is shown in figure 7. This model was 'calibrated' against the USAF results presented in reference [4]. Details of the 'calibration' procedure are brought in reference [5]. It is mentioned here that the vertical fin was not modeled (to be consistent with the USAF approach presented in ref. [4]), this based on their observation that the flutter mechanisms of wing/stores was not coupled with the vertical tail.

Surface spline is used to 'relate' the structural displacement degrees of freedom (D.O.F) set with the aerodynamics D.O.F set. Figures 8 and 9 show a typical example of the same mode presented in the structural model and the aerodynamic model. These plots were plotted using MSC/PATRAN – Flight Loads & Dynamics

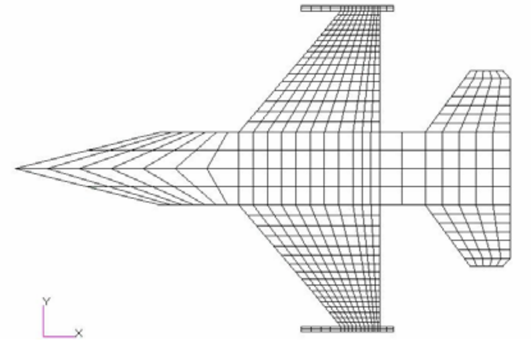


Fig 7. Unsteady Aerodynamic model for F-16

Figure 10 presents a typical V-f, V-g plot. The plot consists of two subplots. The upper subplot presents the calculated aeroelastic frequencies of the different modes versus the forward A/C speed (f-V). The lower subplot presents the calculated aeroelastic damping of the different modes versus the forward A/C speed (g-V). Flutter is defined where the aeroelastic damping becomes non-negative.

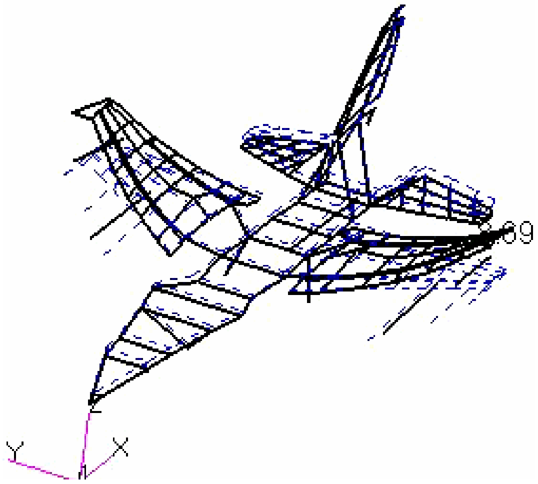


Fig 8. Mode displacement presented in the structural model

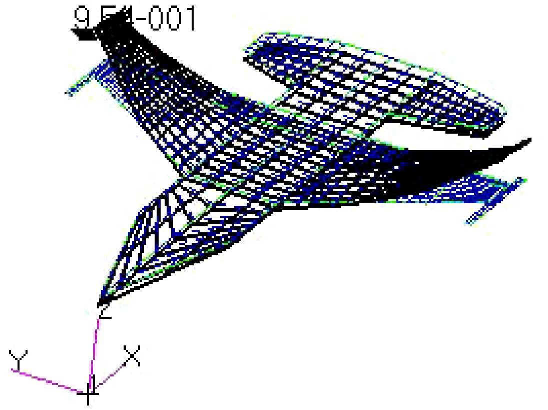


Fig 9. Mode displacement presented in the aerodynamic model

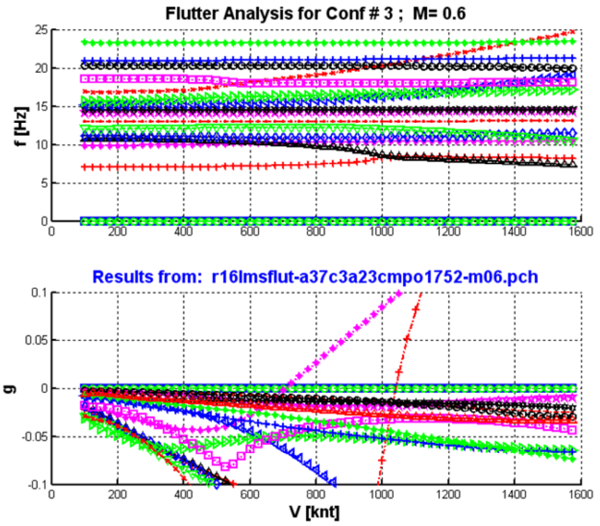


Fig 10. Typical V-f, V-g plot

The comparison between the flutter analyses results for the three ALQ pods (ALQ-NEW; ALQ-OLD and ALQ-119) is shown in Figures 11 and 12. Figure 11 presents a diagram of calculated flutter speed versus Mach for conf. #3. Figure 12 presents the diagram of calculated flutter speed versus Mach for conf. #4. All the analysis results are for sea-level calculations. The two plots show the general trend, that the analytical flutter speed for the ALQ-NEW configuration is consistently higher (by around 100 to 150 knots) than for both ALQ-119 and ALQ-OLD pod configurations

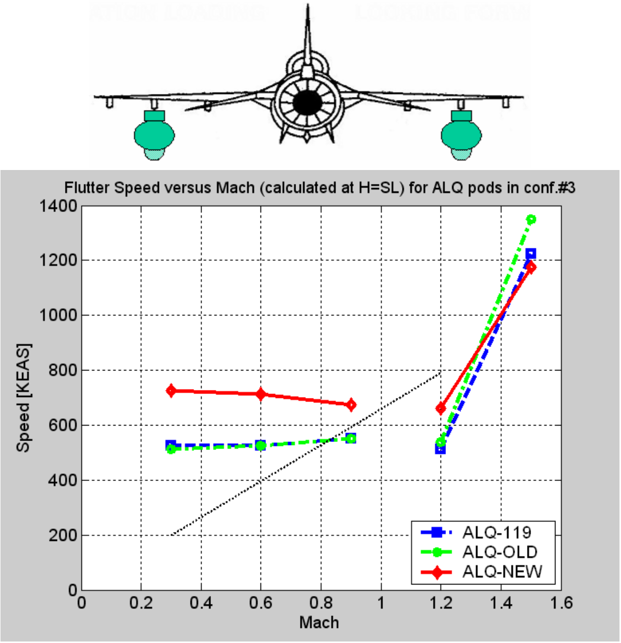


Fig 11. Flutter Velocity VS. Mach number (Conf. #3)

Based on the presented results, it is concluded that the KF-16 is cleared to fly in the ALQ-NEW configurations replacing the defined ALQ-OLD and ALQ-119 configurations subject to the restrictions defined for these configurations in the flight manual.

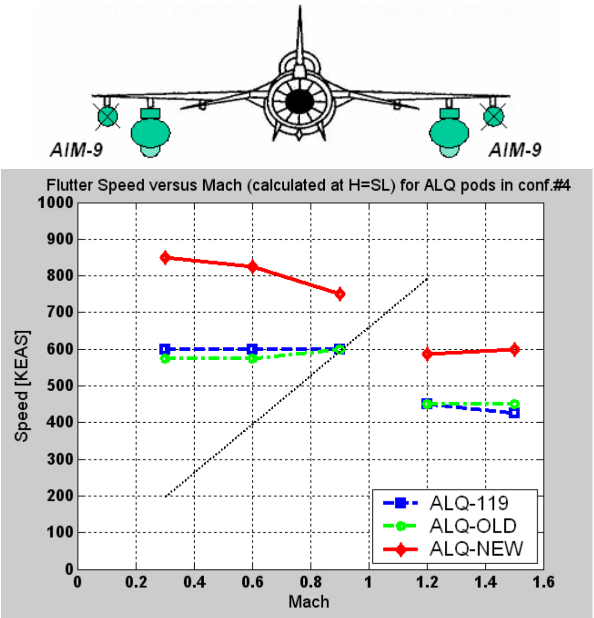


Fig 12. Flutter Velocity VS. Mach number (Conf. #4)

3. Conclusion

Comparative linear flutter analyses were performed for KF-16 carrying ALQ-NEW pod, replacing the ALQ-119 (and ALQ-OLD) ECM pods. The analyses were performed for the a priori known critical configurations, which are stores symmetric configurations denoted conf. #3 and #4 in this study. The flutter analyses were performed using GVT measured modal data. The flutter clearance philosophy was presented and showed to be consistent with the flutter clearance philosophy of both Lockheed Martin and USAF. The results showed that the flutter calculated speeds for the ALQ-NEW configurations were consistently higher than the corresponding calculated flutter speed for both the ALQ-119 and ALQ-OLD configurations. These results were indeed in-line with the expectations from the initial comparison of the inertia properties of the different ECM pods. It is concluded that that the KF-16 is cleared to fly in the ALQ-NEW configurations replacing the defined ALQ-OLD and ALQ-119 configurations subject to the restrictions defined for these configurations.

References

[1] MIL-HDBK-1763, Aircraft/Stores Compatibility: System Engineering Data Requirements and Test Procedures, Department of Defense, 1998.

[2] K.H.Byun, C.Y.Park, J.H Kim. Ground Vibration Test on KF-16D. *Journal of KSASS*, Vol. 33, No.5, pp41-49, 2005.

[3] William P. Rodden, Erwin H. Johnson. *MSC/NASTRAN Aeroelastic Analysis User's Guide* Ver.68 .MSC Software Corporation. Los Angeles, CA, USA. 1994.

[4] Denegri Jr. *Limit Cycle Oscillations Flight Test Results of a Fighter with External stores.* AIAA-2000-1394, 2000.

[5] D.V. Smith. F-16 C/D Block 40 Flutter analysis report, 16PR7752,24.Oct. 1989.