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FLUTTER PREDICTION OF A SWEPT BACK PLATE USING EXPERIMENTAL MODAL PARAMETERS

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ABSTRACT

The model parameters such as eigen values & vectors play a very important role in formulation of unsteady/steady aerodynamics and the subsequent derived aeroelastic results like flutter speeds etc. Slight variations in these values have noticeable changes in flutter characteristics. In the procedure proposed in this paper, the eigen values and mass normalized eigen vectors replace the values obtained through a normal modes solution of the equivalent finite element model of a swept back plate by invoking a Direct Matrix Abstraction Program (DMAP) sequence in the flutter solution of NASTRAN using statements available in DMAP. In case of use of ZAERO software for flutter computations, the eigen values and eigen vectors in the normal modes results file, obtained from NASTRAN is replaced directly with the experimentally obtained values. The flutter solution of the structure continues with the replaced eigen values and vectors. The flutter results obtained by using the FE model of a swept back plate with known geometric and material properties has been compared with the developed program sequence using experimental modal parameters. The studies have been done for both the cases, using unsteady doublet lattice aerodynamics in case of NASTRAN and ZONA6 aerodynamics for ZAERO software. Thus the errors, that result in a finite element normal modes analysis, caused due to improper representation of the boundary conditions, material properties and damping has been eliminated and the program sequence helps in a realistic prediction of flutter characteristics of the structure with the only requirement of the geometric configuration of the structure and need no material property, mass or stiffness related parameters for the finite element modeling of the structure.

Key Words: Flutter, Finite Element Method, DMAP, Modal Parameters

NOMENCLATURE

A	System Matrix
B	Generalized Aerodynamic damping
C	Generalized structural damping
D	Generalized aerodynamic stiffness
F	Generalized aerodynamic force
I	Identity matrix
K	Generalized structural stiffness
M	Generalized Mass
V	Air flow velocity
f	Aerodynamic forces
k	Structural stiffness
m	Structural Mass
q	Modal coordinates
λ	Eigen values of System matrix
φ	Eigen Vector
ω	Natural Frequencies
ξ	Damping Ratios

1. INTRODUCTION

Detailed modeling of the structures having full knowledge of the system in terms of distributions of stiffness and inertia is essential for the purpose of dynamic analysis using theoretical/computational methods. Numerical methods (like Finite Element Method, Finite Difference Method) are routinely used to model structural systems to determine the dynamic characteristics like natural frequencies and normal mode shapes which are necessary to predict the flutter under some anticipated aerodynamic loading. The parameters defining the dynamic characteristics determined by analytical tools are often checked with experimental results to ensure their reliability. Thus experimental methods are often used to validate the results of a theoretical investigation that needs full details of a structure of known configuration. However, when the exact details of structural system parameters (like mass and stiffness distributions) are unknown, any theoretical/numerical method alone cannot be used to model the structure or to determine its dynamic characteristics. There are cases of aircrafts in service for which there is no access to drawings, construction details, material properties, etc. or FE model of airframe structures/components. i.e., no knowledge about mass and stiffness distribution is available. Prediction of flutter boundaries of such aircrafts by conventional analytical/numerical/experimental methods is difficult. Under such circumstances, one has to resort only to experimental procedures to determine the

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dynamic characteristics of the structure and identify/determine its system parameters that can substitute for the unknown distributions of stiffness and mass. These parameters (like modal scaled stiffness and mass) obtained from accurate experimental tests can be used as an input to predict the flutter characteristics of the structure accurately[1]. The present work is aimed at predicting the flutter characteristics of an aircraft structure of unknown configuration under an anticipated aerodynamic loading using software such as MSC Nastran/ ZAERO and experimental modal parameters, (like mode shapes, natural frequencies and damping) from Ground Vibration Tests as input. The method is validated for a swept back cantilever plate by comparing its results with those from numerical methods where full details of the actual stiffness and mass distributions are used. A Direct Matrix Abstraction program (DMAP) has been written for NASTRAN that reads the modal parameters like eigenvalues and eigenvectors obtained from ground vibration tests (GVT) as an input in NASTRAN bulk data through a file using the direct matrix input module available in NASTRAN. These eigenvalues and mass normalized eigenvectors replace the values obtained through a normal modes solution of the equivalent finite element model of the structure by invoking a DMAP sequence in the flutter solution of NASTRAN using statements available in DMAP.

2. PROCEDURE

A finite element model having the same number of nodes as the test points on the structure is created. Appropriate boundary conditions and constraints corresponding to the test structure are applied on the FE model. The nodes corresponding to the response points are left free in the direction of acquired response. The eigen values and the mass normalized eigen vectors of the structure obtained from the test are replaced after the normal modes analysis and inserted in the section for further use by the flutter module. At this stage the generalized mass matrix corresponds to unity and the generalized stiffness matrix corresponds to the eigen values obtained from ground vibration tests.

GeneralizedStiffness =$K = \varphi^T k\varphi = \omega^2$Generalized

Mass= $M = \varphi^T m\varphi = [1]$

Generalized Aerodynamic Force =$F = \varphi^T f$

The generalized aerodynamic force matrix is computed using the eigen vectors obtained from ground vibration tests and further solution of the flutter problem continues by considering together the structural equations, that leads to generalized equations of motion in the classical form [2].

$$M\ddot{q} + (\rho VB + C)\dot{q} + (\rho V^2 D + K)q = 0 \quad \ldots (1.0)$$

Where M, B, C, D, K are the structural inertia, aerodynamic damping, structural damping, aerodynamic stiffness, and structural stiffness matrices in generalized coordinates q (typically modal coordinates)respectively. A key difference to generalized structural damping and stiffness matrices is that the aerodynamic matrices are non-symmetric, leading to the flutter aeroelastic instability and also the damping and stiffness is dependent upon the flight condition, including the Mach number.Thus equation (1) can be simplified to:

$$[I]\ddot{q} + (\rho VB + C)\dot{q} + (\rho V^2 D + \omega^2)q = 0 \quad \ldots (2.0)$$

The stability of the system is explored using an eigenvalue approach. The aeroelastic equation can be expressed in state space terms as:

$$\begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix}\begin{Bmatrix} \dot{q} \\ \ddot{q} \end{Bmatrix} - \begin{bmatrix} 0 & I \\ -(\rho V^2 D + \omega^2) & -(\rho VB + C) \end{bmatrix}\begin{Bmatrix} q \\ \dot{q} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix}$$

The equation can be solved by assuming the classical eigensolution form: $(\mathrm{A} - \mathrm{I}\lambda)\mathrm{q} = 0$;Where A is given by :

$$\begin{bmatrix} 0 & I \\ -(\rho V^2 D + \omega^2) & -(\rho VB + C) \end{bmatrix} \quad \ldots (3.0)$$

For an oscillatory system, such as the aeroelastic system considered here, the eigenvalues λof the system matrix A occur in complex conjugate pairs and are in the form:

$$\lambda_j = -\zeta_j \omega_j \pm i\omega_j \sqrt{1 - \zeta_j^{\,2}} \quad \text{j=1…N}$$

whereω_j1...N, are the natural frequencies and ξ_j = 1...N, are the damping ratios. Thus the upper (or lower) halves of the eigenvectors yield the mode shapes in terms of generalized coordinates. If the real part of the complex eigenvalues is positive then the system becomes unstable. A Direct Matrix Abstraction program has been written for the procedure as an input in NASTRAN bulk data through a file using the direct matrix input module available in NASTRAN as explained in the following section.

3. NASTRAN DMAP

NASTRAN software has a modular program structure with each functional module operating as an independent subprogram and free of other modules. They may call or maybe called by other modules through the executive section of NASTRAN. Each module executes many sub-routines and communication between them is achieved through the parameters in each module. This structure has an advantage that modification of a module or addition of a new module need not require modifications in other existing modules. Standard solution sequences are available in NASTRAN for different analyses like static, dynamic, heat transfer, aeroelastic analysis etc. These solution sequences consists of different modules required for a particular analysis and minor alterations in the solution sequences like reading a matrix, replacing the existing values of a matrix, getting a matrix printout etc. can be made by the use of ALTER statements.DMAP or Direct Matrix Abstraction Program is a Macro, high-level and symbolic programming language. The language is data block (tables or matrices) oriented, used to drive MSC/NASTRAN and construct MSC/NASTRAN built-in solution sequences. The basic functions are to convert input lists to tables and matrices, perform matrix solutions and convert matrices to output lists and tables. Other features includes access to any module, Alters that may be used to change the problem flow, providing an alternative to built-in solution sequences and is very similar to Fortran. DMAP has many rules which must be followed to be interpretable by the NASTRAN DMAP compiler. Like any language, results based on instructions that are syntactically correct may be misinterpreted when the results are not as anticipated. It may be used to obtain an intermediate result, add a previously excluded effect, circumvent an error or isolate errors.

The DMAP sequence is placed in the executive section of the NASTRAN deck. The eigen values and vectors obtained from GVT are read from a file through the input module by direct matrix input (DMI). The original eigen values & vectors in the flutter solution section is replaced by an alter call. The flutter solution continues with the solution of the flutter equation using the replaced eigen values and vectors.

3. TEST SPECIMEN

The test specimen under consideration for evaluation of the new sequence is a swept back plate with sweep back angle 23.8^0 at the leading edge. The plate has a thickness of 3 mm, length of 300 mm and chord varying from 130 mm to 70 mm.In the experimental set-up, responses were obtained at 40 points on the plate as shown in Figure 1.The equivalent finite element mesh of the plate, modeled by using Hypermesh software, corresponds to the locations and nodes of the accelerometers in the experimental set-up (Figure 1). The mass of the accelerometer has been lumped as concentrated mass (CONM2) elements on the respective node. The material properties used have been shown in Table.1. The geometric properties like the moment of inertia, thickness, torsional constants etc were input through PSHELL entry. The plate model consists of 30 CQUAD4 elements with 40 nodes representing the measured test response points and the remaining four nodes are constrained to represent the fixed boundary conditions.

4. EXPERIMENTAL TEST SET-UP

The experimental setup consists of specimen, data acquisition hardware, sensors, impulse hammer and computer with modal analysis software as shown in the Figure 1. The data acquisition system is a SCADAS III, multichannel 24 bit with inbuilt ADC and signal conditioners for ICP type of accelerometers. Communication between data acquisition hardware and computer system is established through SCASI card. A Laptop with advanced modal analysis software LMS Testlab is used for data acquisition, analysis and extracting the modal parameters such as frequency, damping and modal vectors. PCB made accelerometer with sensitivity of 100mV/g is used for response measurement. The Plate is mounted on a vibration table with four bolts to ensure proper boundary conditions (Figure 1). The specimen is marked with equally spaced 40 measurement points. The response accelerometer location has been chosen at the corner tip of the free end of the plate that gives better response for all the modes without any nodal point. Instrumented impulse hammer is used for exciting at all the locations marked on the plate (Figure 1). The geometry of the specimen is generated in LMS Test Lab as per the test points chosen for measurements (Figure 2). Channels setup is carried out with setting type of sensor, excitation voltage, units, reference point, measurement point IDs and gain settings. In scope settings maximum frequency is set to 512 Hz and spectral lines of 2048 Hz, that gives a frequency resolution of 0.25 Hz. Cross Power Spectrums, Peak Spectra, FRF, and Auto Power Spectra etc. are selected to be stored into the computer database. The test is repeated for the different points using rowing hammer technique and corresponding responses are collected and stored.

4. NUMERICAL MODEL

In the experimental set-up, responses were obtained at 40 points on the plate as shown in Figure 2. The equivalent finite element mesh model of the plate corresponds to the locations and nodes as the accelerometers in the experimental set-up.The mass of the accelerometer have been lumped as concentrated mass (CONM2) elements on the respective node. The model was pre-processed using Hypermesh software. The plate model consists of 30 CQUAD4 elements with 40 nodes representing the measured test response points. The method has been validated with an FE model with the actual material properties of the plate structure. The geometric properties like the moment of inertia, thickness, etc of the plate were input through PSHELL entries.The aerodynamic model for the plate is a mesh consisting of flat panels based on doublet lattice method in NASTRAN and ZONA6 aerodynamics in ZAERO for the lifting surface in case of plate model, idealized by means of trapezoidal boxes lying parallel to the flow direction. Surface spline functions are used to generate the necessary interpolation matrix to estimate the displacement of aerodynamic grids based upon the displacement of structural grids.

5. ANALYSIS AND RESULTS

Dynamic analysis of all the FE models mentioned above have been carried out by constraining the one end of the specimen in all the degrees of freedom. The dynamic frequency spectrum has been obtained by invoking the lanczos method in NASTRAN, with unit mass criteria for normalizing mode shapes. The results obtained have been listed out in Table 2. The normal mode shapes for the the first three modes obtained from GVT and Nastran have been shown in Fig 3 – 8.

The flutter analysis of the models have been carried out after taking into consideration 4 modes, i.e. up to about 450 Hz of the spectrum. The cut off frequency includes mainly the bending and torsional modes. The PK method and g-method of solution has been used in NASTRAN and ZAERO respectively for the flutter analysis. The eigen values and mass normalized eigen vectors obtained from the GVT are replaced in the flutter module as per the new DMAP sequence for the tapered swept back plate model and solved for the flutter analysis. Flutter occurs for the second coupled bending-torsion mode for all the considered cases. The results obtained for the flutter analysis from the finite element model created using the actual structural properties of the specimen has been shown in Table.3 and the corresponding flutter plots have been shown in Figure 9(a) and 9(b) respectively. Similarly the flutter results obtained by replacing the eigen values and eigen vectors computed by the normal modes analysis with the experimental modal parameters has been shown in Table.4 and the corresponding flutter plots have been shown in Figure 10(a) and 10(b) respectively. The flutter speeds evaluated by ZAERO is higher than the values computed by NASTRAN for all the cases. The percentage error in the flutter speeds computed using direct computation by using a Finite Element mesh model of the structure with that by the replacement of eigen values and vectors obtained from experimental modal tests is less than 4 %.

6. CONCLUSION

The modal parameters estimated from the modal vibration tests, representing the true behavior of the structure has been used as an input through a DMAP sequence for predicting the flutter characteristics of the structure. Thus the errors, that result in a finite element normal modes analysis, caused due to improper representation of the boundary conditions, material properties and damping has been eliminated and the accuracy of the determination of eigen values &eigen vectors depend on the accuracy of the experimental measurements only. This program sequence helps in a realistic prediction of flutter characteristics of the structure with the only requirement of the geometric configuration of the structure and need no material property, mass or stiffness related parameters for the finite element modeling of the structure.

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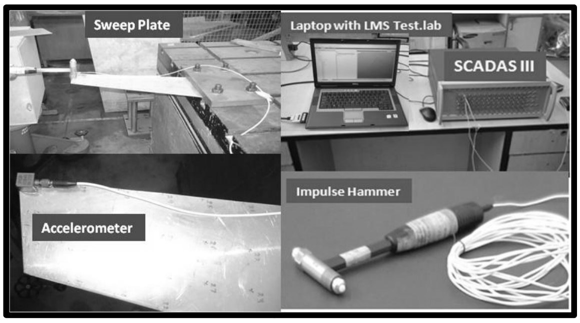


Figure 1.Experimental set-up

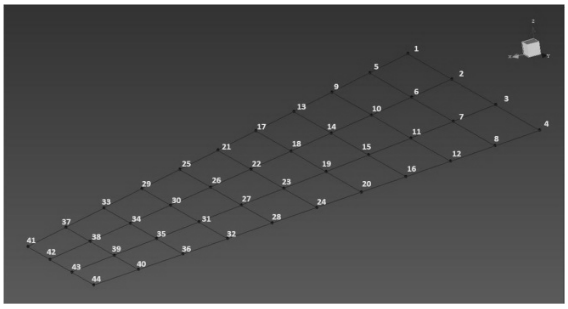


Figure 2.Response points from experiments

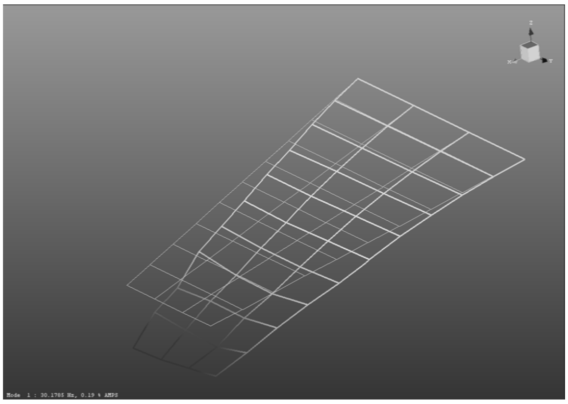


Figure 3.First bending mode (GVT)

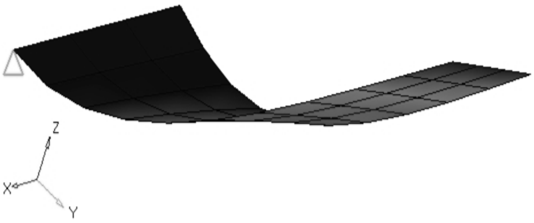


Figure 4. First bending mode (FEM)

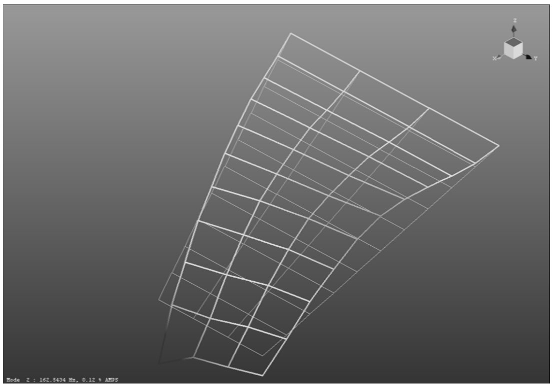


Figure 5.Second bending-torsion mode (GVT)

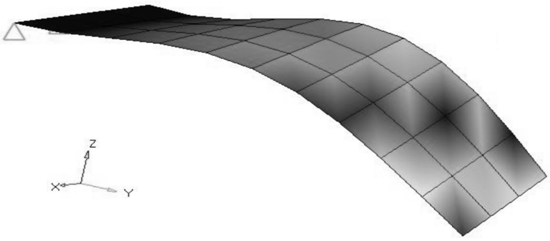


Figure 6.Secondbending-torsion mode (FEM)

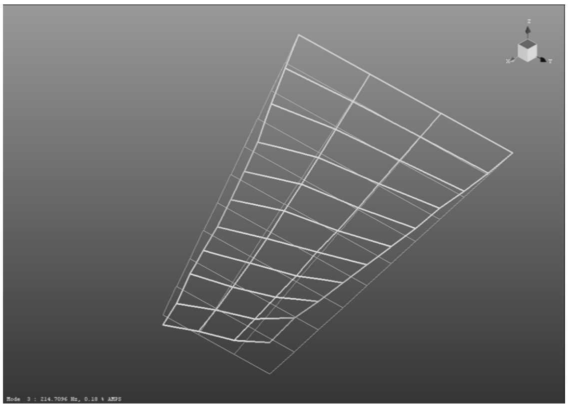


Figure 7.Third torsion mode (GVT)

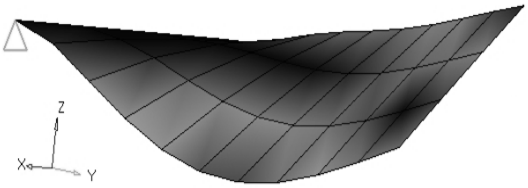
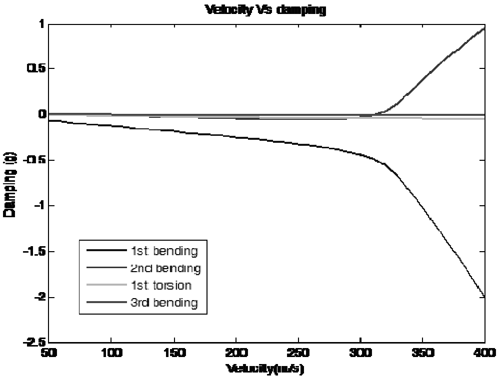
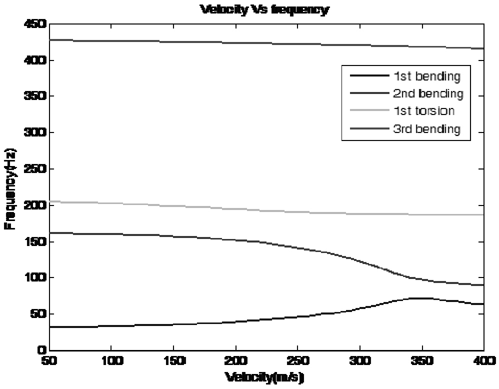


Figure 8.Third torsion mode (FEM)



(a)



(b)

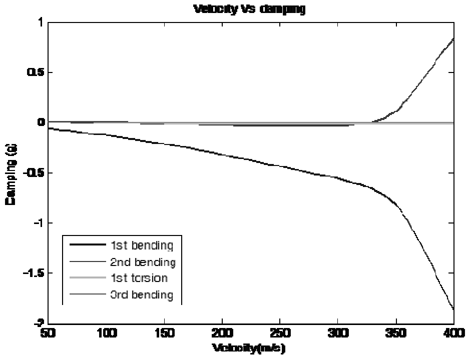
Figure 9.Flutter plots (FEM- Nastran)

Youngs Modulus(E)	71GPa
Poissons Ratio(µ)	0.3
Density(ρ)	2722.77kg/m^3

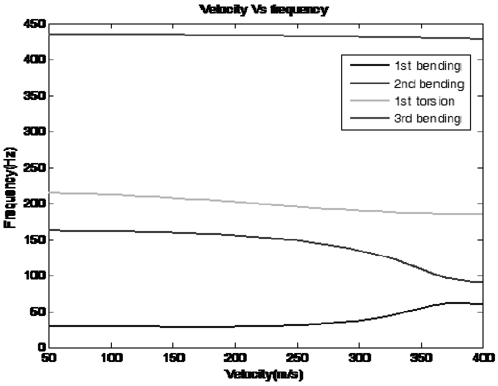
Table 1.Material properties

Sl. No.	Modal Remarks	FEM (Hz)	GVT (Hz)
1.	1st bending	30.395	30.17
2.	Bending-Torsion	161.899	162.54
3.	Torsion	205.118	214.71

Table 2. Natural frequencies



(a)



(b)

Figure 10.Flutter plots (GVT - Nastran)

Flutter Parameters	Nastran	ZAERO
Velocity (m/s)	310.527	340.153
Frequency(Hz)	117.22	114.2

Table 3.Flutter parameters (FEM)

Flutter Parameters	Nastran (GVT)	ZAERO (GVT)
Velocity (m/s)	320.13	360.132
Frequency (Hz)	126.497	121.098

Table 4.Flutter parameters using experimental modal parameters