FLUTTER QUALIFICATION OF A COMPOSITE LIGHT TRAINER AIRCRAFT (CSIR-NAL HANSA - 3 (VT-HOA))

N. G. Vijaya Vittala, A.C. Pankaj, C.N. Sathyanarayana, M.V. Shivaprasad
Scientist
Structural Technologies Division
National Aerospace Laboratories (NAL)
Council of Scientific Industrial Research (CSIR)
Post Box No. 1779, Kodihalli
Bangalore-560 017, India
Email : acpankaj@nal.res.in

Abstract

This paper presents the aeroelastic analysis and flight flutter tests aimed at ascertaining the freedom from flutter instability in the design flight envelope of a composite light trainer aircraft. The critical flutter, divergence and control reversal velocities of the complete aircraft were computed using MSC/NASTRAN and the typical section method. The results thus obtained from the analyses have been correlated with the ground vibration and flight flutter test results. The dispersion in the damping and frequency results obtained from computations and the flight flutter tests were within acceptable limits showing a good correlation. The flutter margins and the total damping of the aircraft satisfy the JAR-VLA/ FAR 23 requirements, thus enabling the aircraft to be type certified for the required flight safety standards.

Keywords: *Flutter, Typical section, Aircraft, Finite element, Flight flutter test*

Nomenclature

b = Half Chord Length
ba = Distance between Mid-chord and Elastic Axis
bc = Distance between Mid-chord and Control Surface Hinge Line
c = Chord Length
h = Translational Degree of Freedom
m = Mass of the Typical Section
v = Flutter velocity
r_a = Radius of Gyration of Total Section about the Elastic Axis
r_β = Radius of Gyration of Control Surface about the Hinge Line
x_β = Distance between Control Surface Hinge Line and its Centre of Gravity
B_s = Modal Damping Matrix
F_s = Generalized Unsteady Force Vector
K_h = Stiffness in Bending
K_s = Generalized Stiffness Matrix
K_α = Stiffness in Torsion
K_β = Rotational Stiffness of Control Surface
L = Lift per Unit Span
M_s = Generalized Mass Matrix
M_α = Aerodynamic Moment about the Elastic Axis per Unit Span
M_β = Aerodynamic Moment about the Aileron Hinge per Unit Span
α = Torsional Degree of Freedom
β = Control Surface Rotational Degree of Freedom
ξ = Generalized Displacement Vector

Abbreviation

FFT = Flight Flutter Tests
GVT = Ground Vibration Tests

Introduction

The dynamic and aeroelastic analysis of an aircraft forms an essential aspect in the finalization of its design cycle and the stability within the designed flight envelope has to be demonstrated by flight flutter tests for obtaining

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the certification [1]. Due to complexity of the aircraft structures the analytical results obtained from the mathematical model of the aircraft have to be correlated with the ground vibration test results thus enhancing the confidence factor [2]. However based on these inputs, carefully planned flight flutter tests have to be conducted and the results obtained from the flight test data and its correlation with the analytical results have a final say in clearing and certifying the aircraft. A complete cycle of these operations for a light composite aircraft is presented in this paper.

HANSA-3 (VT-HOA) is an all composite two seater light aircraft designed ab-initio for training, sport and hobby flying, It has a cantilever low wing, tractor engine and side by side seating with dual controls. The technical specifications of the aircraft and the aircraft in flight are presented in Table-1 and Fig.1.

Finite Element and Aerodynamic Mesh Model

Individual FE component models of the aircraft generated using shell elements of MSC/NASTRAN [3], were checked for their mass, centre of gravity details and then integrated to realize full FE aircraft model (Fig.2). This was updated with the non-structural masses, balance masses and the stiffness of the actuating mechanisms for control surfaces and consisted of 9144 elements and 7717 nodes with a total of 46,300 degrees of freedom.

Aerodynamic meshes of individual components consisting of flat panels of trapezoidal boxes totaling to 1267 for the lifting surfaces were integrated to realize the aerodynamic model of the full aircraft with the interference between various components taken into consideration by declaring interference groups (Fig.3).

Table-1 : Basic Technical Specifications of the Aircraft

Particulars	Values
Overall Length, m (ft)	7.6 (25)
Wing Span, m (ft)	10.47 (34.35)
Empty Weight, kg	550
All-up Weight, kg	750
Usable fuel capacity, 1	85
Max. cruise speed, KIAS	96
Max. rate of climb, ft/min	650
Stall speed with 20° flaps, KIAS	47
Endurance, hours	4
Landing distance, ft (m)	1770 (540)
Take-off distance, ft (m)	1355 (415)

Ground Vibration Test

The aircraft with full fuel, dummy masses anchored at the pilot seats and its tires deflated to 50% pressure to simulate nearly the free-free boundary condition, was subjected to ground vibration tests to establish its dynamic characteristics. The modal parameters of the aircraft were obtained on deployment of MIMO test configuration which had three exciters appropriately located to excite the full aircraft modes with a 50% burst random excitation signal in the frequency bandwidth of 0-100Hz, with a resolution of 0.2Hz. The acquired modal parameters such as natural frequencies, mode shapes and modal damping were verified with analytical test results leading to enhanced confidence levels in planning and execution of flight flutter tests.

Analysis

Initially free vibration analysis of the aircraft was carried out with all control surfaces in completely locked condition, having the design control circuit stiffness to establish the dynamic characteristics. Subsequent to the ground vibration tests, rotational modes of control surfaces obtained from FE analysis were fine tuned to realize the rotational mode frequencies obtained from GVT of the aircraft and its dynamic frequency spectrum was reestablished for further usage in the flutter analysis.

The flutter analysis of the aircraft was carried out considering all the aero models of the lifting surfaces in one interference group by taking the first 30 modes into consideration, up to 35.28 Hz of the dynamic spectrum. The cut off frequency included rotational modes of the control surfaces, bending and torsion modes of the lifting surfaces which are susceptible to flutter. The PK and KE methods in NASTRAN [3] have been used for flutter solutions in the velocity range starting from 50 m/sec to 110 m/sec in steps of 10 m/sec. Additionally a typical section approach using the dynamic characteristics from the analysis and ground vibration tests were separately deployed in aeroelastic computations to establish flutter, divergence and control reversal speeds for the aircraft.

The flutter equation solved by the PK method in NASTRAN is given in Eq.1, where the generalized unsteady aerodynamic forces F_S $(i\omega)$ are calculated by Doublet

Lattice Method. The flutter equation solved by the K method is given in Eq.2.

$$\left(-\omega^2\left[M_s\right]+i\,\omega\left[B_s\right]+\left[K_s\right]\right)\{\xi\,(i\omega)\} = \{F_s\,(i\omega)\} \qquad (1)$$

$$\left(\left[M_s\right]+\left[F_s\,(ik)\right]-\left[\lambda\,K_s\right]\right)\{\xi\} = 0 \qquad (2)$$

Where $\lambda = \frac{(1+ig)}{\omega^2}$ is the complex eigen value of the above equation. The addition of structural (or hysteretic) damping is artificial; the eigen values that are being found allow determination of the structural damping required to give zero overall damping at that flight condition. Consequently, for a stable condition the dampings that are determined are negative and vice-versa for a fluttering system. To solve for the eigen values the generalized aerodynamic force $F_s\,(ik)$ values are evaluated at a number of reduced frequencies ($k = \omega\, b/v$). The flutter speed, frequency and the damping coefficient (g) are given in the equations below.

$$v = \frac{(\omega c)}{2k}\;;\quad \omega = \frac{1}{\sqrt{\mathrm{Re}\,(\lambda)}}\;;\quad g = 2\gamma = \frac{\sqrt{\mathrm{Im}(\lambda)}}{\sqrt{\mathrm{Re}\,(\lambda)}}$$

Whereas for the typical section approach, classical bending-torsion- control surface rotation equation [4,5],

$$\begin{bmatrix} m & m\,x_\alpha & m\,x_\beta \\ m\,x_\alpha & m\,r_\alpha^2 & m\,r_\alpha^2 + m\,x_\beta\,(bc-ba) \\ m\,x_\beta & m\,r_\alpha^2 + m\,x_\beta\,(bc-ba) & m\,r_\beta^2 \end{bmatrix} \begin{Bmatrix} \ddot{h} \\ \ddot{\alpha} \\ \ddot{\beta} \end{Bmatrix} + \begin{bmatrix} k_h & 0 & 0 \\ 0 & K_\alpha & 0 \\ 0 & 0 & K_\beta \end{bmatrix} \begin{Bmatrix} h \\ \alpha \\ \beta \end{Bmatrix} = \begin{Bmatrix} L \\ M_\alpha \\ M_\beta \end{Bmatrix} \qquad (3)$$

was solved (Eq.3). The unsteady aerodynamic forces acting on the typical section airfoil for pure sinusoidal motion were calculated using Theodorsen's approach.

Results

Free vibration analysis of the aircraft results in clear rigid body modes, followed by the elastic modes in which the wing bending and torsion modes are well separated. Coupling of symmetric and anti-symmetric modes of lifting surfaces with longitudinal and lateral movement of fuselage has been observed in mode shapes. Fuselage torsion occurs well before the fuselage longitudinal and lateral bending modes. The HT asymmetric and symmetric torsion modes are well separated and the VT has high torsional rigidity. A correlation of few key modes with GVT results is presented in Table-2.

Table-2 : Comparison of Finite Element and Ground Vibration Test Results

Mode Remarks	GVT		FEM	Difference between FEM and GVT Frequencies (%)
	Frequency (Hz)	Modal Damping (%)	Frequency (Hz)	
Fuselage Torsion	6.98	4.46	6.00	16.3
HT Asymm. bending + VT Lateral	7.66	1.68	7.74	1.03
Wing 1st Symmetric bending	7.78	1.73	8.82	11.79
VT Lat. + HT Asymm. + Fus. Lateral	10.73	1.57	9.51	12.82
Rudder rotation	15.96	0.62	12.72	25.47
HT 1st Symm. bending	9.94	2.58	13.60	26.91
Fus. Longitudinal bending	13.05	3.22	15.04	13.23
Fus Lat + Elevator 3rd Asymm. bending	22.12	1.69	22.46	1.51
Wing Torsion Asymmetric	26.45	1.85	29.55	10.49
Wing Torsion Symmetric	27.64	1.92	30.48	9.31

Table-3 : Summary of Critical Flutter Speeds and Flutter Margins

Mode	Method	Flutter Velocity (m/s)	Flutter Velocity (Knots)	Flutter Margin w.r.t Vd (%)	Flutter Margin w.r.t Vne (%)
Wing Torsion (Asymm.) and Aileron Rotation (Asymm.)	NASTRAN (PK)	83.8	162.89	20.78	32.99
Wing Torsion (Asymm.) and Aileron Rotation (Asymm.)	NASTRAN (KE)	83.7	162.69	20.75	32.95
Wing Torsion (Asymm.) and Aileron Rotation (Asymm.)	Typical Section (FEM)	84.1	163.82	21.07	33.31

Flutter analysis of the aircraft shows that the wing torsion mode couples with aileron rotation, leading to flutter at a velocity of 83.8 m/sec and 28.83 Hz (Table-3). The corresponding flutter velocity for the lowest flutter margins computed by the typical section approach is obtained at 84.1 m/s for the combination of wing asymmetric torsion and aileron asymmetric rotation The divergence and reversal velocities are seen to be far higher than the computed flutter velocities.

Flight Flutter Tests

Having established the dynamic and flutter characteristics of the aircraft analytically and observation of its good correlation with the ground vibration tests, a set of flight flutter tests were planned and executed to extract the critical parameters like modal frequency and damping from the flight data acquired under different flight conditions.

Aircraft Instrumentation

In planning flight flutter tests the instrumentation used constrains the number of flight data acquisition channels resulting in deployment of an optimal number of sensors on the aircraft. As is observed from the aircraft flutter analysis that the wing bending and torsion modes, aileron rotation modes and their combinations are critical from the flutter view-point, the sensors are deployed only in that region. In order to record the structural vibrations in the frequency range of interest, during the flight flutter tests of the aircraft, six accelerometers on each wing, four on each aileron and in total twenty were mounted on the aircraft as shown in Fig.4. The response data from all the accelerometers were recorded on-board flash memory of KAM-500 data acquisition a part of the Flight Test Recorder (FTR) and was mounted in the aircraft cockpit. The Flight Test Recorder consisted 5 main components.

- Power Supply
- Data Acquisition System
- Personal computer
- Sensors, and
- Cockpit Display Unit

The signals coming from the sensors were fed to corresponding modules of KAM 500, which is an extremely flexible high performance data acquisition system supporting PCM encoding and integrated data-logging with 13 user slots. The modular system is designed for harsh aerospace applications where space is at premium. A wide range of user modules are available and any user module can go into any user slot in any combination. The isolated power supply unit is at each end of the chassis and is used to convert a nominal 28VDC to that used by the modules. Each chassis has a back plane and controller/encoder. The controller synchronizes the module operation and transfers data from one module to another. The controller also contains the programming interface and is polarized to prevent it being plugged into user slot. The Controller/Encoder also contains a complete IRIG-106 PCM generator. Back plane has a 16-bit bi-directional address/data bus control lines which read parameters write latch the address and select the module. Back plane transfer is synchronized using an 8 MHz system clock from which all module timings are derived. Total weight of the Data Acquisition unit installed including battery and sensors is 24.474 Kg. The entire unit is compactly fastened on to the copilot seat so that the acquisition and recording of in flight structural vibration responses during a test flight can be had by click of a switch by the pilot, which initiates the recording of signals. The data are to be recorded for at least one minute duration and pilot has to stop the recording by clicking off the switch. He also has to record the test case selected in terms of aircraft speed and altitude. The procedure has to be repeated for all the selected test points.

In the present set up only an offline data analysis can be carried out. The flight data recorded on the flash memory card of the KAM-500 system are extracted and converted to MAT format. Custom built software named Flight Flutter Test (FFT) module of the LMS Test Lab software converts these MAT files into TDF format which can be used for the analysis. The system accepts and analyses a maximum of twenty channels of calibrated digital dynamic data and ten slow channels of aircraft parameter data. The random response of aircraft due to self turbulent excitation, acquired as explained earlier are subjected to cross power spectrum techniques and operational modal analysis to yield the modal parameters namely the natural frequencies, damping and modeshapes for every test point considered. Frequency and damping values for identified modes are presented for different flight test points against the aircraft speed/altitude etc.

Test Procedure

Figure 5 shows the design flight envelope of the aircraft. The dive speed (*Vd*) of the aircraft was fixed at 69.6 m/s or 134.9 knots TAS and the never exceeding speed (*Vne*) for the aircraft was 122.5 knots TAS. To ascertain the flutter freeness, the aircraft was flown at speeds as shown in Table-4. At each of these speeds the vibration response data were recorded by switching on the event marker in the cockpit for a minute and then switching it off. The operational modal analysis method which deploys only measured responses for dynamic characteristics of structures has been adopted. Further this requires only natural operational excitation. The recorded signals have been analyzed for the frequencies and total damping for each mode using LMS Test Lab.

Table-4 : Flight Flutter Test Speeds

Altitude (feet)	IAS (Knots)	TAS (Knots)	TAS (m/sec)
8000 - 7000	60	69.6 - 68.4	35.8 - 35.18
8000 - 7000	70	81.2 - 79.8	41.77 - 41.05
8000 - 7000	80	92.8 - 91.2	47.74 - 46.91
8000 - 7000	90	104.4 - 102.6	53.7 - 52.78
7000 - 6000	100	114 - 112	58.6 - 57.6
7000 - 6000	110	125.4 - 123.2	64.51 - 63.37
7000 - 6000	120	136.8 - 134.4	70.37 - 69.14

Test Results

The wing asymmetric torsion mode which is critical from the view of flutter as obtained from the flutter analysis and flight tests are shown in Fig.6 and7. The variation of damping coefficient (*g*) with velocity at various test altitudes as obtained from Nastran, shown in Fig.8 reveals that the variation in damping with the test altitudes is negligible and therefore the results obtained at mean altitude 7000 feet have been taken as the reference Nastran result to compare with the flight flutter test results. Fig.9 shows that the total damping vs velocity plot obtained from the flight flutter tests for both the modes. It should be noted that the total damping in the flight flutter tests and the modal damping from GVT is obtained in terms of non-dimensional viscous damping coefficient (γ) and is positive for a stable condition and vice-versa. Thus damping coefficient (*g*) for the sake of conventional v-g flutter plots in case of flight flutter tests are computed accordingly as:

Damping Coefficient (g) = 2 x (Modal damping - Total damping) (4)

Where a negative damping coefficient (*g*) indicates stability and vice-versa as explained in the analysis section. The graphical flutter plots obtained through NASTRAN and flight flutter tests for both the modes are shown in Fig.10 to 13. The damping coefficient (*g*) from NASTRAN and the flight flutter tests are negative throughout the flight test envelope indicating that the aircraft is free from flutter and the total damping obtained from the flight flutter tests has values greater than 4%. The dispersion in the damping and frequency results obtained from NASTRAN and the flight flutter tests are within acceptable limits and show a good correlation.

Conclusions

- It is observed that the dynamic characteristics of the aircraft shows a good correlation between the analytical and experimental results.
- The flutter velocities obtained by PK and KE methods in NASTRAN and results from typical section approach are consistent and predict the same trend for the modes leading to flutter. The wing torsion mode coupled with the aileron rotation goes to flutter at a velocity of 83.8 m/s or 162.89 knots (TAS) as seen from the flutter summary Table-3.
- The excitation from the engine leading to structural turbulence during the flight was sufficient to excite the

targeted modes of interest, especially at higher speeds, thus eliminating an explicit excitation. The damping coefficient (*g*) obtained through NASTRAN and the flight flutter tests are negative throughout the flight test envelope and does not cross the zero line, indicating the flutter freeness of the aircraft. The total damping obtained from the flight flutter tests are also positive throughout the flight test envelope and is greater than 4%.

- The dispersion in the damping and frequency results obtained from NASTRAN and the flight flutter tests are within acceptable limits and show a good correlation. The damping values obtained from flight flutter results are less than the analytical values as is evident from the frequency plots for the same, wherein the frequencies obtained from analysis is greater than the values obtained from the flight flutter tests.
- The flight test report from the pilot further substantiated that the handling quality of the aircraft was satisfactory and there were no excessive buffet vibration and controllability problems at the planned test speed and altitudes.

Acknowledgements

For conducting successful flight flutter tests, not only readiness of the aircraft, weather conditions but the close interaction with various design and test groups ready to operate in a flexible manner with a short notice are highly essential. As such the authors acknowledge all the support received from colleagues of different groups in the laboratory. The authors are grateful to the Director, National Aerospace Laboratories, Bangalore, India, for his kind permission to publish the paper.

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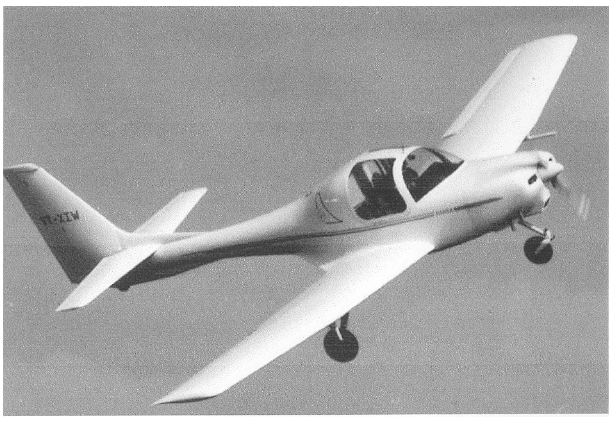

Fig.1 Flying View of the Aircraft

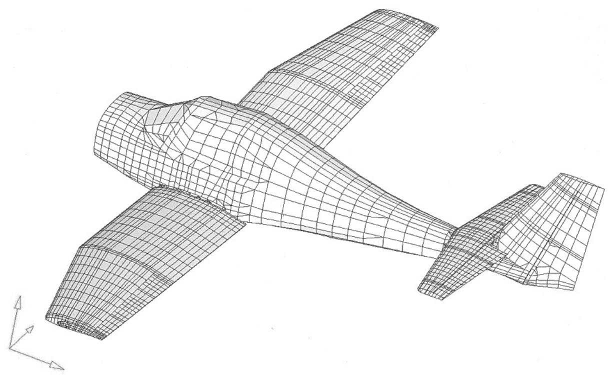

Fig.2 Finite Element Model of the Aircraft

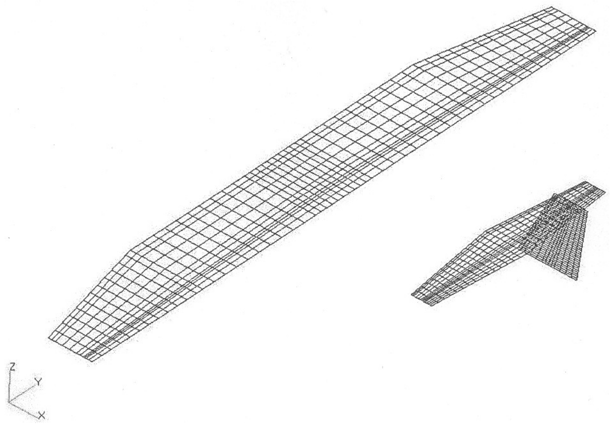

Fig.3 Aerodynamic Model of the Lifting Surfaces

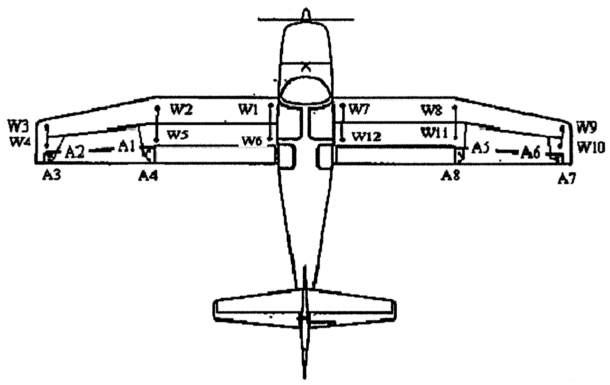

Fig.4 Accelerometer Locations on the Aircraft

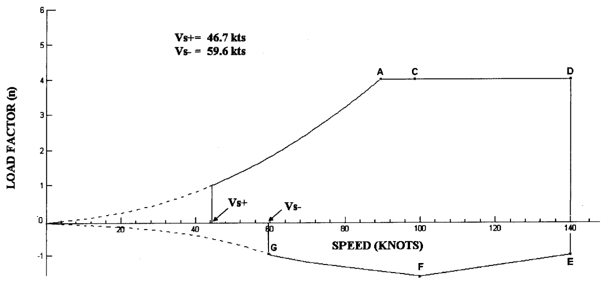

Fig.5 Design Flight Envelope of the Aircraft (V-n Diagram)

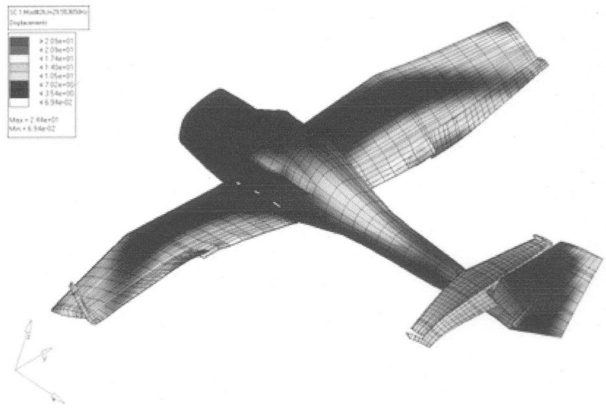

Fig.6 Wing First Asymmetric Torsion Mode (FEA)

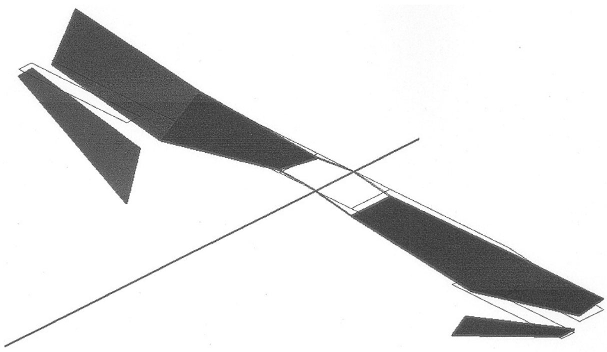

Fig.7 Wing Asymmetric Torsion Mode (Flight Flutter Tests)

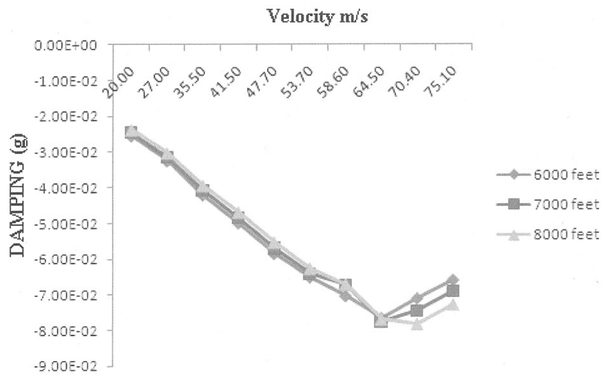

Fig.8 Velocity vs Damping at Various Test Altitudes (Asymmetric Torsion)

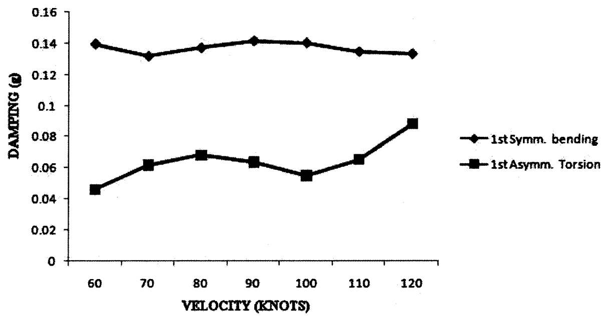

Fig.9 Velocity vs Total Damping (Flight Flutter Tests)

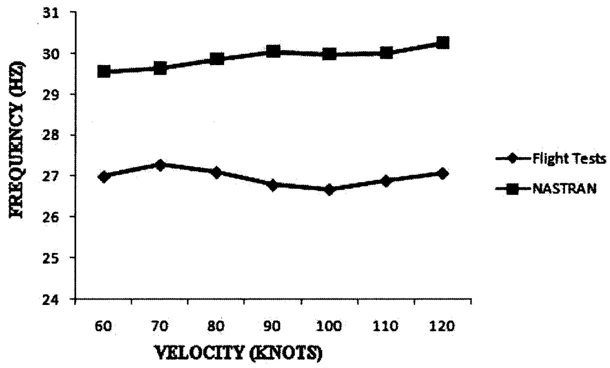

Fig.12 Velocity vs Frequency (Asymmetric Torsion)

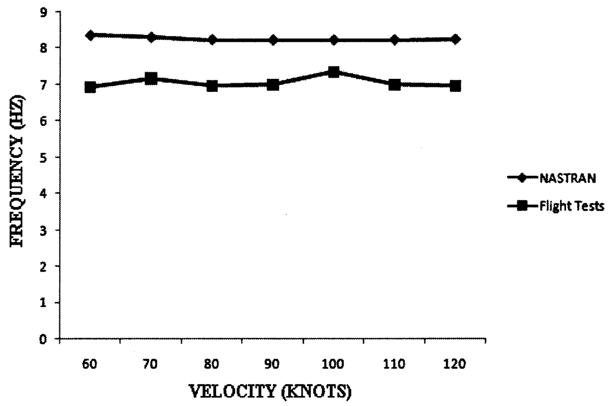

Fig.10 Velocity vs Frequency (Symmetric Bending)

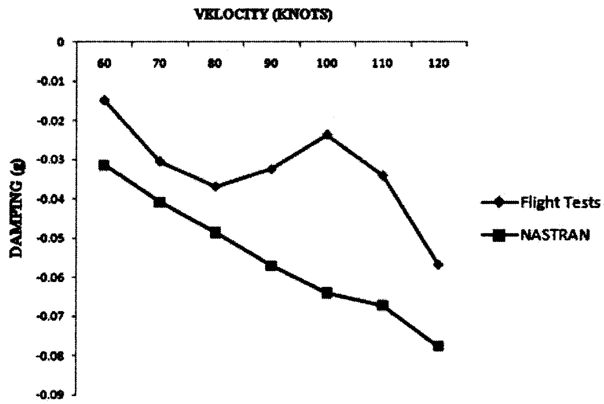

Fig.13 Velocity vs Damping (Asymmetric Torsion)

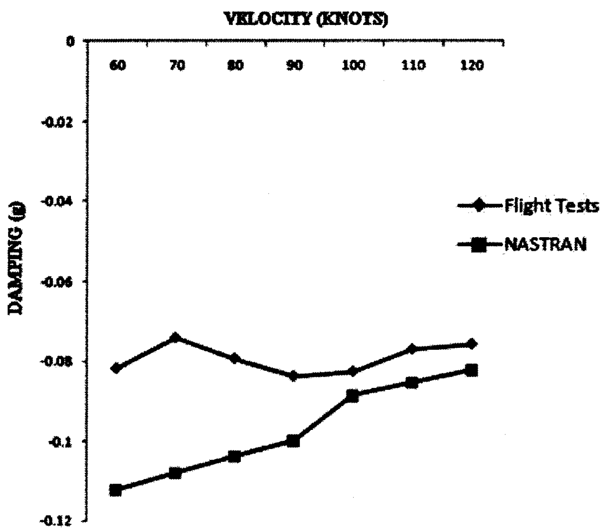

Fig.11 Velocity vs Damping (Symmetric Bending)