Parametric Studies on Flutter Speed of Composite Laminates

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ABSTRACT

Aeroelastic phenomenon is required to be studied for design and development of aircraft, particularly for high speed as well as high aspect ratio wing. In the design of Unmanned Aerial Vehicles (UAVs), the flutter speed has to be estimated and sufficient dive speed to flutter speed margin has to be established to ensure the safety of the UAVs. The interaction of the elastic, inertia and aerodynamic forces is a dynamic phenomena resulting in flutter. Flutter will occur when the artificial structural damping equals the actual damping of the structure. It is computed using velocity-damping method by idealizing the wing as the plate. Flutter speed is a function of structural properties like mass distribution, stiffness of the structure. If the structure is made up of composite material, the stiffness is dependant on the characteristics of the laminates namely thickness, material, fiber orientation of the individual lamina and number of such laminas that make up the laminate. This paper highlights velocity-damping method with a case study applied to a general composite laminate and studies how the laminate properties affect the flutter speed. This study will result in having optimum laminate properties so that the flutter speed can be enhanced.

1.0 INTRODUCTION

The prime objective of the structural engineer is to design an airframe whose flight envelope is limited by engine power rather than its structural limitations [1]. The use of filamentary composite materials in aircraft structures offers a great potential for weight savings over the metallic construction. In addition to the high specific strength and stiffness, the use of composite materials in the aircraft design offers greater advantages to tackle the dynamic aeroelastic problems such as flutter and gust response.

2.0 AEROELASTIC FLUTTER PROBLEM (U-g METHOD)

The flutter problem is formulated using an indirect method widely known as the u-g method. In this method, the structural damping coefficient (g), introduced into the equations of motion is plotted versus velocity for each vibration mode. Since solutions to the equations to the motion represent conditions for neutral stability, the value of g obtained in this manner represents the amount of damping that must be added to the structure to attain neutral stability (flutter) at the given Velocity. Flutter will occur when the artificial structural damping equals the actual damping of the Structure. To simplify calculations, the flutter problem will be formulated using only the equations of motion from the two-term deflection equation. As a first step strain energy of the aniostropic plate [5]

$V = \frac{1}{2}\int_0^l \int_{-c/2}^{+c/2} \nabla^2\nabla^2 \mathrm{w}\,\mathrm{dy}\,\mathrm{dx}$ gets modified to the composite as given below,

$$= \frac{1}{2}\int_0^l \int_{-C/2}^{+C/2} \begin{bmatrix} D_{11}(W_{,XX})^2 + 2D_{12}W_{,XX}W_{,YY} + D_{22}(W_{,YY})^2 \\ +4D_{16}W_{,XX}W_{,XY} + 4D_{26}W_{,YY}W_{,XY} + 4D_{66}(W_{,XY})^2 \end{bmatrix} \mathrm{dy}\,\mathrm{dx} \tag{2.1}$$

where $D_{ij} = \sum_{k=1}^{n} \left[Q_{ij}^{\theta}\right]_k \left[Z_k^3 - Z_{k-1}^3\right]/3$

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As a second step the kinetic energy of the plate can be written as

$$T = \frac{1}{2}\int_{0}^{l}\int_{-c/2}^{+c/2} m\left\{\dot{\omega}\right\}^2 dxdy \, , \tag{2.2}$$

where $m = \rho_w t_w$, where ρ_w is the specific gravity of the wing structure and t_w is the thickness of the wing.

As a third step the Lagrange's equation [7] is given as

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) + \frac{\partial V}{\partial q_i} - \frac{\partial T}{\partial q_i} = Q_i \tag{2.3}$$

Assuming sinusoidal motion for the vibration mode and neglecting warping stiffness of the structure, the equations of motion can be written as

$$-\omega^2\left[M_{ij}\right]\begin{Bmatrix} q_1 \\ q_2 \end{Bmatrix} + \left[K_{ij}\right]\begin{Bmatrix} q_1 \\ q_2 \end{Bmatrix} = \begin{Bmatrix} Q_1 / e^{i\omega t} \\ Q_2 / e^{i\omega t} \end{Bmatrix} \tag{2.4}$$

Where

$$\left[M_{ij}\right] = \begin{bmatrix} mclI_4 & 0 \\ 0 & \dfrac{mclI_5}{12} \end{bmatrix} \quad \text{and} \tag{2.5}$$

$$\left[K_{ij}\right] = \begin{bmatrix} \dfrac{D_{11}cI_7}{l^3} & \dfrac{2D_{16}I_6}{l^3} \\ \dfrac{2D_{16}I_6}{l^2} & \dfrac{4D_{66}I_8}{cl} \end{bmatrix} \tag{2.6}$$

I_4, I_5, I_6, I_7 I_8 are Non-dimensional integral expressions as given in [6]

The aerodynamic forces acting on the structure [8] can written as

$$L_E = \omega^2\pi\rho b^3\left[\{L_1 + iL_2\}\frac{w_E}{b} + \{L_3 + iL_4\}\alpha\right]e^{i\omega t}$$

$$L_1 + iL_2 = 1 - \frac{2i}{k}c(k) \tag{2.7}$$

$$L_3 + iL_4 = a + \frac{2c(k)}{k^2} + \frac{i}{k}\left[1 + (1 - 2a)c(k)\right]$$

$$M_E = \omega^2\pi\rho b^4\left[\{M_1 + iM_2\}\frac{W_E}{b} + \{M_3 + iM_4\}\alpha\right]e^{i\omega t}$$

$$M_1 + iM_2 = 1 - \frac{i(1+2a)}{k}c(k) \tag{2.8}$$

$$M_3 + iM_4 = \left(\frac{1}{8} + a^2\right) + \frac{(1+2a)c(k)}{k^2} + \frac{i}{k}\left[\left(\frac{1}{2} - 2a^2\right)c(k) - \left(\frac{1}{2} - a\right)\right]$$

$$Q_1 = \omega\pi\rho b^3 \{[L_1 + iL_2]\ ll_4 q_1/b + [L_3 + iL_4]\ ll_3 q_2/c\} e^{i\omega t} \quad (2.9)$$

$$Q_2 = \omega^2 \pi\rho b^4 \{[M_1 + iM_2]\ ll_3 q_1/bc + [M_3 + iM_4]\ ll_3 q_2/c\} e^{i\omega t}$$

The flutter problem can be formulated as

$$[K - \omega^2 A]\ \{q\} = 0 \quad (2.10)$$

Where the stiffness matrix K and aerodynamic matrix A [4] are defined below

$$K_{11} = cD_{11} I_7/l^3$$
$$K_{12} = 2D_{16}\, I_6/l^2 \quad (2.11)$$
$$K_{21} = 2D_{16}\, I_6/l^2$$
$$K_{22} = 4D_{66}\, I_8/cl$$
$$A_{11} = mclI_4 + \pi\rho bI_4[L_1 + iL_4] \quad (2.12)$$
$$A_{12} = \pi\rho lb^3 I_3/c\ [L_1 + iL_4]$$
$$A_{21} = \pi\rho lb^3 I_3/c\ [M_1 + iM_4]$$
$$A_{22} = mclI_5/12 + \pi\rho lb_4 I_5/c^2[M_1 + iM_4]$$

c = chord length of the wing

The flutter frequency w, the damping ratio g and the flutter speed u are extracted as

$\omega = 1/\sqrt{Real\ (z)}$

g = imaginary (z)/real (z)

u = bω/k , b = semi chord length and k = strouhl number

The algorithm is iterated for different suitable values of k till the damping ratio becomes zero.

3.0 MATERIAL AND GEOMETRIC DETAILS

Three different material configuration were chosen for our parametric study namely Hercules AS/3501-6 Graphite Epoxy laminate, High modulus Epoxy laminate and S-Glass Epoxy laminate. The material properties of each material configuration are given in Table 1.

4.0 EFFECT OF LAMINATE ORIENTATION ON FLUTTER SPEED

The normalized flutter speeds were estimated using the Matlab code for different laminate orientation corresponding to different material configuration. Table 2 gives the flutter speed corresponding to each laminate orientation and material configuration. The variation of flutter speed with laminate orientation is given in Fig 1. The various U-g plots required for the estimation of the flutter speed is placed in Appendix- A.

A study was also carried out to see the effect of laminate orientation on the flutter for a case where the sequencing of the laminates were done primarily to take care of the inter laminar shear stress. The results of this study shows that flutter speed is maximum for the case, which is designed to take, care ILSS. The U-g plots for that case is also placed in Appendix - A.

5.0 CONCLUSIONS

The main objective of the work was to study the effect of laminate orientation on the flutter speed for the composite laminates. The study was carried out for three different material configurations, each having the same laminate orientation variation. From the results, it is clear that the flutter speed is maximum for a orientation dominated by the 45° plies. This is because of the fact that the torsional stiffness (GJ) influences more on the flutter speed. The design for maximizing the ILSS involves distributing more number of 45° plies in a suitable manner, which in a way enhances the flutter speed.

In summary, aero elastic tailoring of aircraft wings can be an effective tool for enhancing the flutter speed margin of the aircraft. As a future work, an optimum stacking orientation can be arrived in order to satisfy the strength, stiffness, buckling, and frequency and flutter speed.

6.0 REFERENCES

1. Weishaar, T. A., and Foist, B.L., "Vibration and Flutter of Advanced Lifting surfaces", Proceedings of 24th AIAA/ASME/ASCE/AHS structures, structural dynamics and Materials conference, Lake Tahoe, Nev., May 1983, pt.2, pp.498-508
2. Bennet, G., Modeling of wing weight for High Altitude long Endurance Aircraft, Part1, Unmanned systems, Volume 13, No.1. Winter 1995
3. Houser. J.M., and Manual Stein., Flutter Analysis of Swept wing subsonic Aircraft with parameter studies of composite wings. NASA TN D-7539, 1974
4. Howell, S.J., "Aeroelastic Flutter and Divergence of Graphite/Epoxy Cantilevered plates with bending torsion coupling", M.S. Thesis, Department of Aeronautics and Astronautics, M.I.T., January, 1981
5. Aston, J.E., and Whitney, J.M., Theory of Laminated plates, Technomic publishing co., Stanford, conn., 1970
6. Dugundji., Brain J. Ladsberger., " Experimental Aeroelastic behaviour of unswept and forward swept cantilever graphite/epoxy wings"., J. aircraft ., Aug 1985, pp 679-686
7. Richardson, J. R., " A more realistic method for routine flutter calculations ", AIAA symposium on structural dynamics and aeroelasticity, Boston/Massachussets, August 30 -September 1, 1965, pp. 10-17
8. Fung, Y.C., The theory of Aeroelasticity. Galcit Aeronautical series, John Wiley and sons, May 1955

Table 1: Material Properties of the Laminate

Parameter	Hercules AS3501	High modulus Epoxy	S-Glass Epoxy
E_L (Pa)	130×10^9	1.72×10^{11}	5.29×10^{10}
E_T (Pa)	10.5×10^9	1.17×10^{10}	1.90×10^{10}
Poisson LT	0.28	0.28	0.25
G_{LT} (Pa)	6.00×10^9	4.41×10^9	3.92×10^9
Ply thickness (m)	1.34×10^{-4}	1.34×10^{-4}	1.34×10^{-4}
Density kg/ m³	1.52×10^3	1.6×10^3	2.0×10^3

Table 2: Normalized Flutter Speed Vs Laminate Orientation

Orientation No	Orientation	Flutter speed Normalized-- AS 3501-Δ	Flutter speed Normalized - High modulus Epoxy -□	Flutter speed Normalized - S Glass ♦
1	[0/0/90]s	0.92	0.87	0.948
2	[0/0/60]s	0.98	0.97	0.986
3	[0/0/45]s	1.0	1.0	1.0
4	[0/0/30]s	0.99	0.97	0.986
5	[0/0/15]s	0.94	0.9	0.961

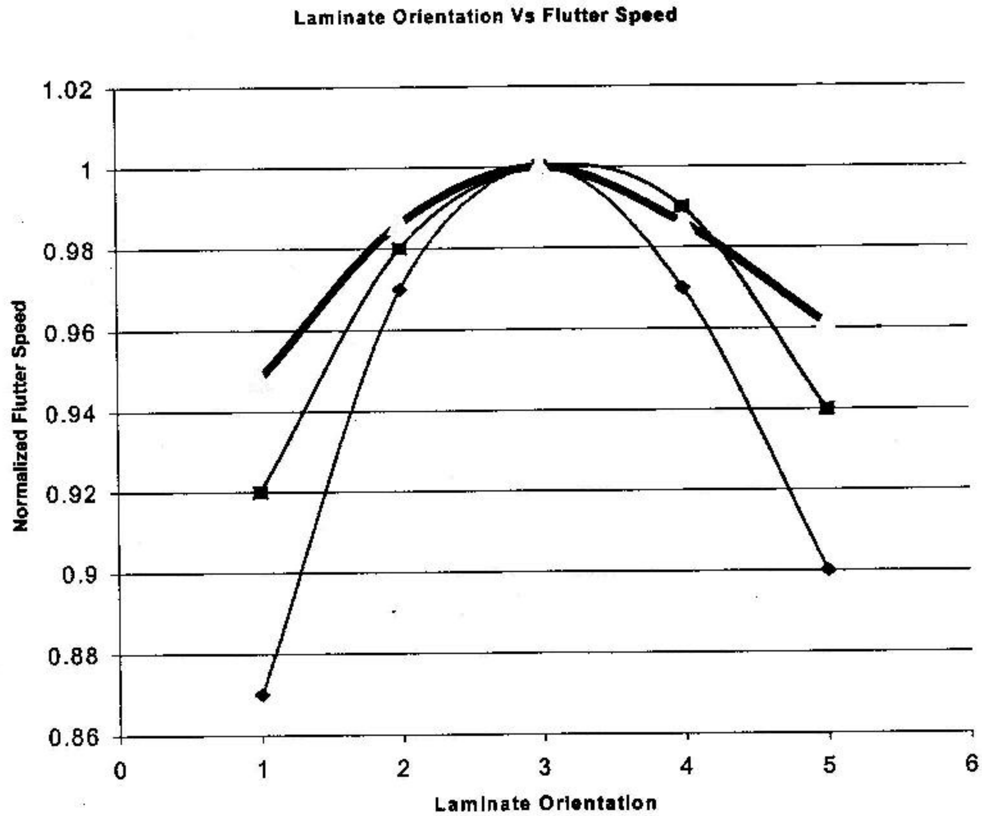
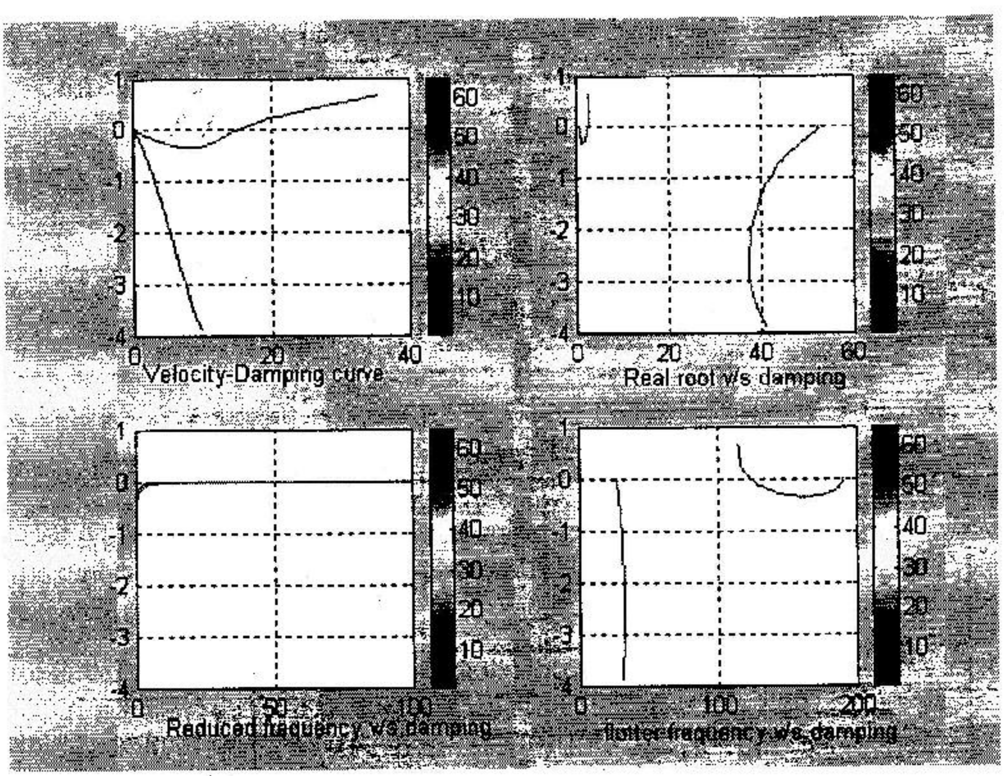
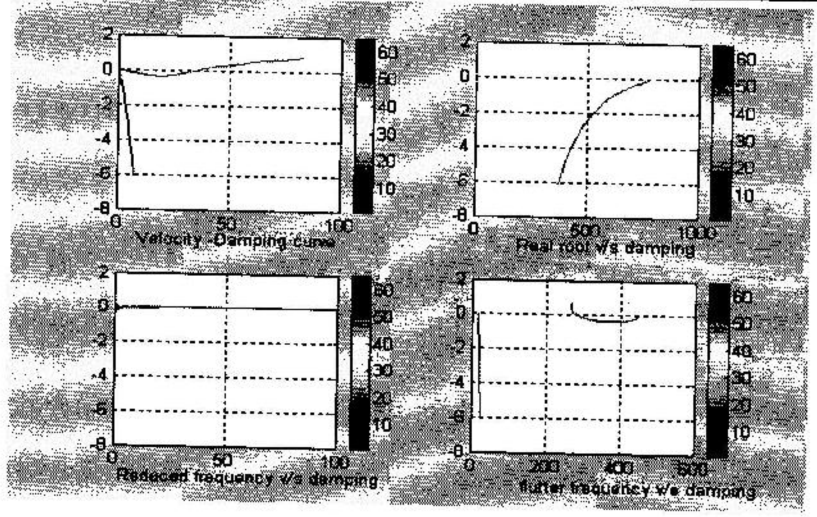


fig 5: Effect of Laminate Orientation on Flutter Speed

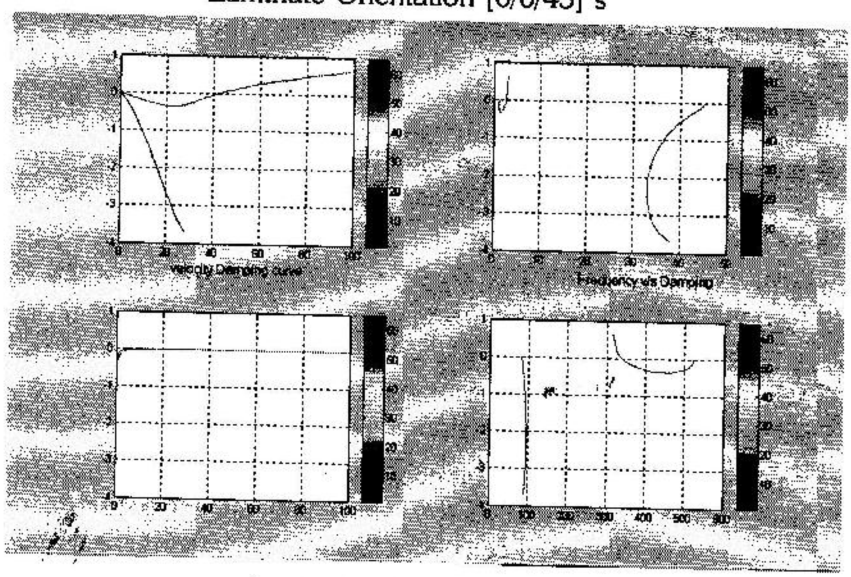
APPENDIX - A



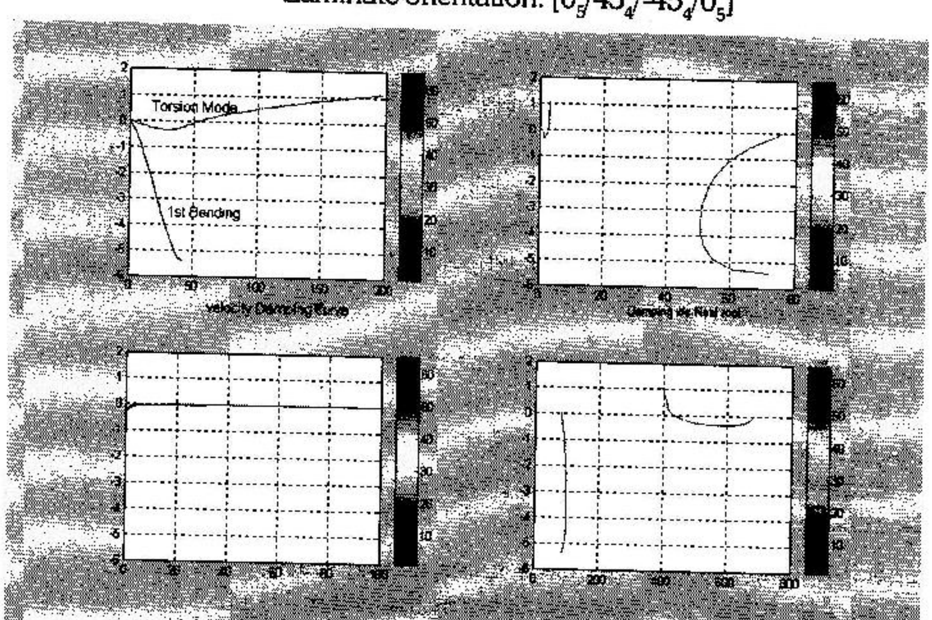
Laminate Orientation [0/0/90] s



Laminate Orientation [0/0/45] s



Laminate orientation: $[0_5/45_4/-45_4/0_5]$



Laminate orientation: $[0_2/45_2/0_2/-45_2/0]$ s