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AEROELASTIC BEHAVIOUR OF A METAL WING STRUCTURE WITH VARYING FUEL LOCATIONS

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ABSTRACT

This paper discusses and compares the analytical (FE) dynamic aeroenastic analysis on the FE wing models of the actual metal wing box and a simplified wing (beam) model. The variation of the fuel locations as a lumped mass and its effect on the dynamic aeroelastic instability, (flutter) on the simplified wing model is analyzed and presented. One of the main dynamic aeroelastic instabilities is the flutter, and must be outside the flight envelope of the flight vehicle to avoid any structural failure. These aeroelastic instabilities are depended very much on the dynamic characteristics of the wing box, which are in the forms of eigenvalues and eigenvectors. The detailed and simplified wing models are generated using the finite element codes, MSC/PATRAN (Pre and Post-processors), analysed using MSC/NASTRAN, ([Rodden, 1994]). The root section of the two wing models is fixed to simulate a cantilevered boundary condition. The obtained results showed that simplifying the wing structure for the above analysis provides a good agreement at low cost in terms of model complexity, size, and running time compared with the detailed wing model. It is a very useful approach to the structure designers especially at the early design stage of the aircraft structures. Wing structure with a full outer fuel tank has a significant effect on the natural frequencies and mode shapes compared with other fuel cases, whereas the flutter speed of the simplified wing box is found higher when the middle fuel tank is full compared with the inner and outer fuel tanks.

INTRODUCTION

During the design process of any flight vehicle, the structure designers are must investigate the aircraft structure form any static and dynamic aeroelastic instabilities and others. One of the important dynamic aeroelastic instabilities is the flutter, and must be outside the flight envelope of the flight vehicle to avoid any structural failure. These aeroelastic instabilities such as flutter are depended on the dynamic characteristics of the wing box. The dynamic characteristics of the wing structure models are in the form of natural frequencies and mode shapes, ([Ashawesh, 2003]).

The wing box of the aircraft is constructed from Aluminium material. The airfoil sections are NACA 23015 and NACA 23012 at the root and the tip of the wing respectively. As in any real wing structure, the wing consists of upper and lower skin, front and rear spars, stringers, and ribs. The outer dimensions of the wing box are semi-span of 4.9 m, 0.8128 m root chord and 0.254 m tip chord. For more details, the reader should refer to ([Potter, 1968]*)*.

The detailed and simplified wing models are generated using the finite element code, MSC/PATRAN (Pre and Post-processors), analysed using MSC/NASTRAN, ([Rodden, 1994]). In the first detailed model, (wing^1), two-dimensional CQUAD4 shell flat plate element and TRIA3 elements are used in the construction of the skins, and CQUAD4 for the spar webs, and ribs, whereas beam with offset is used in the modelling of the stringers, spar caps, and rib caps as shown in (Figure 1), ([Taig, 1986]). The simpified wing model, (wing^2) is constructed using a beam element (with offset) with lumped masses (CONM2), see (Figure 2). The root section of the wing models is fixed to simulate a cantilevered

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boundary condition. The fuel is modelled in the simplified beam model as lumped mass in three locations along the wing structure with all the possibilities of the fuel variations.

Normal mode and aeroelastic (Flutter) analysis are carried out on the wing models (including fuel cases) and the results are further compared and discussed.

WING STRUCTURE

The airfoil section of the wing box at the root is NACA 23015 and at the tip NACA 23012. The details of the wing box employed are as per ([Potter, 1968]*)*. The wing box is constructed from Aluminum material, L72. The primary dimensions of the wing structure, having a semi-span of 4900 mm from aircraft centre line, 812.8 mm root chord and 254 mm tip chord. As with any traditional wing structure it comprised of front spar and rear spar, spar caps, root and tip ribs, fifteen intermediate ribs located along the semi-span of the wing box, stringers and upper and lower skins.

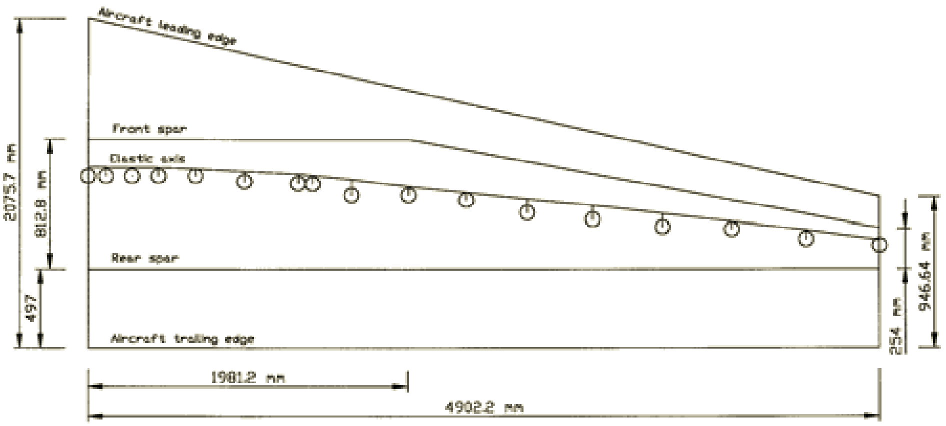

Figure 1: Simplified wing model (lumped beam) with the primary dimensions.

WING STRUCTURE MODELS

Two wing models are constructed using the MSC/PATRAN and MSC/NASTRAN as pre-processor, post-processor and analyzer respectively.

The first detailed wing model, (wing^1) is generated using the combination of CQUAD4 shell plate elements and TRIA3 node elements for the upper and lower skins; CQUAD4 for the ribs and spar webs and beam element (with offset) for stringers and spar caps as shown in (Figure 1).

The second wing model is the simplified, (wing^2) is constructed using baem element along the elastic axise of the wing box and lumped mass, CONM2 element loacted at the centre of gravity of the wing sections along the wing semi-span as ahown in (Figure 2). Bending stiffness, (EI), torsion stiffness, (GJ), location of the elastic axis, and location of the centre of gravity along the semi-span of the wing structure are calculated using the approach outlined in ([Bruhn, 1973]). The accuracy of the results is depends on these calculations. Both bending and torsion rigidities are located along the elastic axis, whereas a lumped masses and mass moment of inertia are located along the centre of gravity axis. All wing models are constrained at the root to simulate fixed-free boundary condition. The verifications of the elements in all wing models are checked according to ([Rodden, 1994]).

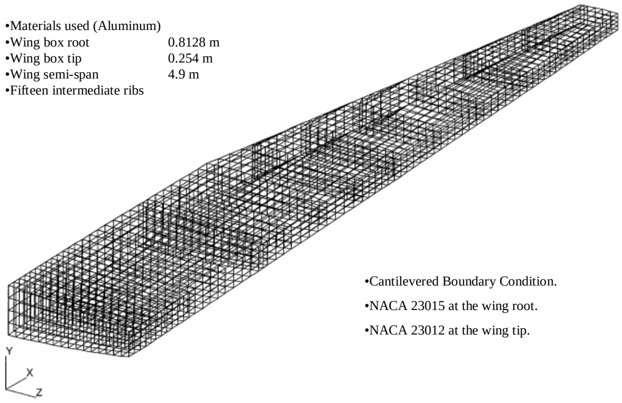

Figure 2: Detailed finite element model of the actual metal wing box.

VIBRATION ANALYSIS

Normal mode analysis is carried out for the two wing models without fuel in the wing using Lanczos method provided in MSC/NASTRAN. Results from both of the analysis are further compared and discussed. It is showed that how close the results of the simple beam model compared with the experimental results, ([Stacey, 1976]) and the mode shapes of the first, (wing[1]) and second (wing[2]) wing models are as shown in (Figures 3-6) and (Figures 7-10) respectively.

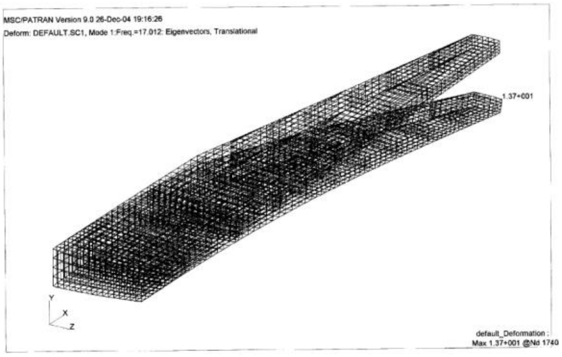

Figure 3: 1st bending mode, wing[1], (17.012 Hz)

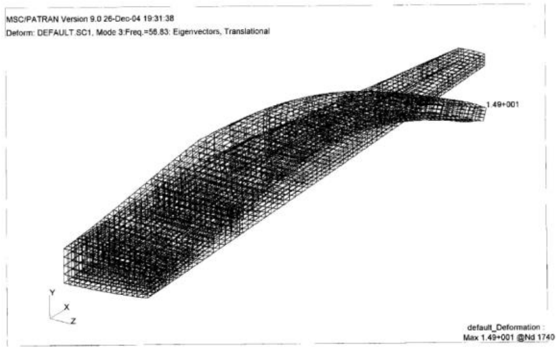

Figure 4: 2nd bending mode, wing[1] (56.83 Hz).

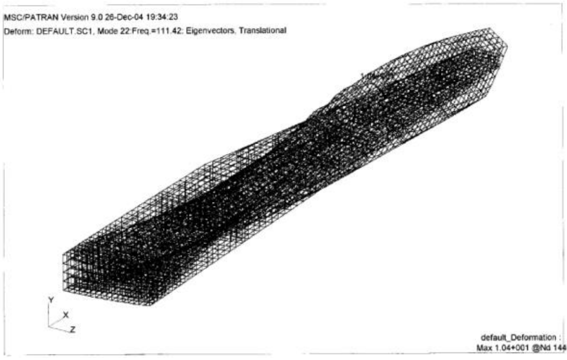

Figure 5: 1st Torsion mode, wing[1], (111.42 Hz)

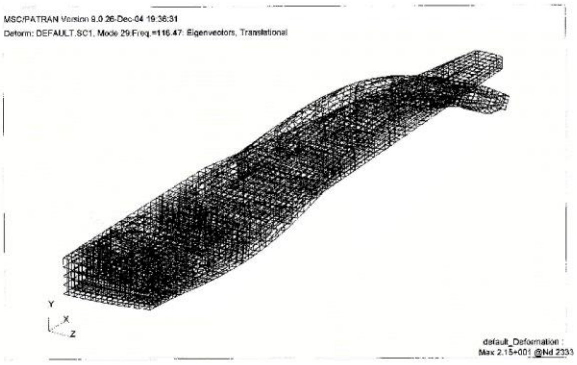

Figure 6: 3rd bending mode, wing[1] (116.47 Hz).

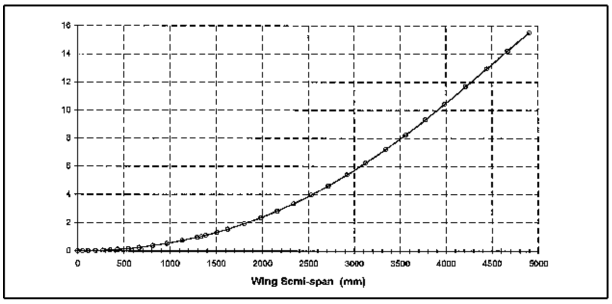

Figure 7: 1st bending mode, wing[2], (15.7 Hz)

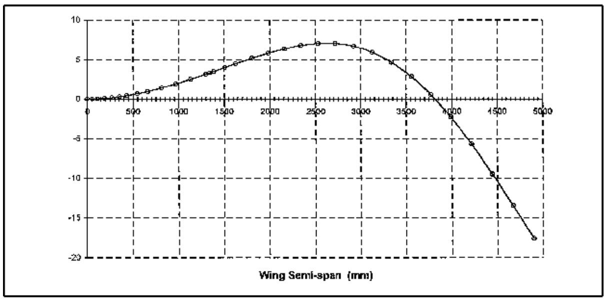

Figure 8: 2nd bending mode, wing[2] (55.6 Hz).

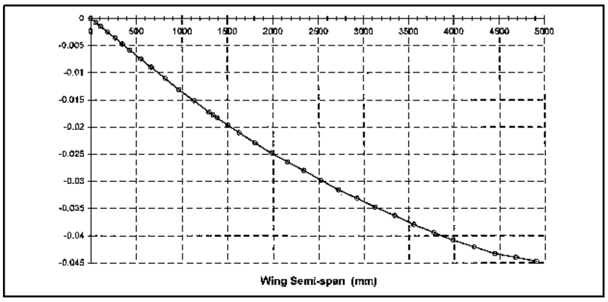

Figure 9: 1st Torsion mode, wing[2], (119 Hz)

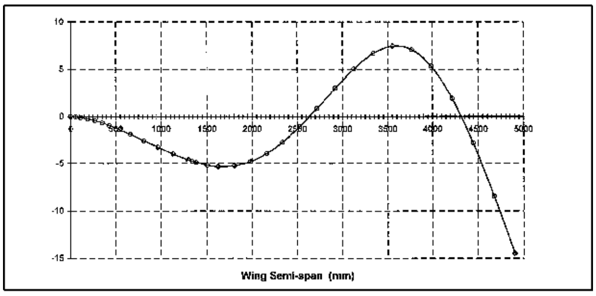

Figure 10: 3rd bending mode, wing[2] (129 Hz).

Results of the wing models are closely examined and presented in (Table 1). The results showed that simplifying the wing structure for the above analysis provides a good agreement at low cost in terms of model complexity, size, and running time. It is a very useful approach to the structure designers especially at the early design stage of the aircraft structures.

Table 1: Comparison of the natural frequencies (Hz) of the wing models (without fuel).

Mode No./Type	Detailed Wing[1]	Simplified Wing[2]	Experimental	Difference in %	
	NASTRAN	NASTRAN	([Stacey, 1976])	Wing[1]	Wing[2]
1) 1st Bending	17.012	15.70	16.7	-1.85	5.98
2) 2nd Bending	56.83	55.6	54.4	-4.04	-2.20
3) 1st Torsion	111.42	119.0	106.0	-5.10	-12.26
4) 3rd Bending	116.47	129.0	120.0	2.94	-7.50

DYNAMICS WITH VARYING FUEL

After validation of the wing models, It is assumed that the wing structure is constructed with three small fuel thanks along the semi-span. The fuel tanks are located at three different positions, the first tank is called as inner fuel tank, located at 431 mm to 965.2 mm from the root of the wing box, whereas the second fuel tank (middle fuel tank) is located at the middle section of the wing box, (1384.3 mm–1981.2 mm). The outer fuel tank of the wing box is located between two wing sections, (2717.8 mm and 3556 mm) from the wing root section. The weight of the fuel is considered as 24 Kg per tank. The length of the inner, middle, and outer fuel tanks is 534.2 mm, 596.9 mm, and 838.2 mm respectively. The mass per unit length of the inner, middle, and outer fuel tanks is obtained as 44.93 Kg/m, 40.21 Kg/m, and 28.63 Kg/m respectively.

The simplified wing model, (wing[2]) is then modified using MSC/PATRAN program to simulate the fuel in three locations. The fuel is considered as a lumped non structural mass located at the centroid of the fuel tanks. The effect of the fuel movements (sloshing) on the natural frequencies and mode shapes are ignored. Seven possibilities or cases for the fuel tanks are considered in the analysis, see (Table 2).

The dynamic characteristics in the form of natural frequencies and mode shapes of the simplified wing box simulating all the cases presented in (Table 2) are carried out and presented in (Table 3). It can be seen that there are coupled modes occured after the second bending mode due to the fuel weights.

After close analysis of results, it is found that the outer fuel tank has a significant effect on the natural frequencies when it is full of fuel compared with the inner and middle fuel tanks, see (Table 3).

Table 2: Variations of the fuel cases along the wing structure.

Case No.	Inner fuel tank	Middle fuel tank	Outer fuel tank
1	Full	Full	Full
2	Full	Full	Empty
3	Full	Empty	Empty
4	Full	Empty	Full
5	Empty	Full	Full
6	Empty	Full	Empty
7	Empty	Empty	Full

Table 3: Variation of the fuel locations Vs. Natural frequencies (Hz).

Case No.	1st bending Mode	2nd bending Mode	1st torsion+ 3rd bending Mode	1st torsion+ 3rd bending Mode	4th bending + torsion Mode
1	10.704	40.623	78.880	-	119.02
2	15.041	43.613	103.487	-	119.143
3	15.608	54.490	118.032	120.283	-
4	10.923	45.532	99.703	-	119.052
5	10.714	40.977	80.970	-	119.045
6	15.063	44.226	106.587	-	119.147
7	10.931	45.872	106.526	-	119.069

FLUTTER ANALYSIS

One of the main conditions of flutter speed (binary flutter) to occur is the coupling condition of the fundamental bending and torsion frequencies modes (ω_b/ω_t=1) during flight, ([Ashawesh, 2003])

However, there is another important factor to both flutter speed and divergence speed; it is the interaction of the direction of air flow with the wing sweep angle, or direction of the fibre orientation in the case of composite wing structure. This interaction will lead to a nose up deformations and nose down deformations. Nose up deformation produces a wash-in and nose down deformation produces a wash-out. Wash-in deformation increases the flutter speed, where as wash-out deformation is more beneficial to the divergence speed, see ([Weisshaar, 1983; Lottati, 1985; Lin, 1989; Seung, 1994; Koo, 1994 and Georghiades, 1995]).

The aerodynamic surface of the wing models is constructed using Doublet Lattice Method, DLM provided by MSC/NASTRAN with 10 elements along the semi-span and 4 elements along the chord of the wing models.

Dynamic aeroelastic (Flutter) analysis is then carried out on for (wing^1) and (wing^2) models (without fuel), using the PK method provided by MSC/NASTRAN program. The first four eigenvalues and associated eigenvectors are only included in the flutter analysis as presented in (Table 1). From the definition of flutter speed, as the speed at which the overall damping is zero, ([Abdullah and Sulaeman, 2013)]. The variation of the speed versus damping is shown in (Figure 11), from which the flutter speed is found to be 655.231 and 659.03 m/sec for the detailed and simplified wing models respectively. The cooresponding flutter frequencies are 41.54 Hz and 41.99 Hz, see (Figure 12).

Table 4 shows that the flutter speed and flutter frequency of the simplified model, (wing^2) is well agreed with the flutter speed obtained from the detailed wing model, (wing^1) with less than 1% error for the flutter speed and less than 2% error for the flutter frequency.

Table 4: Comparison of flutter speed and frequency of the wing models (without fuel).

	Simplified wing model, Wing^2	Detailed wing Model, Wing^1	Difference in, %
	MSC/NASTRAN	MSC/NASTRAN	
Flutter speed, (m/sec)	659.03	655.231	-0.5798
Flutter frequency, (Hz)	41.99	41.54	-1.083

After the flutter results validation of the detailed and simplified wing models, flutter analysis is carried out for the simplified wing model with adding fuel in different locations (cases) specified in (Table 2) above. The first four eigenvalues and associated eigenvectors are only included in the flutter analysis as presented in (Table 3).

The variation of the speed versus damping and frquency of case number 7 are presented for completeness in (Figures 13-14), from which the flutter speed is found as 702.513 m/sec and the corresponding flutter frequency 36.551 Hz.

The obtained flutter results of all caseses, see (Table 2) are presented in (Figure 15) as a nomdimensional flutter speed, taking the empty wing flutter speed (without fuel) as reference flutter speed, V_{ref}.

After the analysis of all cases results for flutter speed as shown in (Figure 15), It is found that the middle fuel tank has a significant effect on the flutter speed, higher flutter speed when its full of fuel compared with the inner and outer fuel tanks.

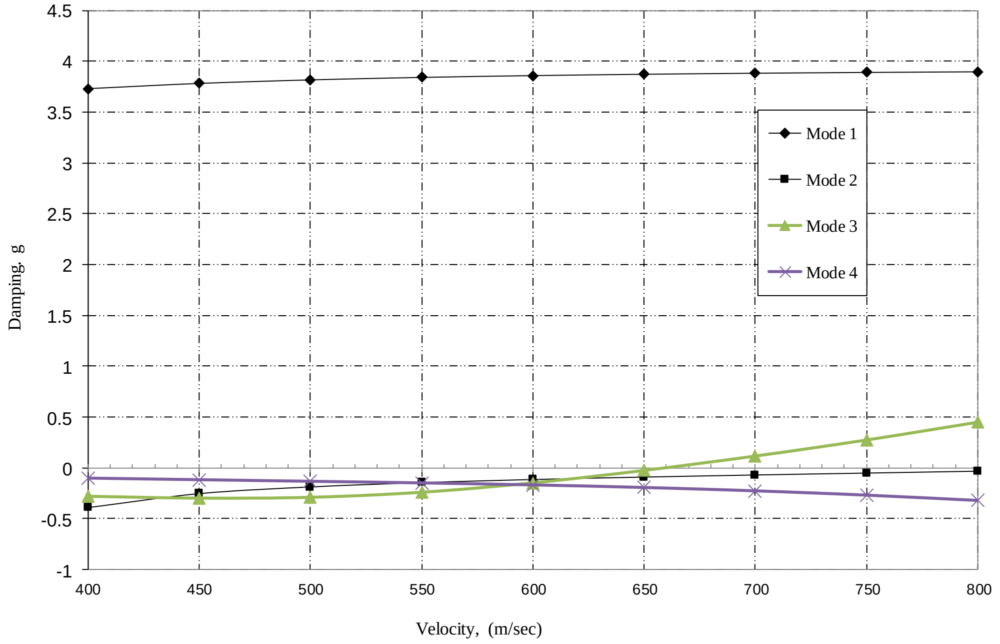

Figure 11: Variation of velocity with damping for the simplified wing mode, (without fuel)

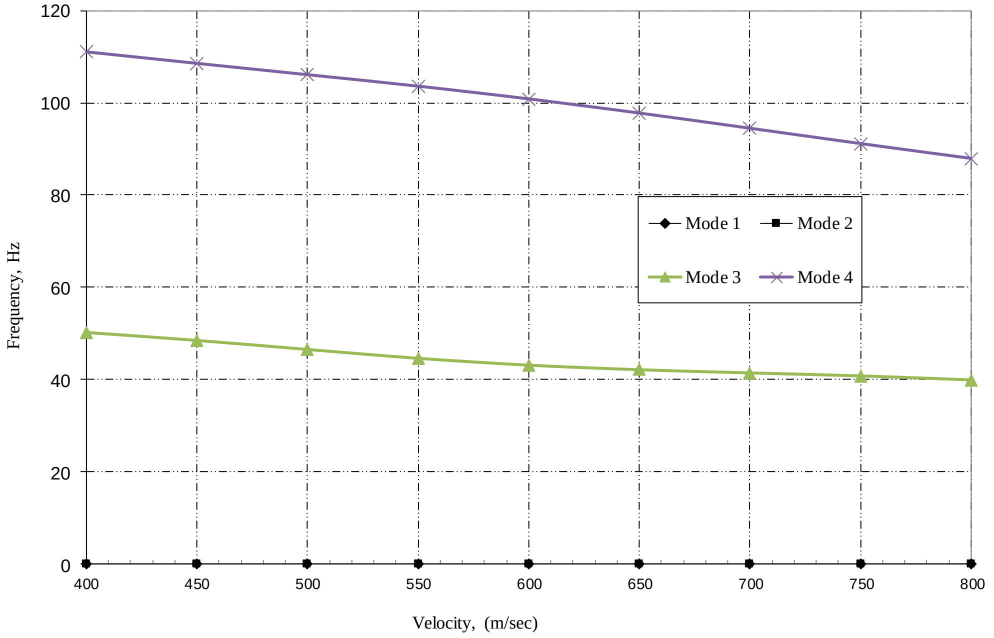

Figure 12: Variation of velocity with frequency for the simplified wing mode, (without fuel)

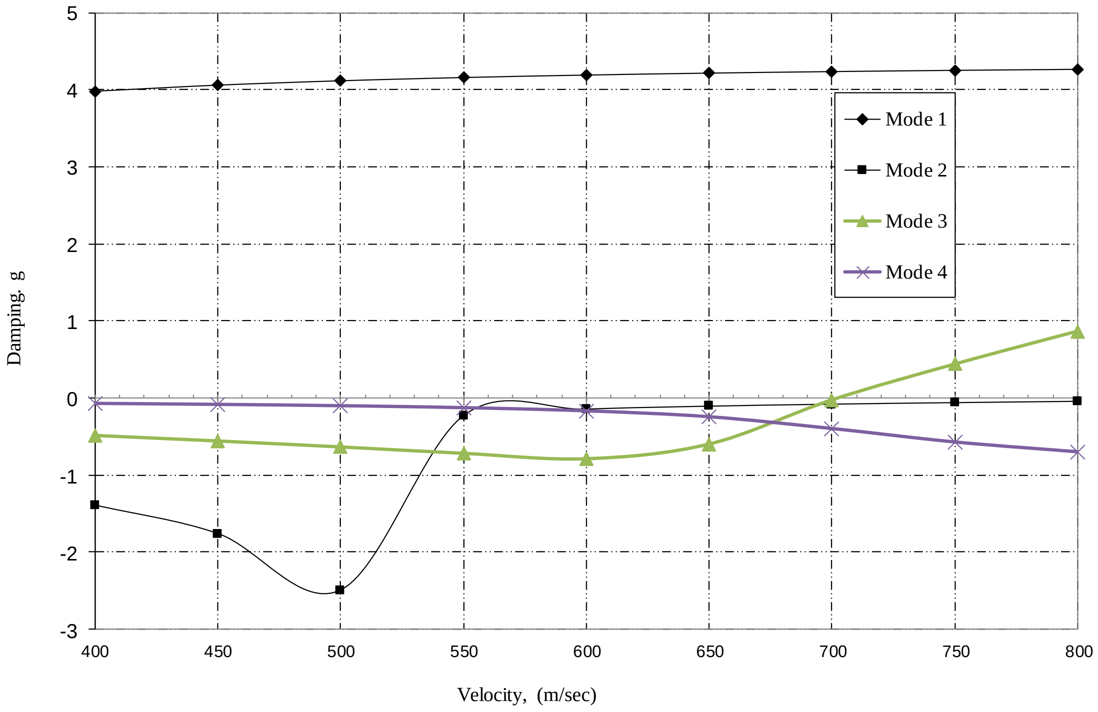

Figure 13: Velocity versus damping for case 7 of the simplified wing mode, (with tip fuel).

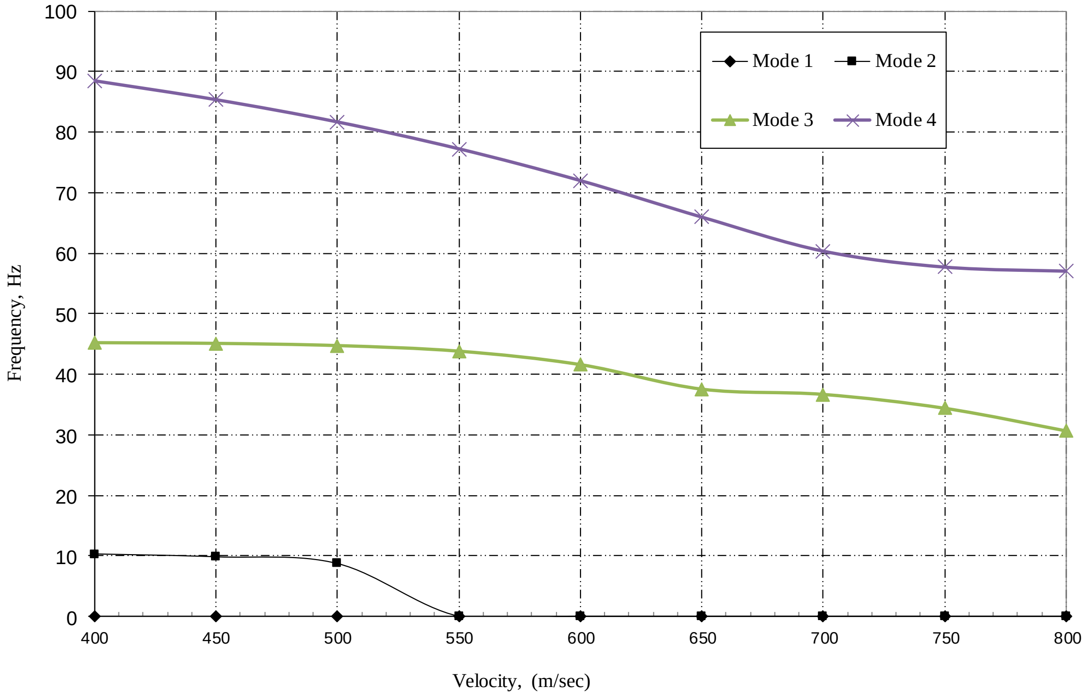

Figure 14: Velocity versus frequency for case 7 of the simplified wing mode, (with tip fuel).

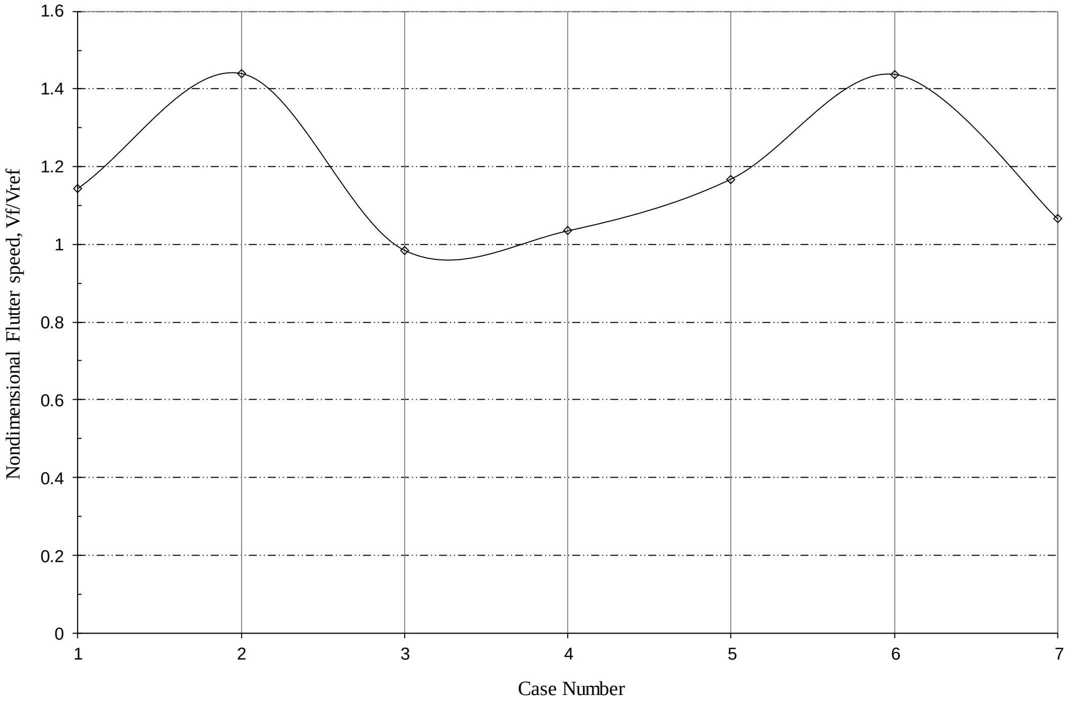

Figure 15: Nondimensional flutter speed Vs fuel locations (cases).

CONCLUSIONS

Free vibration and flutter analysis are carried out successfully on the detailed and simplified wing models using the finite element program MSC/NASTRAN. Results from both of the above analysis showed the important of representing the structure component with the proper element (beam with offset) for the stiffeners such as stringers and spar caps. It is showed also that how close the results of the simple beam wing model compared with the experimental results and the detailed wing models. Tip or outer fuel tank has a significant effect on the natural frequencies and mode shapes compared with the inner and middle fuel tanks. Wing model with full middle fuel tank shows a higher flutter speed compared with both inner and outer fuel tanks. It is concluded that simplifying the wing structure (Beam element with lumped masses) for the above analysis provides a good agreement at low cost in terms of model complexity, size, and running time. It is also a very useful approach to the structure designers especially at the early design stage of the aircraft structures.

References

Abdullah N. A. And Sulaeman E. (2013) Flutter analysis of supersonic wing with external stores, 2nd International Conference on Mechanical, Automotive and Aerospace Engineering, Kuala Lumpur, Malaysia, 2-4 July 2013.

Ashawesh G. M. (2003) Effect of wash-in and wash-out on the flutter characteristics of composite aircraft wings, Proceeding of 10th International Conference on Aerospace Science and Aviation Technology, Cairo, Egypt, May 13-15 2003.

Bruhn, E. F. (1973) Analysis and design of flight vehicle structures, Jacobs Publishing Inc., 1973.

Georghiades G. A.,Guo J. S. and Banerjee J. R. (1995) Flutter analysis of composite wing using an exact dynamic stiffness matrix method, AIAA-95-1488-cp, PP. 3019-3027, 1995.

Koo N. K. and Lee I. (1994) Aeroelastic behaviour of a composite wing plate with structural damping, Compouters&Structure, vol. 50, no. 2, PP. 167-176, 1994.

Lin K., P.J. Lu and Jiann-Quo T. (1989) Flutter analysis of a cantilevered composite plates in subsonic flow, AIAA journal, vol. 27, no. 8, PP. 1102-1109, August 1989.

Lottati I. (1985) Flutter and divergence aeroelastic characteristics of composite forward swept cantilevered wing, Journal of aircraft, vol. 22, no. 11, PP. 1001-1007, 1985.

Potter, J.G. and Ward, E.R. (1968) Design of aerobatic aircraftwing, MSc Thesis, Cranfield University, UK, 1968.

Rodden, P.W. and Johnson, H.E. (1994) Dynamic analysis handbook for MSC/NASTRAN, Version 69, the MacNeal-Schwendler Corporation, California U.S.A, 1994.

Seung I. L. and M. Hirokazu (1994) Static aeroelastic characteristics of a composite wing, Journal of aircraft, vol. 31, no. 6, PP. 1413-1416, Jan. 1994.

Stacey, J.A. (1976) The development of finite element aeroelasticcalculation package and its application to the AerobaticAircraft, MSc Thesis, Cranfield University, Uk, 1976.

Taig, I.C. (1986) Modelling for the finite element method, InAGARD Practical application of finite element analysis toaircraft structure design, pp.1-18, 1986.

Weisshaar T. A. and Foist L. B. (1983) Vibration and flutter of advanced lifting surface, AIAA-83-0961, PP. 498-508, 1983.