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THE EFFECT OF FIBER ORIENTATION ANGLE AND PLY THICKNESS ON SUBSONIC AND SUPERSONIC FLUTTER CHARACTERISTICS OF A COMPOSITE MISSILE FIN

Ceyhun TOLA[1] and Altan KAYRAN2[2]
Middle East Technical University
Ankara, Turkey

ABSTRACT

The main purpose of this study is to determine the effect of fiber orientation on subsonic and supersonic flutter characteristic of a composite missile fin. The most suitable lamina orientation among the several cases examined is determined without changing the geometry. Modal analysis of the missile fin has been performed for different lamina orientations and ply thicknesses and the change of the frequencies of bending and torsion modes are examined. Then, subsonic and supersonic flutter calculations are conducted using ZAERO commercial software. As a result, variations of flutter speed with respect to lamina orientation and with respect to ply thickness are determined for both subsonic and supersonic regime.

INTRODUCTION

Flutter, one of the catastrophic phenomena that a structure can encounter during the flight, can be described as a dynamic instability of a flight vehicle associated with the interaction of aerodynamic, elastic and inertial forces [Hodges and Pierce, 2002]. In order to avoid the catastrophic failures during the flight, flutter characteristics of a design has to be analyzed and required improving should be done. Therefore many theoretical, numerical and experimental studies on flutter have been conducted so far.

Generally, flutter analysis has a significant effect on the design of UAV wings since their aspect ratio can be very high. Therefore, it can be said that the geometry of the aircrafts' component has an important influence on aircrafts' aeroelastic behavior. On the other hand, flight regime has another significant parameter which determines the flutter characteristics of the structure. Even a missile fin can also be encountered flutter while it was cruising at lower altitudes during both subsonic and supersonic flight. Therefore, flutter characteristics of fins has to be analyzed carefully during the design steps of the missiles.

A missile fin should be both stiff and light as it was necessary for many aircraft materials; so, recently composite fins are preferred by manufacturers. Usage of the composite structure in the aviation industry leads to the initiation of studies on flutter analysis of composite lifting surfaces. Petrolo, conducted flutter analysis of lifting surfaces which are made up from composite materials using 1-D structural models coupled with the Douplet Lattice Method. Performing flutter analysis for various structural configurations, effects of stacking sequence and sweep angle are investigated within the content of that study [Petrolo, 2012]. Polynomial Chaos Expansion (PCE) method is applied in order to investigate the effect of uncertain material properties and severity of damage on a composite wing's aeroelastic response (such as variation of flutter speed) [Georgiou, Manan and Cooper, 2012]. After that, designers focused on the optimization of aeroelastic characteristics of composite structures by changing various structural parameters. Kameyama and Fukunaga are examined the flutter and divergence characteristics of composite plate wing with various sweep angle. Effects of laminate configuration on the flutter and divergence characteristics are investigated. Finally, genetic algorithm method is used to determine the minimum weight design to optimize the flutter and divergence characteristics of the composite plate wing within the design constraints [Kameyama and Fukunaga, 2007]. An aeroelastic optimization study on an aerobatic aircraft wing structure is also conducted.

[1] GRA. in METU Aerospace Engineering Department, Email: ctola@roketsan.com.tr
[2] Prof. in METU Aerospace Engineering Department, Email: akayran@metu.edu.tr

Wing is re-designed from composite structures focusing on the minimizing the weight of the wing. Then, aeroelastic optimization process is completed arranging the fiber orientations. As a result of the study, significant amount of weight is saved and composite wing's flutter speed is increased optimizing the fiber orientations of the structure [Guo, 2007]. Researchers also focused on the flutter characteristics of composite structures during supersonic flight regime to analyze and optimize fin like aircraft and missile structures. Singha and Mandal examined the panel flutter behavior of laminated composite plates and cylindirical panel under supersonic flow conditions. Within the content of the study, effects of laminate stacking sequence, air flow direction and shell curvature on supersonic flutter characteristics are investigated [Singha and Mandal, 2007]. Singha and Ganapathi also conducted numerical studies on a composite skew plate in order to investigate the effect of skew angle, fiber orientation and boundary conditions, damping and thermo-mechanical loads on flutter characteristics of it [Singha and Ganapathi, 2005]. The supersonic flutter characteristics of composite plates with variable fiber spacing are also examined. This research showed that fiber distribution on structures has considerable effect on the coalescent flutter modes [Kuo, 2011]. Oh and Kim, conducted a study on vibration characteristics and supersonic flutter behavior of cylindrical laminated panels with large thermal deflections. They revealed that structural parameters such as radius, shallowness angles and lamination type have big influence on vibration and flutter characteristics of cylindrical composite panels [Oh and Kim, 2009].

For making further contributions on composite missile fin design methodology, effects of fiber orientation angle of the laminae and ply thickness on subsonic and supersonic flutter characteristics of a composite fin are examined within the content of this study. Aeroelastic analyses are performed using ZAERO commercial software both in the subsonic and supersonic flight regime [ZAERO User's Manual]. For this purpose, different fin designs are identified which have subsonic and supersonic flutter speeds. Then, the effects of layer orientations and ply thickness on the flutter speeds of the composite missile fins are investigated.

METHOD

Generally, flutter is encountered due to coupling of bending and torsion modes of a structure. With the increment of dynamic pressure, frequency of bending mode increases, while frequency of torsion mode decreases. At a dynamic pressure where the bending and the torsion modes merge, flutter is encountered.

The main aim of this study is to examine the variation of flutter speed with variation of ply thickness and ply orientation in subsonic and supersonic regime without changing the geometry. In order to conduct flutter analysis, modal analyses are conducted for each case and change of the frequencies of bending and torsion modes are observed. As a mid-step, probable good lamina orientations can be estimated by looking the change of the difference between bending and torsion modes. If the difference is increased then it can be concluded that flutter speed may increase to a higher value considering that flutter is encountered due to coupling of bending and torsion modes of a structure. After the modal analysis step, flutter analyses are conducted using the ZAERO commercial software which is developed for making various types of aeroelastic analysis. As a result, the variation of flutter speed with respect to the ply orientation and thickness is determined. Thus, it is possible to orient the fibers in laminae on a fin in order to produce an aeroelastic efficient design having same cost and weight.

A generic composite missile fin that is analyzed within the content of study can be seen from Figure 1.

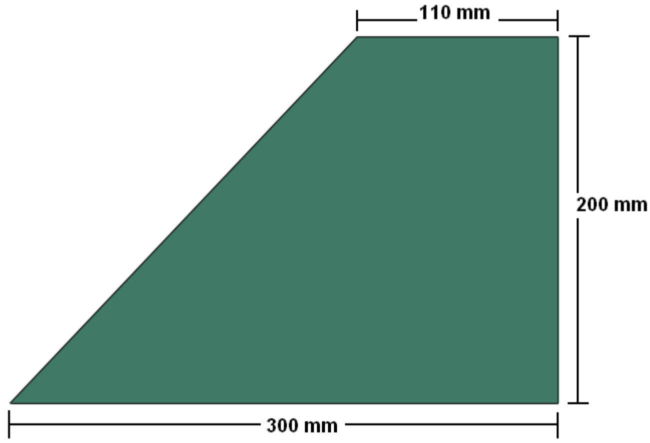

Figure 1: *Composite Missile Fin*

MATERIAL PROPERTIES

T300 / N5208 Graphite Epoxy is used as the fin material. Properties of the material in the fiber and transverse directions are summarized in Table 1.

Table 1: *Mechanical Properties of* T300 / N5208 Graphite Epoxy

Modulus in the fiber direction [E_1]	181.00 GPa
Modulus transverse to fiber direction [E_2]	10.30 GPa
Modulus transverse to fiber direction [E_3]	10.30 GPa
Shear Moduli [G_{12}]	7.17 GPa
Shear Moduli [G_{13}]	7.17 GPa
Shear Moduli [G_{23}]	7.17 GPa
Poisson's Ratio (υ_{12})	0.28
Density (ρ)	1600 kg/m^3

BOUNDARY CONDITIONS AND THE FINITE ELEMENT MODEL

Assuming that the fin is fixed to fin support, fixed boundary condition is applied to its root edge. 63 quadrilateral elements having 80 nodes are used in finite element model. Boundary conditions and finite element model can be seen in Figure 2.

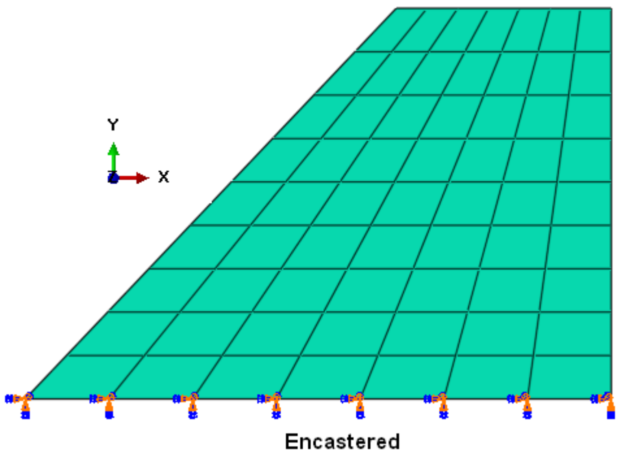

Figure 2: *Finite Element Model and the Boundary Conditions*

AEROELASTIC MODEL

Aerodynamic loads are calculated by ZAERO using panel method. Locations of the aerodynamic boxes and structural nodes can be seen in Figure 3.

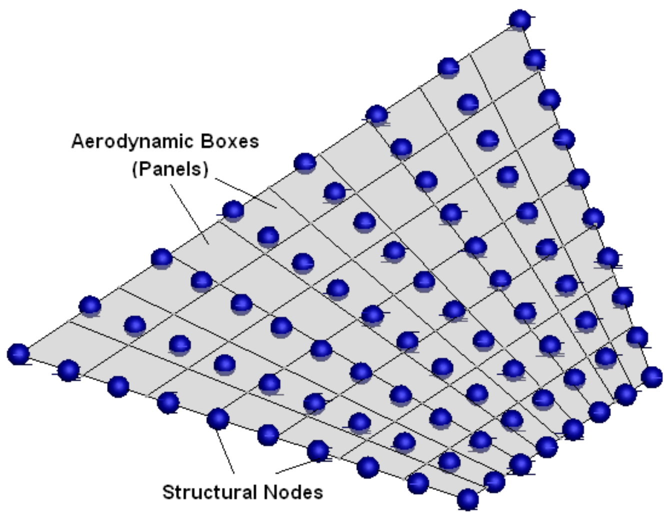

Figure 3: *Location of* Structural Nodes and Aerodynamic Panels

Aerodynamic panel dimensions are determined considering the Mach number, reference chord length and maximum examined frequency value. Maximum panel dimensions (ΔX) can be calculated using the following formula:

$$\Delta X < 0.08\frac{V}{f}\frac{1}{A} \quad where \quad A = \begin{Bmatrix} \left(\frac{M}{\beta}\right)^2, & \frac{M}{\beta} > 1 \\ 1 & \frac{M}{\beta} \leq 1 \end{Bmatrix} \quad \beta = \sqrt{|M^2 - 1|}$$

where f: Maximum examined frequency value

V: Minimum examined velocity value

M: Mach Number

Spline function (infinite plate spline) is used in order that aerodynamic panels can follow the structural mode shapes. Figure 4 shows aerodynamic panels following first mode of the fin via spline functions.

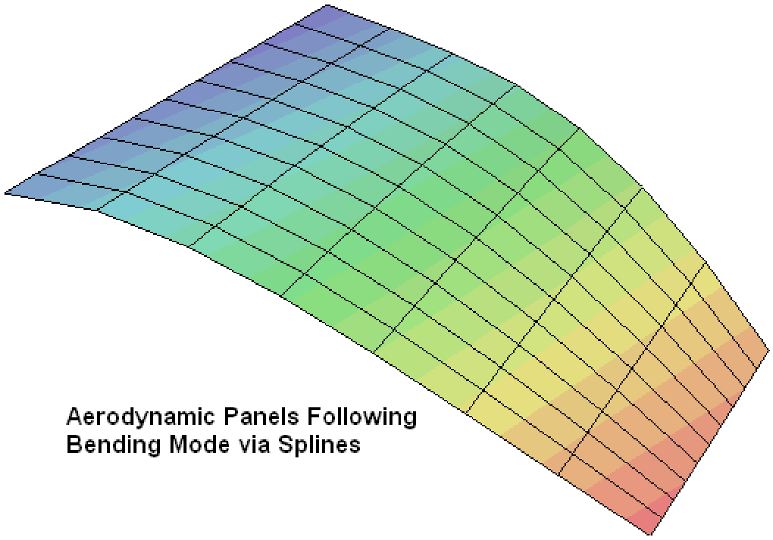

Figure 4: *Aerodynamic Panels Following the Bending Mode*

Flutter analysis are conducted for different fin combinations under subsonic and supersonic regime at the sea level under standard atmospheric conditions.

FIN COMBINATIONS

Fin combinations which are examined within the content of this work are summarized in Table 2.

Angles in Table 2 represent the fiber direction. Figure 5 shows the reference fiber angle with respect to fin geometry.

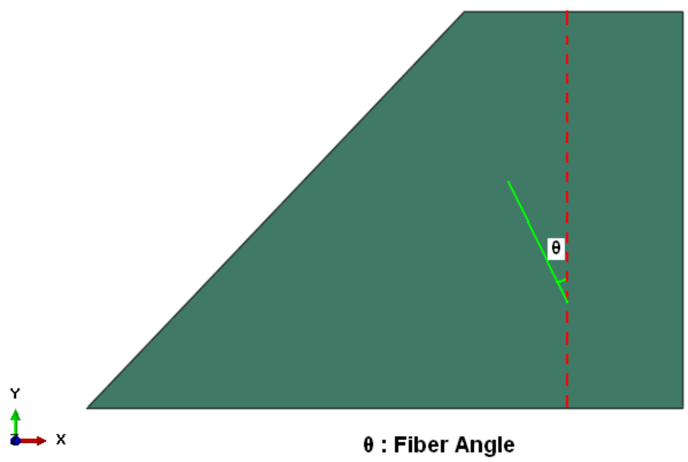

Figure 5: *Definition of the Fiber Orientation Angle*

First 15 fin models are prepared for investigating the variation of flutter speed with ply thickness and ply orientations in the subsonic regime. For the first 15 fin models thicknesses are 2 mm or 2.4 mm. On the other hand, models between Fin-16 to Fin-25 are prepared for examining the variation of flutter speed with ply thickness and ply orientations in the supersonic regime. For the supersonic regime, laminate thicknesses are taken as 3.2 mm or 3.6 mm.

Table 2: *Fin Combinations*

Case	Number of Plies	Ply Thickness (mm)	Total Thickness (mm)	Ply Orientation
Fin-1	8	0.25	2	[0 45 90 -45 -45 90 45 0]
Fin-2	8	0.3	2.4	
Fin-3	8	0.25	2	[-45 90 45 0 0 45 90 -45]
Fin-4	8	0.3	2.4	
Fin-5	6	0.333	2	[0 60 -60 -60 60 0]
Fin-6	6	0.4	2.4	
Fin-7	6	0.333	2	[-60 60 0 0 60 -60]
Fin-8	6	0.4	2.4	
Fin-9	4	0.5	2	[90 90 90 90]
Fin-10	4	0.6	2.4	
Fin-11	4	0.5	2	[0 0 0 0]
Fin-12	4	0.6	2.4	
Fin-13	8	0.25	2	[0 0 0 0 0 0 0 0]
Fin-14	4	0.5	2	[45 -45 -45 45]
Fin-15	4	0.6	2.4	
Fin-16	8	0.4	3.2	[0 45 90 -45 -45 90 45 0]
Fin-17	8	0.45	3.6	
Fin-18	6	0.533	3.2	[0 60 -60 -60 60 0]
Fin-19	6	0.6	3.6	
Fin-20	4	0.8	3.2	[90 90 90 90]
Fin-21	4	0.9	3.6	
Fin-22	4	0.8	3.2	[0 0 0 0]
Fin-23	4	0.9	3.6	
Fin-24	4	0.8	3.2	[45 -45 -45 45]
Fin-25	4	0.9	3.6	

MODAL ANALYSIS RESULTS

Before the flutter analysis, modal analyses are performed for each case and variation of the bending and torsion frequencies with respect to ply thickness and ply orientation are observed.

After the fixed boundary condition is applied to roots of the fin models, free vibration analysis are performed for each fin configurations via Abaqus FEA commercial software and results are summarized in Table 3.

Table 3: *Modal Analysis Results*

Case	Ply Thickness (mm)	Ply Orientation	Bending Mode Frequency (Hz)	Torsion Mode Frequency (Hz)	Ratio of Torsion/Bending Frequency
Fin-1	0.25	[0 45 90 -45 -45 90 45 0]	74.78	158.04	2.11
Fin-2	0.3		89.53	188.47	2.11
Fin-3	0.25	[-45 90 45 0 0 45 90 -45]	50.35	170.48	3.39
Fin-4	0.3		60.31	203.27	3.37
Fin-5	0.333	[0 60 -60 -60 60 0]	78.88	147.06	1.86
Fin-6	0.4		95.71	175.57	1.83

Fin-7	0.333	[-60 60 0 0 60 -60]	37.75	178.01	4.72
Fin-8	0.4		45.22	212.11	4.69
Fin-9	0.5	[90 90 90 90]	22.70	61.85	2.72
Fin-10	0.6		27.23	74.01	2.72
Fin-11	0.5	[0 0 0 0]	86.87	130.72	1.50
Fin-12	0.6		103.96	156.29	1.50
Fin-13	0.25	[0 0 0 0 0 0 0 0]	86.87	130.72	1.50
Fin-14	0.5	[45 -45 -45 45]	39.56	164.40	4.16
Fin-15	0.6		47.30	195.74	4.14
Fin-16	0.4	[0 45 90 -45 -45 90 45 0]	118.70	247.50	2.09
Fin-17	0.45		133.10	276.56	2.08
Fin-18	0.533	[0 60 -60 -60 60 0]	126.78	230.74	1.82
Fin-19	0.6		142.21	257.78	1.81
Fin-20	0.8	[90 90 90 90]	36.29	98.03	2.70
Fin-21	0.9		40.81	109.90	2.69
Fin-22	0.8	[0 0 0 0]	137.68	206.54	1.50
Fin-23	0.9		154.26	231.17	1.50
Fin-24	0.8	[45 -45 -45 45]	62.60	256.23	4.09
Fin-25	0.9		70.16	285.28	4.07

Mode shapes of Fin-1 can be seen from Figure 6. Similar results can be observed for different fin configurations. Therefore, only the modes shapes of Fin-1 are given as sample.

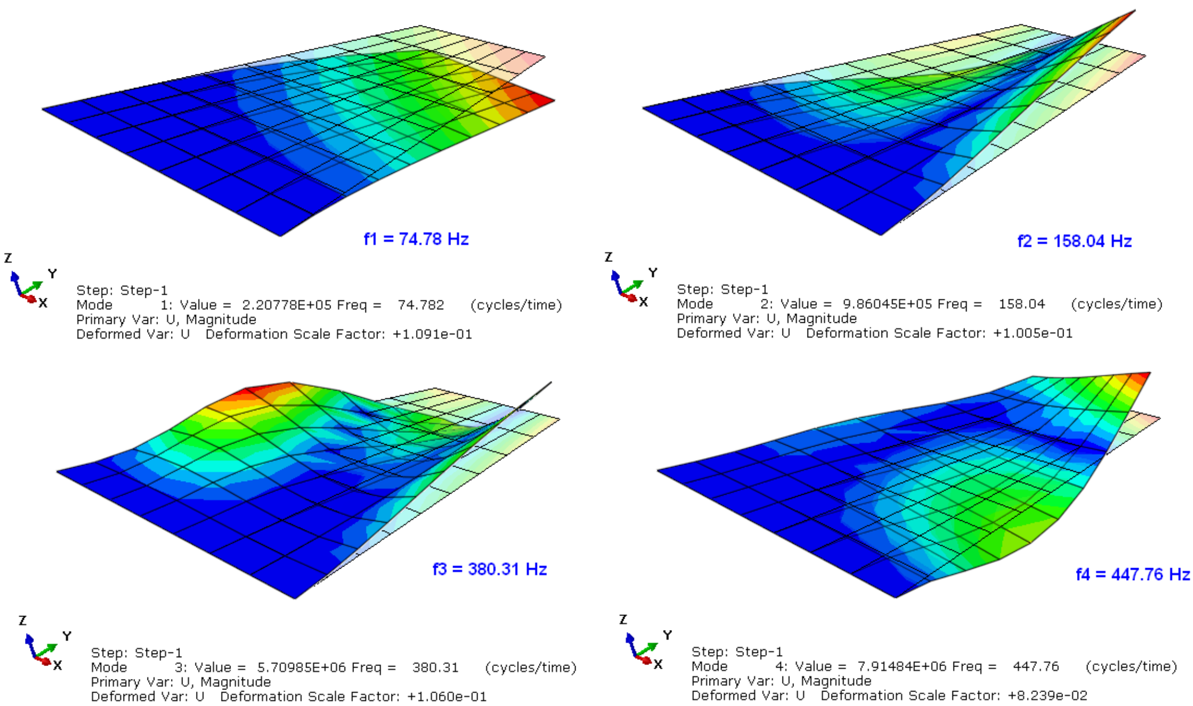

Figure 6: *Mode Shapes of Fin-1*

Examining the variation of bending and torsion frequencies, it can be said that it is possible to change the flutter speed without increasing the weight and cost of the fin, since it is possible to change the ratio of bending/torsion frequency only by changing the sequence of the plies as it is observed between Fin-1 and Fin-3. On the other hand, changing the ply thickness without changing the ply angle and the total thickness does not change the torsion/bending frequency ratio since stiffness and mass of the system does not change. This can be seen by making a comparison between Fin-11 and Fin-13. Additionally, it is observed that changing the ply thickness and the total fin thickness does not change the torsion/bending frequency ratio since the ratio of the bending and torsion frequencies are almost equal for the same stacking sequence. Therefore, ratios of torsion/bending frequency values are almost equal to each other for fins having the same ply orientation.

AEROELASTIC ANALYSIS RESULTS

After the modal analysis, flutter analyses are performed for each case via ZAERO commercial software and variation of the flutter speed with respect to ply thickness and ply orientation are obtained. Matched point flutter analyses are performed under standard atmospheric conditions at the sea level. Flutter speed of fin combinations are determined as a result of iterative flutter analyses. Results of the analyses are summarized in Table 4.

Table 4: *Flutter Analysis Results*

Case	Ply Thickness (mm)	Total Thickness (mm)	Ply Orientation	Flutter Speed (m/s)	Flutter Speed (Mach #)	% Difference
Fin-1	0.25	2	[0 45 90 -45 -45 90 45 0]	205	0.60	35.9
Fin-2	0.3	2.4		278	0.82	
Fin-3	0.25	2	[-45 90 45 0 0 45 90 -45]	322	0.95	37.6
Fin-4	0.3	2.4		443	1.30	
Fin-5	0.333	2	[0 60 -60 -60 60 0]	176	0.52	35.5
Fin-6	0.4	2.4		238	0.70	
Fin-7	0.333	2	[-60 60 0 0 60 -60]	323	0.95	35.1
Fin-8	0.4	2.4		436	1.28	
Fin-9	0.5	2	[90 90 90 90]	77	0.23	32.3
Fin-10	0.6	2.4		101	0.30	
Fin-11	0.5	2	[0 0 0 0]	115	0.34	33.3
Fin-12	0.6	2.4		153	0.45	
Fin-13	0.25	2	[0 0 0 0 0 0 0 0]	115	0.34	
Fin-14	0.5	2	[45 -45 -45 45]	269	0.79	35.2
Fin-15	0.6	2.4		364	1.07	
Fin-16	0.4	3.2	[0 45 90 -45 -45 90 45 0]	652	1.92	50.2
Fin-17	0.45	3.6		980	2.88	
Fin-18	0.533	3.2	[0 60 -60 -60 60 0]	460	1.35	55.8
Fin-19	0.6	3.6		716	2.11	
Fin-20	0.8	3.2	[90 90 90 90]	157	0.46	22.0
Fin-21	0.9	3.6		192	0.56	
Fin-22	0.8	3.2	[0 0 0 0]	252	0.74	23.7
Fin-23	0.9	3.6		312	0.92	
Fin-24	0.8	3.2	[45 -45 -45 45]	1005	2.96	44.3
Fin-25	0.9	3.6		1450	4.27	

Subsonic Flutter Speed
Supersonic Flutter Speed

Flutter mode shapes belonging to Fin-1 can be seen in Figure 7. Similar results can be observed for different fin configurations. Therefore, only the flutter mode of Fin-1 is given as an example.

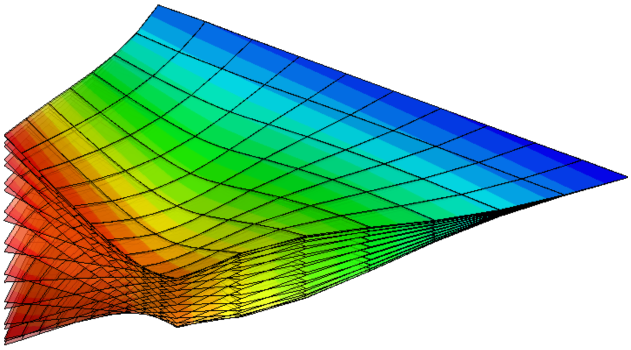

Figure 7: *Fin-1 Flutter Mode*

Examining the variation of flutter speed, it can be commented that, there are 4 factors affecting the flutter speed which are:

- Ply Orientation
- Torsion/Bending Frequency Ratio
- Level of the Torsional Frequency
- Total Thickness of the Structure

Increase of the total thickness always leads to the increase of the flutter speed although the ratio of torsional and bending frequencies does not change. It is seen that the effect of thickness increase is less effective in the subsonic regime rather than in the supersonic regime. It can be seen from Table 4 that thickness increment provides much more flutter speed increment for the supersonic regime. Therefore, if the fin is designed for supersonic flight regime then thickness increment is more preferable solution rather than changing the ply orientations.

On the other hand, increase of only the torsion/bending frequency ratio is not enough for the increase of the flutter speed. In order to offset the flutter speed to the higher values, both torsional frequency level and torsion/bending frequency ratio or only the level of the torsional frequency has to be increased. For example, Fin-1 and Fin-9 have torsion/bending frequency ratios of 2.11 and 2.72 respectively. However, flutter speeds of Fin-1 and Fin-9 are 205 m/s and 77 m/s respectively. Thus, it can be concluded that since Fin-9's torsional frequency value (61.85 Hz) is much lower than Fin-1's torsional frequency value (151.84) Fin-1 has much higher flutter speed than Fin-9. Torsion/bending frequency ratio and level of torsional frequency are also related to the ply orientation. Therefore, the effect of ply orientation on flutter speed is also examined via these two parameters.

Examining Fin-1 and Fin-3 it can be said that flutter speed can also be shifted to higher values without changing the weight and cost of the fin, only by changing the stacking sequence of the laminate. From the results of fins 1-4 and 5-8, it is observed that by placing the off-axis plies in the outer layers (such as 45 degree layers in fins 3 and 4 and 60 degree layers in fins 7 and 8) flutter speed can be increased substantially. By comparing the flutter speeds fins 9-12 and 14,15 in the subsonic regime and fins 23-25, it can be concluded that in the supersonic regime angle ply laminates have much higher flutter speeds than the 0 degree or 90 degree ply laminates when compared to the subsonic case.

According to Table 4, Fin-3 (for the subsonic regime) and Fin-25 (for supersonic regime) can be selected.

Finally, it can be said that it is possible to offset flutter speed to higher values by changing the ply orientations. However, a flutter efficient fin may have lower strength. Therefore, this should be considered in the design stage.

CONCLUSION

The effect of fiber orientation angle and the ply thickness on the subsonic and the supersonic flutter characteristics of a composite missile fin is investigated within the content of this study. Modal analyses are conducted via Abaqus commercial FEA software and change of the frequencies of bending and torsion modes are obtained. Then, matched point flutter analyses are conducted using the ZAERO commercial software at the standard atmospheric conditions in the subsonic and supersonic regime. As a result of the analyses it is concluded that 4 factors affect the flutter speed which are the ply orientation, torsion/bending frequency ratio, level of the torsional frequency and total thickness of the structure. Torsion/bending frequency ratio and level of torsional frequency are directly related to the ply orientation. Therefore, the effect of ply orientation on flutter speed is examined via these two parameters. It is found out that increase of the total thickness always offsets flutter speed.to higher values and the thickness increment is less effective in the subsonic regime compared to the supersonic regime. Additionally, to shift the flutter speed to higher values, both, torsional frequency level and torsion/bending frequency ratio or only the level of the torsional frequency has to be increased. Analyses also revealed that, solely changing the sequence of the plies is enough for shifting the flutter speed to higher values without changing the weight and cost of the fin. In sum, it is possible to offset flutter speed to higher values with changing ply orientations or increasing thickness. If the fin is designed for supersonic flight regime then thickness increment is better solution rather than changing ply orientations. Finally, strength analysis should also be performed and design should be optimized considering the flutter analysis results and strength analysis results, since a flutter efficient fin may have lower strength.

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