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STRUCTURAL OPTIMIZATION OF AN AEROELASTICALLY TAILORING COMPOSITE FLAT PLATE MADE OF WOVEN FIBREGLASS/EPOXY

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ABSTRACT

Effects of aspect ratio, sweep angle, and stacking sequence of laminated composites were studied to find the optimized configuration of an aeroelastically tailored composite wing idealized as a flat plate in terms of flutter speed. The aeroelastic analysis has been carried out in frequency-domain. The 2D finite element analysis in conjunction with Doublet-lattice Method (DLM) has been opted for structural and unsteady aerodynamic analysis, respectively. The interpolation between aerodynamic boxes and structural nodes has been done using surface spline. To study the effect of stacking sequence the classical lamination theory (CLT) has been chosen. All the analyses have been implemented in MSC.NASTRAN/PATRAN. The parametric studies showed the effective ply orientation angle to be somewhere between 15 and 30 degree, while the plates with lower aspect ratio seems to have higher flutter speed. Forward swept configurations show higher flutter speed, yet imposed by divergence constraint.

Keywords: *Aeroelastic tailoring, flutter, optimization, Doublet-lattice Method.*

1.0 INTRODUCTION

Due to their destructive nature, aeroelasticity phenomena have always put a constraint for structural designers to increase the flight envelope. Such phenomena are brought about by mutual interaction of an elastic body and aerodynamic forces. One way to put off aeroelastic effects is to make the airframe more rigid which consequently introduces weight penalty in the gross weight of the aircraft. However, one of the objectives in the process of aircraft design is to reduce the overall weight, thus, this method of solution cannot be the ultimate response to the demand of designing weight-critical vehicles such as aircraft and spacecraft.

During the past few decades, one of the tasks of structural designers has been seeking for alternative materials which can replace the conventional metallic

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structures where high stiffness is required without increasing the weight. Therefore, they have come up with composite materials which possess all of these criteria. As a matter of fact, the introduction of composite materials into the realm of aircraft design has led to new airframe design concepts and also to re-evaluation of older concepts [1]. Not only do composites materials in general and laminated composites in particular offer weight advantage over conventional metal airframe constructions, but provide this opportunity to passively control the aeroelastic response of a lifting surface as well. The technology to design for a desired aeroelastic response of a lifting surface using advanced filamentary composite materials has been named aeroelastic tailoring [2].

The aeroelastic tailoring terms was first introduced by Wassoups et al. [3] when they were pursuing the application of advanced composites for design improvements. They demonstrated that the directional properties of composites could be used to provide a significant level of anisotropy to create coupling between bending and twisting deformation.

Wisshaar [1] discussed several effects of laminate lay-up and fiber orientation upon aeroelastic divergence, wing load redistribution, and lateral control effectiveness of the swept-back and swept-forward wings. Structural wing model (the laminated box-beam) in this work was characterized by three parameters, EI, GJ, and K, which represents beam bending stiffness, torsional rigidity, and the bend-torsion coupling parameters, respectively. The author concluded that tailoring involving bending-torsion coupling was seen to be effective for high-aspect ratio wings as well as low-aspect ratio wings. In the same year, Sherrer et al. [2] demonstrated the principle of aeroelastic tailoring with advanced composite materials to increase the divergence speed of a forward-swept wing through low-speed wind tunnel tests. This work resulted in increasing the divergence dynamic pressure and tailoring the composite materials for bend-twist coupling.

Rogers and Brayment [4] presented a design methodology involving aeroelastic tailoring. This work sought three objectives through two tailored (wash-out; upward bending/nose down twist and wash-in; upward bending/nose up twist – models) and one non-tailored wing models. Additionally, a rigid wing was fabricated for comparison purpose. This work exhibited significant reduction of transonic drag due to lift compared to the non-tailored and rigid wings using wash-out wing. Moreover, the increase in lift-curve slope was obtained with the aid of wash-in wing.

To add to the limited experimental data on aeroelastic tailoring, Hollowell and Dugundji [5] investigated the effect of bending-torsion stiffness coupling on both the divergence and flutter velocities of unswept lifting surfaces made of graphite/epoxy in compressible flow. The lifting surfaces were idealized as cantilevered flat plates. This work exhibited that bending-torsion coupling could be advantageous in delaying or suppressing divergence while delaying the onset of stall flutter as well.

Analogous to Hollowell and Dugundji work, Lin et al. [6] developed a general methodology for the flutter analysis of plate-like composite structures. The results of the work demonstrated that structural tailoring could provide a harmonious balance to the sweep angle effects on the stability characteristics of the wing. Isogai [7] showed that by aeroelastic tailoring the transonic flutter characteristics of a transport-type high-aspect-ratio forward-swept wing could be improved by about 60-80% over that of the non-tailored wing, while the divergence phenomenon was eliminated.

Kuttenkeuler and Ringertz [8], studied numerically as well as experimentally the optimal design of wing structures made of laminated composites subjected to aeroelastic constraints. While considering the laminate orientation and the size of a number of the concentrated masses used for mass balancing as the design variables, the authors asserted that the flutter speed is a discontinuous function of the laminate orientation. This work proved to be accurate enough for aeroelastic tailoring as long as sufficient care is taken in the whole procedure.

Recently, Chattopodhyay et al. [9] combined the concept of active control of fixed wing aircraft represented by a cantilevered composite plate using piezoelectric materials and aeroelastic tailoring to reduce static displacement, improved passenger comfort during gust and increased damping. The wing was made of 24 ply graphite/epoxy commercial material. This study also exhibited considerable improvement in the design objectives and physically meaningful optimal designs.

Qin, Z. et al. [10] developed a unified aeroelastic model and showed that the elastic tailoring and warping restrain played a significant role on the flutter instability and dynamic response of composite aircraft wings.

The present work, however, is aimed at optimizing the flutter speed through aeroelastic tailoring of wing made of laminated woven fiber composites. One simplification that has been made in this research is to idealize the composite wing as a composite flat plate which resembles the low to moderate aspect ratio wings. The optimization process begins with a parametric study in which the effects of aspect ratio, sweep angle, and ply orientation angle on flutter speed of a composite flat plate made of woven fiberglass/epoxy will be investigated in order to highlight the importance and sensitivity of these design variables, which is essential prior to setup a formal optimization problem. The aeroelastic analysis of this research has been carried out in the range of incompressible and subsonic flow.

2.0 THEORY

To understand the fundamental principles underlying the aeroelastic tailoring of composite materials it is essential to understand both mechanics of composite materials and aeroelastic theory.

A woven composite with its weaves perpendicular to each other as is used in the current study are considered as orthotropic materials. When several laminas are bonded together they form a laminated composite. The following relations make up the so called classical lamination theory (CLT).

Forces and moments resultants related to mid-plane strains and curvatures of the laminate are expressed in the following relations:

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} + \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix}$$
$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} + \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix} \quad (1)$$

where N_x and N_y are the normal force per unit length, N_{xy} is the shear force per unit length, M_x and M_y are bending moments per unit length, and M_{xy} is the twisting moment per unit length. [A], [B] and [D] matrices are called the extensional, coupling and bending stiffness matrices respectively. The elements of these matrices can be calculated as following:

$$A_{ij} = \sum_{k=1}^{n} \left[(\overline{Q}_{ij})\right]_k \left(h_k - h_{k-1}\right) i=1,2,6 \quad (2)$$

$$B_{ij} = \frac{1}{2}\sum_{k=1}^{n} \left[(\overline{Q}_{ij})\right]_k \left(h_k^2 - h_{k-1}^2\right) \; i=1,2,6 \quad (3)$$

$$D_{ij} = \frac{1}{3}\sum_{k=1}^{n} \left[(\overline{Q}_{ij})\right]_k \left(h_k^3 - h_{k-1}^3\right) \; i=1,2,6 \quad (4)$$

where $\overline{Q}_{ij}$ is the off-axis lamina modulus of the kth ply.

Some comments regarding the classical lamination theory are worth elaborating. The flexural modulus components D_{ij} of a laminated advance plate depend on both the fiber orientation and stacking sequence of the individual laminas [5]. Moreover, the components D_{11}, D_{66}, and D_{16} are termed as theoretical bending stiffness, torsional rigidity and bend-twist coupling elements, respecfively. The bending – torsion stiffness coupling ratio ($D_{16} / \sqrt{D_{11} D_{66}}$) is called the primary aeroelastic tailoring parameter [3] and is used herein to compare the level of tailoring in our analysis.

After evoking some fundamentals of mechanics of composites, some fundamental theory on the solution of aeroelasticity is presented in the proceeding paragraphs. The aeroelastic equation of motion can be written in the form of:

$$[M]\ddot{u} + [B]\dot{u} + [K]u = F(u, \dot{u}, \ddot{u}, t) \quad (5)$$

where [M], [B], and [K] are the generalized mass matrix, generalized damping matrix, and the generalized stiffness matrix, respectively. While u is the generalized displacement vector.

Let $F(u, \dot{u}, \ddot{u}, t) = F(u, \dot{u}, \ddot{u}) + \overline{F}(t)$, where $\overline{F}(t)$ represents motion independent external forces. Eq. (5) can be written as:

$$[M]\ddot{u} + [B]\dot{u} + [K]u = [A_1]\ddot{u} + [A_2]\dot{u} + [A_3]u + \overline{F}(t) \tag{6}$$

For stability we solve the homogenous equation from initial stage:

$$[M]\ddot{u} + [B]\dot{u} + [K]u = [A_1]\ddot{u} + [A_2]\dot{u} + [A_3]u \tag{7}$$

The above equation can be solved either in time domain or frequency domain (eigenvalue problem). Using the Laplace transformation and introducing modal coordinates as $\{u_h\}$, Eq. (7) can now be written as:

$$M_{hh}\ddot{u}_h + \overline{B}\dot{u}_h + K_{hh}u_h - 1/2\rho V^2 [A_{hh}]u_h = 0 \tag{8}$$

Assume that the structural response is separable and synchronous: $\{u_h\} = \{q_h\}e^{st}$. $\{q_h\}$ is independent of time and $s = \sigma + i\omega$, so Eq. (8) becomes:

$$[\,M_{hh}s^2 + B_{hh}s + K_{hh}s - 1/2\rho V^2\, A_{hh}\,]\{q_{hh}\} = 0 \tag{9}$$

Where $[K_{hh}\ s\ -½\rho V^2 A_{hh}]$ is the aeroelastic stiffness matrix and A_{hh} is the generalized aerodynamic forces. Eq. (9) is the basic flutter eigenvalue equation.

To solve A_{hh} there are numerous methods and techniques. For the present study the Doublet-Lattice method (DLM) has been adopted. This theory was presented by Albano and Rodden, Giesing, Kalman and Rodden, and Rodden, Giesing, and Kalman [12]. The theoretical basis of DLM is linearized aerodynamic potential theory. The undisturbed flow is uniform and is either steady or varying (gusting) harmonically. All lifting surfaces are assumed to lie nearly parallel to the flow. The DLM is an extension of the steady Vortex-Lattice method to unsteady flow [12].

To solve Eq. (9), there are several iterative solutions such as K method, K-E method, P-K method, P method and state space. For the current research, the P-K method has been chosen. This method is the Hassing's modified version of the Frazer and Duncan. The great advantage of P-K method is that it can utilize airloads that have been formulated for simple harmonic motion [13]. In addition, in this method the rate of convergence to the desired root is very rapid, thus it requires less computational effort. On the contrary, this method is valid where a low level of damping is considered.

While expressing s as: $s = \frac{Vk}{b}(\gamma + i) = \frac{V}{b}P$, the fundamental equation for solving Eq. (9) by the P-K method is:

$$\left\{\left[\frac{V}{b}\right]^2 P^2 M_{hh} + \frac{V}{b}PB_{hh} + K_{hh} - \frac{\rho V^2}{2}A(k)_{hh}\right\}q_h = 0 \tag{10}$$

where V is the selected free-stream speed, b is the reference semi-chord, $P \equiv k(\gamma + i)$ is the complex response frequency and eigenvalue, $A_{hh} = [A^R + iA^I]$ is the generalized aerodynamic matrix which is a function of Mach number and reduced frequency, ρ is the free-stream density, k is the reduced frequency ($k = \omega b/V$), q_h is the eigenvector of modal coordinated, γ is the damping factor, and $i \equiv \sqrt{-1}$. In this method matrices which are real but non-symmetric would yield complex roots. For the real roots, the damping is expressed as the decay rate coefficient, which is the distance, traveled (measured in chord length) to half (or double) amplitude [12]: $g = 2\gamma = \frac{2Pc}{(\ln 2)V}$.

Like classical V-g method, in P-K method the negative values of damping indicate that the structure is stable, while positive values indicate instability. Flutter occurs when the damping coefficient g is tending to zero.

3.0 COMPUTATIONAL RESULTS AND DISCUSSION

3.1 Validity Test of the Computational Procedure

In order to validate the procedure of computational work associated with this research, two aeroelastic models have been chosen and successfully validated against the existing published results [8, 11]. The first model is a 0.254 × 0.254*m* square flat plate made of aluminum alloy 6061 the result of which has been reported in Ref. [11]. The second model is a 15^0 swept wing with 1200 mm span, 200 mm root chord and 100 mm tip chord made of pre-fabricated 0/90 woven-fiberglass/epoxy [8]. The validation results as well as those obtained with MSC.NASTRAN are shown in Table 1. Furthermore, Figure 1 provides the flutter V-g and V-F graph obtained with MSC.NASTRAN P-K method.

Table 1: Validation results for computational procedure

	Model One				
	V_f (m/s)	ω_f (Hz)	ω_1 (Hz)	ω_2 (Hz)	ω_3 (Hz)
Ref. [11]	27.43	40.2	6.78	42.02	-
Present	29.5	36.003	6.7767	42.003	101.14
	Model Two				
Ref. [8] – Exp.	47.1	-	-	-	-
Ref. [8] – Calc.	47.8	-	-	-	-
Present	46.7	15.85	4.58	24.74	30.50

3.2 Experimental Verification

With the experimental facilities available at the department of aerospace, University of Putra Malaysia, all the experimental verifications have been done in the 1m by 1m low-speed wind tunnel. The aeroelastic test apparatus of the wind tunnel is a side-wall mount type which can be used for testing a semi-span cantilevered model. In the current work for the purpose of verification two unswept configurations with aspect ratios of 5 (0.09 ×0.45 m) and 6 (0.09 × 0.54 m) and [0/0/0] stacking sequence have been tested the test data of which are presented in Table 2. The results demonstrate a good agreement between computation and experiment.

Table 2: Experimental verification of flutter

	Aspect Ratio 6		
	V_f (m/s)	ω_f (Hz)	Thickness
Experiment	31.2	-	2.2mm
Present	32.8	16.017	2.2mm
	Aspect Ratio 5		
Experiment	37	-	2.2mm
Present	39	20.381	2.2mm

3.3 Model Description

For the current research five cantilevered plates with aspect ratios of 3, 4, 5, 6, and 7 all with a fixed chord of 0.09m and varying sweep angles (-30, -15, 0, 15, 30) made of laminated woven fiberglass/epoxy whose mechanical properties are tabulated in Table 3, have been chosen.

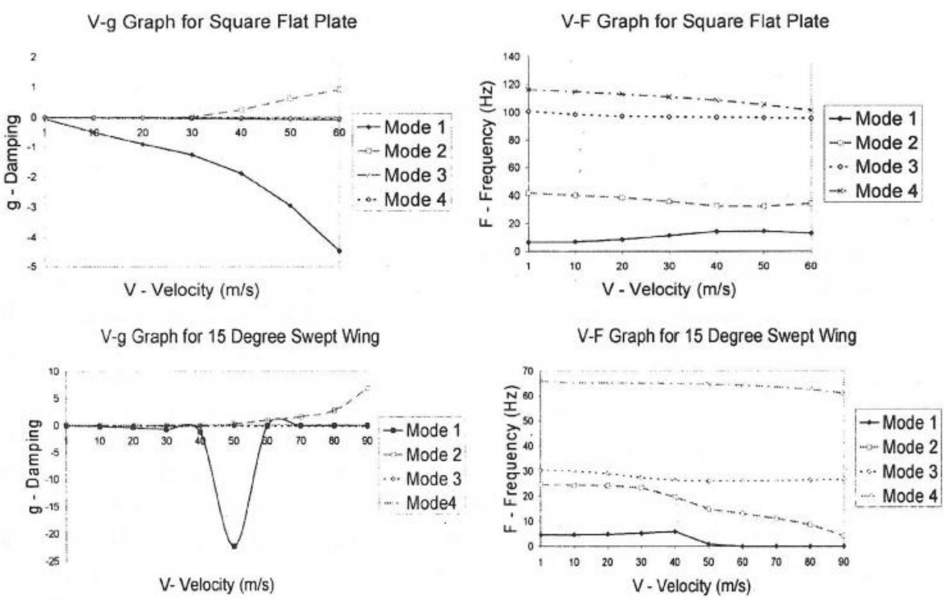

Figure 1: V-g and V-F graph obtained with Msc.NASTRAN P-K for the validity test

Each plate consisted of three layers oriented at stacking sequence of $[\theta_2/0]$ where θ were 0, 15, 30, 45, 60, and 75 degrees. Here θ represents the major fiber direction in a woven fiberglass let's say the fill direction. This assumption is based on the one-dimensional Mosaic model in which the woven fibers are assumed to be in one direction. Figure 2 illustrates the plate layout and the sign conventions for the plate model used herein.

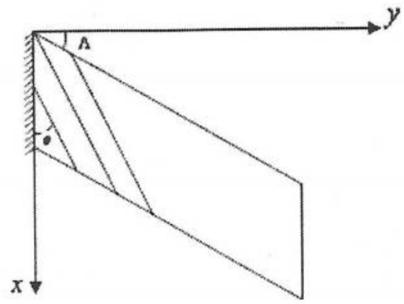

Figure 2: Plate layout and sign conventions
*Λ: Sweep angle, θ: ply orientation angle

Table 3: Mechanical properties of woven fiberglass/epoxy

E_1	12.85 GPa
E_2	10.24 GPa
ν_{12}	0.144
G_{12}^*	1.49 GPa
ρ	1849.711 Kg/m^3
Ply thickness (t_p)	0.606×10^{-3} m

*Calculated according to Ref. [16]

3.4 Effects of Ply Orientation Angle on Flutter Speed

Kuttenkeuler and Ringertz [8] asserted that the flutter speed is a discontinuous function of the laminate orientation. To simulate the effect of ply orientation angle on flutter speed a bending-torsion coupling parameter is used. Based on classical lamination theory which has been elaborated in theory section, the bending stiffness matrix of each laminate with stacking sequence of $[\theta_2/0]$ has been calculated. The bend-twist coupling parameter shows up itself in this matrix as D_{16} element. Table 4 presents the bending stiffness matrix (D_{ij}) of each configuration used in the current work. The variation of the bending–torsion stiffness coupling ratio ($D_{16} /\sqrt{D_{11} D_{66}}$) against the outer ply orientations is plotted and illustrated in Figure 3. This plot shows that at some angle the value of ($D_{16} /\sqrt{D_{11} D_{66}}$) is the highest which is somewhere between 15 degree and 30 degree. Accordingly, at this angle the flutter speed is the maximum. Figure 4 demonstrates this claim by plotting the flutter speed against the ply orientation angles.

Table 4: Bending stiffness matrix elements for each laminate

Laminate	D_{11}	D_{12}	D_{16}	D_{22}	D_{26}	D_{66}
$[0_2/0]$	6.542	0.750	0	5.213	0	0.746
$[15_2/0]$	6.019	1.188	0.918	4.862	-0.597	1.183
$[30_2/0]$	4.910	2.063	1.035	4.221	-0.481	2.059
$[45_2/0]$	4.152	2.501	0.320	4.103	0.320	2.496
$[60_2/0]$	4.270	2.063	-0.481	4.861	1.035	2.059
$[75_2/0]$	4.911	1.188	-0.598	5.970	0.918	1.184

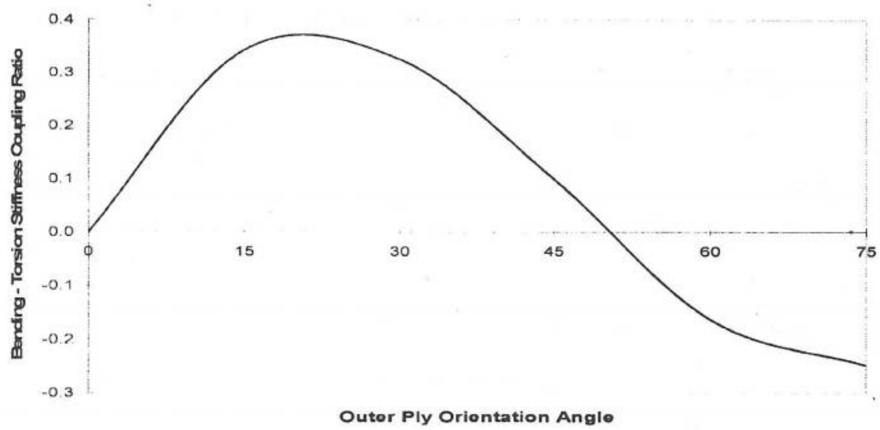

Figure 3: Variation of bending-torsion stiffness coupling ratio against outer ply orientation angle

3.5 Effects of Sweep Angle on Flutter Speed

Swept-back wing will provide a structural wash-out, whereas swept-forward wing will result in a structural wash-in. The former one will decrease the flutter boundary while the latter one will lower the divergence boundary. Uşing composite tailoring can achieve a harmonious compensation to recover, to some degree, the stability deficit caused by the wing sweep angle [6]. This tailoring effect is evident in the bending stiffness matrix of a laminate. As depicted in Ref. [3], this wash-in and wash-out condition in bending stiffness matrix can be illustrated as Figure 5. Based on Table 4, the laminate with $[45_2/0]$ is providing a tailored wash-in condition. The effect of sweep angle on flutter speed for five aspect ratios with varying ply orientation is presented in Figure 6. For [0/0/0], [15/0/15] and [30/0/30] stacking sequences the highest flutter speed will occur at 30 degree sweptforward plates. For [45/0/45] this trend is easily seen except for the aspect ratio of 3 where the highest flutter speed will occur at 15 degree forwardswept plate. This trend in flutter speed for [60/0/60] and [75/0/75] would not be maintained for 30 degree forwardswept plates as it is evident that there are a lot of variations in highest flutter speed. However, the constraint imposed by divergence speed also needs be considered, that is, for forwardswept wings before flutter the plate would have already diverged. For example, for aspect ratio of 3 with [0/0/0] stacking sequence and -30 sweep angle, the flutter speed is around 150 m/s while the divergence speed is 50 m/s. As stated earlier in this section using aeroelastic tailoring it is possible to increase the divergence boundary and create a trade-off between divergence and flutter. In this regard the aeroelastic tailoring seems to be effective to increase the divergence speed as compared to [0/0/0] baseline in all forwardswept configurations and also it has been noted that for aspect ratio of 3 with -15 degree sweep angle and [45/0/45] stacking sequence both the divergence and flutter have been suppressed at least in the speed range in which the analysis has been done. This should be also noted that for all other configurations (unswept and sweptback plates) the flutter will occur before the divergence and these considerations would not be applicable for them.

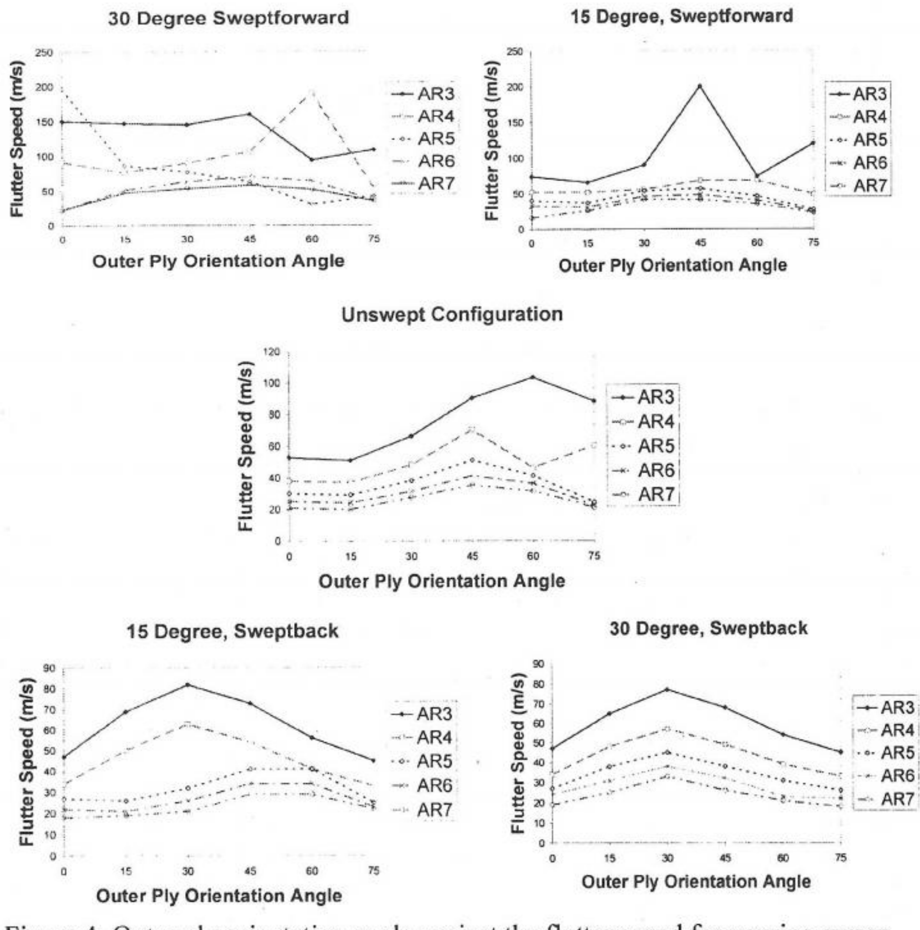

Figure 4: Outer ply orientation angle against the flutter speed for varying sweep angle

3.6 Effects of Aspect Ratio on Flutter Speed

The decrease in aspect ratio generally will result in increase in flutter speed. To visualize this statement the five aspect ratios with varying sweep angles and stacking sequences have been tested. This is illustrated in Figure 7. As it is seen the flutter increment due to the use of composites are usually significant and less sensitive with respect to aspect ratio values [6]. From the picture (Figure 7) it is also indicative that except for -30 sweep angle, the aforementioned statement is true and the flutter speed will decrease while increasing the aspect ratio.

$$D_{ij} \approx \begin{bmatrix} + & + & 0 \\ + & + & 0 \\ 0 & 0 & + \end{bmatrix} \qquad D_{ij} \approx \begin{bmatrix} + & + & + \\ + & + & + \\ + & + & + \end{bmatrix} \qquad D_{ij} \approx \begin{bmatrix} + & + & - \\ + & + & - \\ - & - & + \end{bmatrix}$$

Non-tailored Tailored (wash-in) Tailored (wash-out)

Figure 5: Wash-in and wash-out conditions in bending stiffness matrix

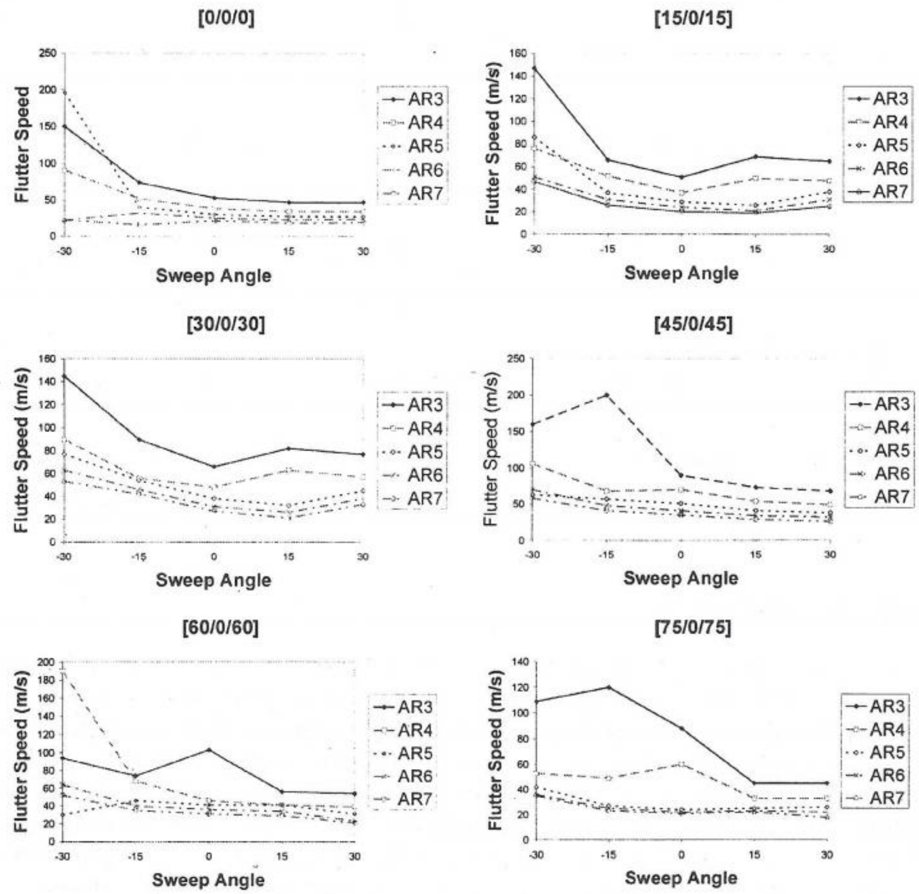

Figure 6: Sweep angle against the flutter speed for varying outer ply orientation

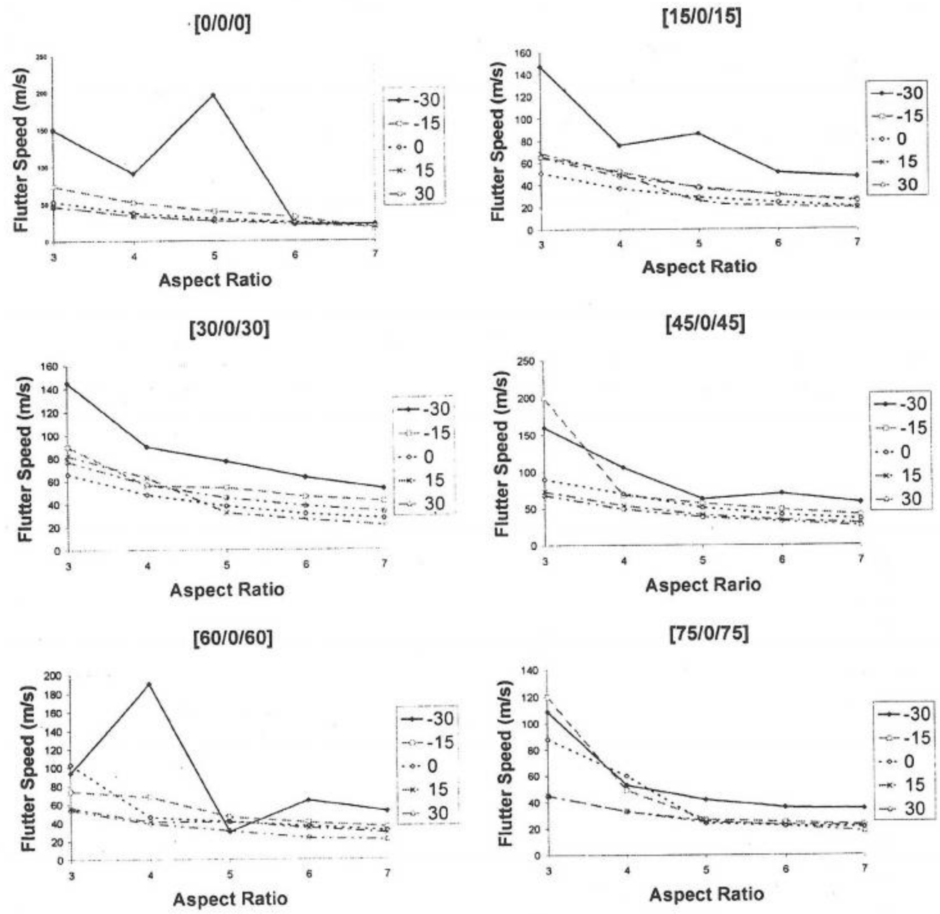

Figure 7: Aspect ratio against the flutter speed for varying outer ply orientation

4.0 CONCLUSION

The effects of ply orientation angle, sweep angle and aspect ratio have been studied on the flutter speed of a cantilevered laminated composites plate made of woven-fiberglass/epoxy, while considering the divergence speed as a constraint on forwardswept wings. The effect of ply orientation angle on flutter speed is investigated through the bending-torsion stiffness coupling ratio. It seems that the most effective angle which produces the best bending-torsion stiffness coupling is between 15 and 30 degrees. Moreover, the forwardswept plates have higher flutter speeds while the constraint imposed by divergence speed also should be considered as the divergence for forwardswept wings will occur first. All in all, using aeroelastic tailoring the increase in divergence boundary has been achieved as a compromise between flutter and divergence. In addition, lower aspect ratio will provide higher flutter speed, as such; all the configurations of the aspect ratio of 3 will provide higher flutter speed.

And finally the parametric studies on the effect of the aforementioned design variables on flutter speed shows that for aspect ratio of 3 with -15 degree sweep angle and [45/0/45] stacking sequence, the flutter and divergence seems to be eliminated due to aeroelastic tailoring at least in the speed range of our analysis.

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