UNIVERSITI PUTRA MALAYSIA

STRUCTURAL OPTIMIZATION OF AN AEROELASTICALLY TAILORED COMPOSITE WING

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

May 2007

To:

My beloved parents and sister

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

STRUCTURAL OPTIMIZATION OF AN AEROELASTICALLY TAILORED COMPOSITE WING

By

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May 2007

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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 modal approach 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. 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.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Master Sains

PENGOPTIMUMAN STRUKTUR BAGI KEAEROELASTIKAN SAYAP KOMPOSIT BERTENUN

Oleh

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Pengerusi: Profesor ShahNor Bin Basri, PhD

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Kesan daripada nisbah bidang, sudut sapuan, dan jujukan tindanan komposit berlapis telah dikaji untuk mencari kongfigurasi optimum bagi sayap komposit terunggul sebagai plat rata dalam sebutan halaju kibaran. Analisis keanjalan udara telah dijalankan dalam julat frekuensi pendekatan ragaman telah dihubungran dengan ”Doublet-Lattice Method” telah dipilih untuk struktur analisis aerodinamik tidak mantap. Interpolasi antara kotak aerodinamik dan nod struktur telah dilakukan menggunakan garisan permukaan. Untuk mengkaji kesan daripada turutan jujukan tindanan, teori pelapisan klasik (Classical Lamination Theory – CLT) telah dipilih. Kajian parameter menunjukkan keberkesanan sudut orientasi lapis berada diantara 15 dan 30 darjah manakala plat dengan nilai nisbah bidang rendah kelihatanyya mempunyai halaju kibaran yang lebih tinggi. Kongfigurasi sapuan kehadapan menunjukkan halaju kibaran lebih tinggi tetapi dikekang oleh kecapahan.

ACKNOWLEDGEMENTS

I would like to take this opportunity and thank my supervisory committee members, Prop. Dr. Ir. Shahnor B. Basri, Dr. Abdul Aziz Jaafar, and Dr.-Ing. Ir. Renuganth Varatharajoo for taking the time and effort to read my thesis and agreeing to serve on my committee. I express additional thanks to Mrs. Dayang Laila bt. Abang Haji Abdulmajid, the project leader, for supporting me throughout my graduate studies. I also would like to thank all the technicians and staff at Department of Aerospace, Faculty of Engineering to provide all the necessary equipment besides their friendly attitude. Finally I thank my family for standing by me during the time and supporting me in my efforts.

This work was supported by IRPA grant number 09-02-04-0899 EA001 from the Ministry of Science, Technology and Innovation, Malaysia.

I certify that an Examination Committee has met on 24th May 2007 to conduct the final examination of Abdolhamid Attaran on his Master of Science thesis entitled "Structural Optimization of an Aeroelastically Tailored Composite Wing" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

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DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

ABDOLHAMID ATTARAN

Date: 12 JULY 2007

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c	Damping Constant
[A]	Extensional Matrix
[B]	Coupling Matrix
[C]	Generalized Damping Matrix
$[C_s]$	Modal Added Damping
[D]	Bending Stiffness Matrix
$[G_{kg}]$	Interpolation Matrix
[K]	Discrete Stiffness Matrix
$[K_s]$	Generalized Stiffness Matrix
“$[K_s] - q[A_{hh}(ik)]$”	Aeroelastic Stiffness Matrix
$[M_s]$	Generalized Mass Matrix
[M]	Discrete Mass Matrix
$[u_g]$	Structural Grid Points
$[u_k]$	Aerodynamic Grid Points
{u}	Generalized Displacement Vector
$\{u_h\}$	Modal Coordinates
{x}	Structural Displacement Vector
$\{\boldsymbol{\Phi}\}$	Baseline Modes
$\{\varphi\}$	Eigenvector
A_{hh}	Generalized Aerodynamic Forces
b	Reference Semi-Chord
D	Flexural Rigidity
E_1	Longitudinal Elastic Modulus
E_2	Transverse Elastic Modulus
F	Frequency
$\{F_s\}$	Generalized Forces
{F(t)}	Force Vector In Discrete Coordinates
$F(\omega)$	Fourier Transform of the System Input
F_F	Flutter Frequency

g	Damping Coefficient
G_{12}	Major Shear Modulus
$H(\omega)$	Frequency Response Function
H_{pq}	Frequency Response Function between Points q and p (excited at p, measured at q)
H_{qp}	Frequency Response Function between Points q and p (excited at q, measured at p)
i	$\sqrt{-1}$
k	Stiffness Constant; Reduced Frequency
m	Mass Constants
M_x, M_y	Bending Moments per Unit Length
M_{xy}	Twisting Moment per Unit Length
N_x, N_y	Normal Forces per Unit Length
N_{xy}	Shear Forces per Unit Length
$P= k(\gamma+i)$	Complex Response Frequency and Eigenvalue
q	Dynamic Pressure
t_p	Laminate Ply Thickness
V	Selected Free-stream Speed
V_F	Flutter Speed
$X(\omega)$	Fourier Transform of the System Output
γ	Decay Rate Coefficient
$\boldsymbol{\varepsilon}$	Vector of Strain Components
θ	Ply Orientation Angle
Λ	Sweep Angle
λ	Eigenvalue
λ_1	Decay Rate (Complex Pole)
λ^*_1	Oscillatory Rate
μ	Dimensionless Aerodynamic Pressure
ν_{12}	Major Poisson’s Ratio
ν_{21}	Minor Poisson’s Ratio
ξ	Damping Factor
ρ	Free-stream Density

ρ_p	Laminate Density
σ	Damping Rate
$\boldsymbol{\sigma}$	Vector of Stress Components
ω_d	Damped Natural Frequency
ω_n	Natural Frequency
ω_i	Eigenfrequency

CHAPTER 1

INTRODUCTION

1.1 Aeroelastic Phenomena

Aeroelasticity is the term used to denote the field of study concerned with the interaction between the deformation of an elastic structure in an air stream and resulting aerodynamic force [1]. Aeroelasticity phenomena can be well illustrated by Collar's aeroelastic triangle (**Figure 1.1**). Generally, these phenomena can be divided in two main groups [2]:

1) Static Aeroelastic phenomena which lies outside of the Collar's triangle, created by Aerodynamic and Elastic forces.
2) Dynamic Aeroelastic phenomena within the triangle since they involve all three types of forces (Aerodynamics, Elastic, and Inertial forces).

Static aeroelastic phenomena can be sorted out as “Load Distribution”, “Divergence”, and “Control Surface Effectiveness/Reversal”, while dynamic aeroelastic phenomena can be classified as “Dynamic Response”, “Limit Cycle Oscillations (LCO)”, “Buffet”, “Flutter”.

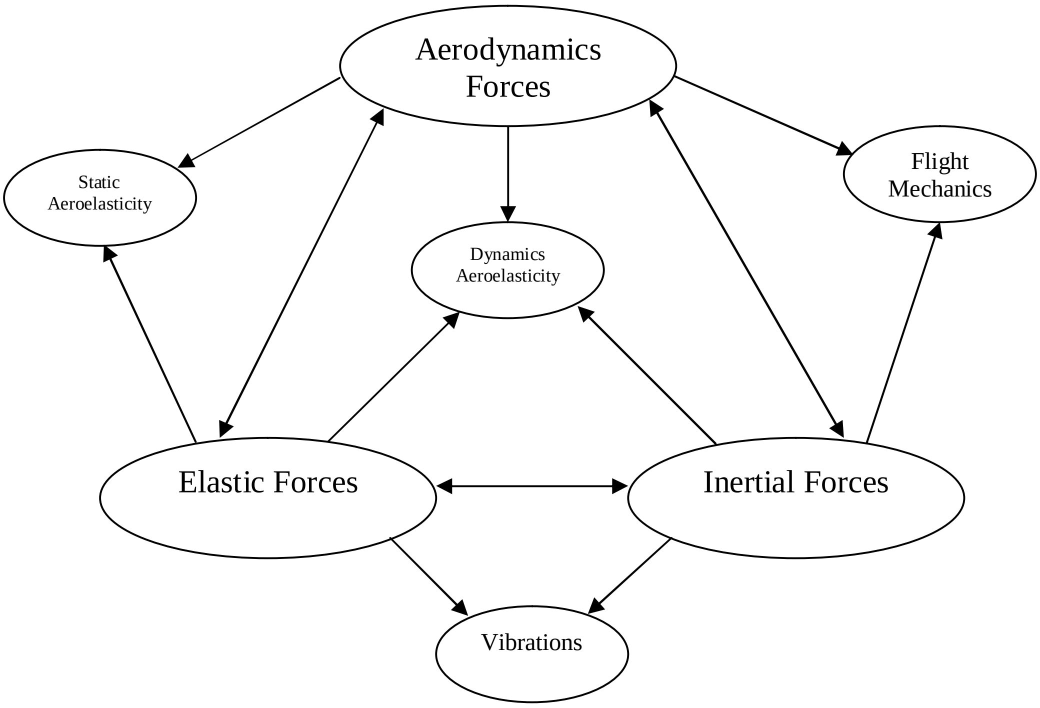

Figure 1.1: Collar's Triangle

1.2 Aeroelastic Flutter

The main focus in the present study would be on flutter, and divergence will be treated as a special case of flutter when the reduced frequency will become zero.

Flutter is a self-excited oscillation, often destructive, wherein energy is absorbed from the airstream [3]. This will produce a divergent response and it is usually resulting of coupling of two or more structural modes: wing bending and torsion, wing bending control surface hinge torsion, wing torsion fuselage bending, horizontal or vertical tail and fuselage.

When a lifting surface that is statistically stable below its flutter speed is disturbed, the oscillatory motions caused by those disturbances will die out in time with exponentially decreasing amplitudes. That is, one could say that the air is providing damping for all such motions. Above the flutter speed, however, rather than damping out the motions caused by small perturbations in the configurations, the air can be said to be providing negative damping. Thus, those oscillatory motions grow with exponentially increasing amplitudes [1].

Figure 1.2 demonstrates the three different cases of flutter when it is stable, neutral, and unstable.

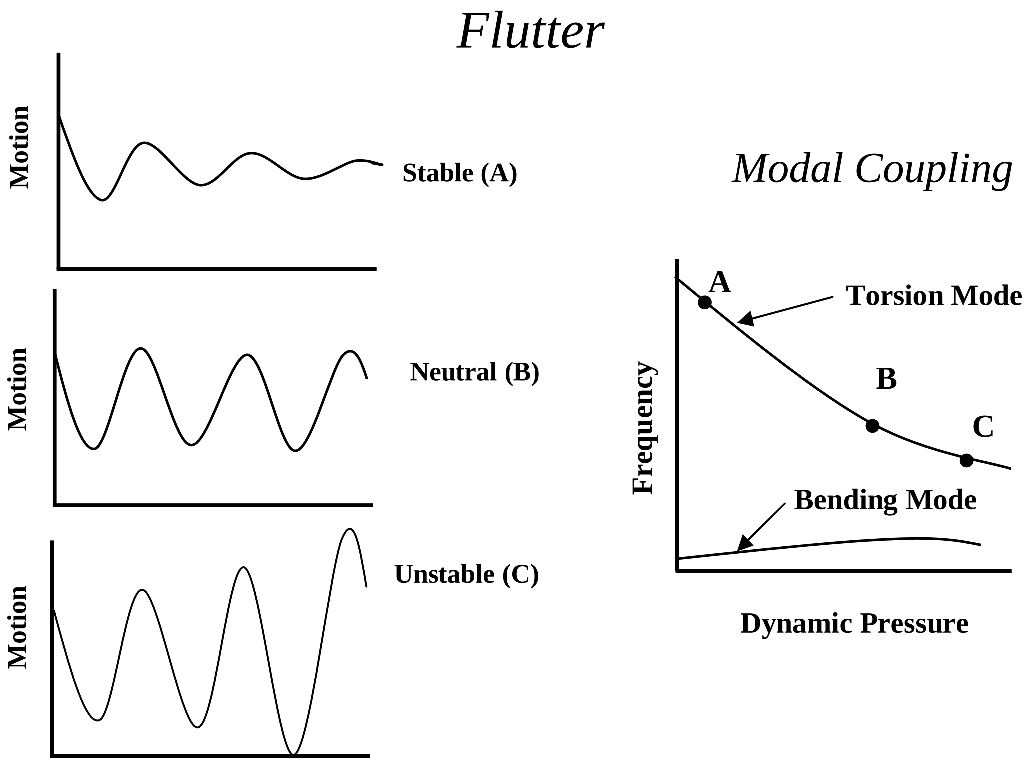

Figure 1.2: Different Cases of Flutter [4]

1.3 Aeroelastic Tailoring Concepts

The destructive nature of flutter has always put a constraint for structural designers to increase the flight envelope since the occurrence of flutter usually leads to structural failure and loss of the vehicle. Meanwhile, there are some methods to put off or even suppress such phenomena. Since aeroelasticity is a stiffness problem, one obvious way is to make the airframe more rigid through utilization of high modulus materials which consequently introduces unfavorable 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, structural designers have been seeking for alternative materials to replace the conventional metallic structures where high stiffness is required without increasing the weight. Therefore, they have come up with composite materials which possess all of these criteria. In 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 [5]. Not only do composites materials in general and laminated composites in particular offer weight advantage over conventional metal airframe constructions, but also they provide this opportunity to passively control the aeroelastic response of a lifting surface.

The technology to design for a desired aeroelastic response of a lifting surface using advanced filamentary composite materials has been named aeroelastic tailoring [6].

This is usually attainable by tailoring the fiber orientations of the composite laminates to the directions of highest loadings. In this respect, Shirk et al. [7] defined the aeroelastic tailoring as following: “Aeroelastic tailoring is the embodiment of directional stiffness into an aircraft structural design to control aeroelastic deformation, static or dynamic, in such a fashion as to affect the aerodynamic and structural performance of that aircraft in a beneficial way”.

1.4 Problem Statement

From the context of aeroelastic tailoring, it is noted that most of the works in this area have been centered on the use of uni-directional composites where there is a high level of anisotropy. However, woven composites have been rarely used in this field leaving a door open for further research and development. Following this direction the present work will investigate the tailoring effects of woven fiberglass/epoxy in plate like wings along some structural parameters i.e. aspect ratio and sweep angle.

1.5 Objective and Research Outline

Bearing in mind that the aeroelastic tailoring itself is an optimization process, the primary objective of the present work is to study the effect of structural parameters, i.e. ply orientation angle, sweep angle, and aspect ratio (as the design variables) on the flutter speed (as the objective function) of a laminated composite wing idealized as a flat plate. A simplified model is sufficient for the purpose of optimization at the preliminary design stage. Another objective is to experimentally verify the aeroelastic tailoring effect in the wind tunnel.

Unlike the conventional optimization problem, where reducing weight is the main objective, by integrating aeroelastic requirements into design process, minimum weight might not be the most important goal to achieve. As with the current work the maximization of flutter speed is sought through an aeroelastically tailored flat plat. The work flow of the current research is depicted in the following flow-chart.

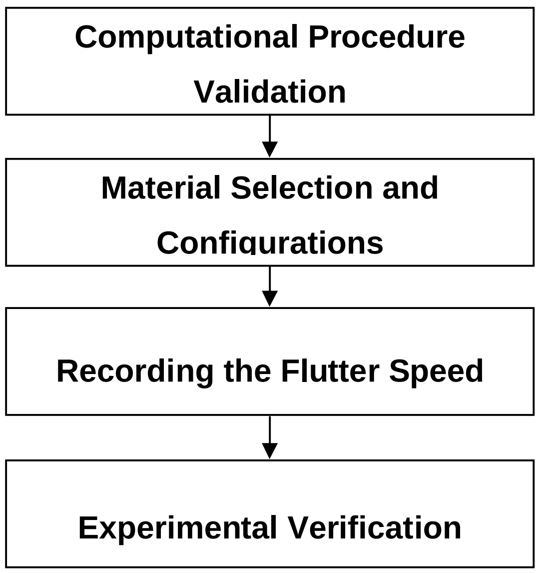

Figure 1.3: The Work Flow of the Current Research

1.6 Thesis Outline

This dissertation consists of six chapters. The first chapter provides an introduction to the present work. Chapter two covers an overview of the previous works in the areas of aeroelasticity and aeroelastic tailoring.