UNIVERSITI PUTRA MALAYSIA

AEROELASTIC TAILORING OF WOVEN CANTILEVERED GLASS-EPOXY PLATE-LIKE AIRCRAFT WING

DAYANG LAILA BT ABANG HAJI ABDUL MAJID

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in in Fulfilment of the Requirements for the Degree of Doctor Philosophy.

June 2008

To:

My family

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chairman: **Professor ShahNor Basri, PhD**

Faculty : **Faculty of Engineering**

The application of uni-directional composites in aeroelastic tailoring has long been established due to their highly directional properties. However, the use of woven, bi-directional textile composite in this area is practically nil due to their lower strength and stiffness, although this class of material is generally cheaper and more conforming. Therefore, the current work presents a new prospect for this type of material in the aeroelastic tailoring of aircraft wings.

The aeroelastic flutter and divergence behaviour of rectangular, woven glass/epoxy cantilevered plates with varying amount of bending and torsion stiffness coupling is investigated in subsonic flow. To do so, a range of tailored plate configurations with various stacking sequence having 6-plies thickness were considered. The ply orientation was varied from -45^0 to 45^0 to provide the widest range of negative and positive bend-twist coupling. Test plates without stiffness coupling were first constructed and subjected to static and dynamic testing in order to characterize the elastic and dynamic behaviour of the plate. Secondly, tailored configurations with varying stiffness coupling were fabricated and tested for flutter in wind tunnel tests. Numerical analyses were also conducted using MSc.Nastran structural analysis in conjunction with ZAERO's flutter program to verify the mechanical and dynamic properties as well as predict the occurrence of flutter and divergence.

Results from the extensive experimental and computational works had successfully shown that flutter speed can be optimized by tailoring the woven composite laminates. It was found that the torsional stiffness and bend-twist coupling play a major role in the aeroelastic behaviour of the woven laminate as compared to the bending stiffness. The bend-twist flutter that occurred was dominated by the torsion mode, thus explained the significant effect it has on the flutter speed. The numerical calculations predicted a 37% improvement whereas the experimental results are more understated at 29%. This improvement is remarkable considering that the configurations are symmetric. Both agreed well in terms of the optimized configuration that gave the maximum flutter speed. The flutter frequency and flutter mode shape was shown to be highly dependent on the coupled structural modes. In addition, divergence occurred when the plate-like wing is swept forward.

Abstrak tesis dikemukakan kepada Senat of Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

PENYESUAIAN AEROELASTIK UNTUK SAYAP KAPAL TERBANG MIRIP PLAT DARI KOMPOSIT KACA-EPOKSI BERTENUN

Oleh

DAYANG LAILA BT. ABANG HAJI ABDUL MAJID

June 2008

Pengerusi : **Professor ShahNor Basri, PhD**

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Aplikasi komposit searah dalam penyesuaian aeroelastik telah lama diketahui berdasarkan sifatnya yang amat terarah. Walau bagaimanapun, penggunaan komposit kain bertenun dwi-arah dalam bidang ini adalah tidak praktikal memandangkan kekuatan dan kekakuannya adalah lebih rendah walaupun ia adalah lebih murah dan senang dibentuk. Oleh itu, kajian berikut bertujuan untuk menghasilkan satu prospek baru untuk bahan ini dalam bidang penyesuaian aeroelastik sayap kapal terbang.

Perlakuan aeroelastik kibaran dan capahan untuk plat segi empat tepat kaca/epoksi tenun berjulur tuas dengan nilai kekakuan hasil gandingan lenturan dan kilasan yang berubah telah dikaji untuk aliran subsonik. Untuk melakukannya, julat konfigurasi-konfigurasi plat berketebalan 6 lapis yang diubahsuai dari segi jujukan tindanan telah dipertimbangkan. Orientasi lapisan telah diubah dari -45^0 to 45^0 agar julat terbesar gandingan lentur-kilas negatif ke positif boleh dihasilkan. Plat-plat ujikaji tanpa gandingan kekakuan telah di bina dan dikenakan ujian statik dan dinamik bagi

mencirikan perlakuan elastik dan dinamik plat tersebut. Kemudian, plat-plat terubah suai dari segi gandingan kekakuan di bina dan diuji untuk kibaran dalam ujian terowong angin. Kajian numerikal juga dijalankan menggunakan analisis struktur MSc.Nastran berserta program kibaran ZAERO untuk memastikan sifat mekanik dan dinamik serta meramal kejadian kibaran dan capahan.

Keputusan dari eksperimen dan komputasi telah berjaya menunjukkan penyesuaian aeroelastik sayap kapal terbang menggunakan komposit bertenun adalah tidak mustahil terutamanya untuk kapal terbang berhalaju rendah. Didapati kekakuan kilasan dan gandingan lentur-kilas lebih memainkan peranan utama dalam mencirikan perlakuan aeroelastik laminat bertenun jika dibandingkan dengan kekakuan lenturan. Kibaran lentur-kilas yang terjadi didominasi oleh mod kilas, sebab itu kesannya tinggi terhadap halaju kibaran. Kiraan numerikal meramalkan pembaikan 37% manakala keputusan eksperimen adalah lebih rendah pada 29%. Pembaikan ini adalah menakjubkan memandangkan konfigurasi telah dikekalkan simetri. Kedua-dua keputusan telah memberikan konfigurasi optimum yang sama yang akan menghasilkan halaju kibaran maksima. Frekuensi kibaran dan mod kibaran amat bergantung kepada mod-mod yang berganding. Selain itu, capahan berlaku apabila sayap mirip plat ini adalah sapu ke depan.

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I certify that an Examination Committee has met on **date of viva** to conduct the final examination of DAYANG LAILA BT ABANG HAJI ABDUL MAJID on her Doctor of Philosophy thesis entitled "AEROELASTIC TAILORING OF WOVEN CANTILEVERED GLASS/EPOXY PLATE-LIKE WING" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommended that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

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This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee are as follows:

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DECLARATION

I 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 and is not concurrently submitted for any other degree at UPM or at any other institution.

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DAYANG LAILA BT ABANG HJ ABD MAJID

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LIST OF ABBREVIATIONS

E_{11}	Longitudinal elastic modulus
E_{22}	Transverse elastic modulus
G_{12}	Major shear modulus
Cp	pressure coefficient
γ_{12}	Major Poisson's ratio
γ_{21}	Minor Poisson's ratio
ω	circular natural frequency
ω_f	flutter frequency
$\hat{\varphi}$	velocity potential
Φ	doublet singularity
λ	eigenvalues
λ_s	shift value
θ	fiber orientation
1,2,3	laminate coordinate system
x,y,z	global coordinate system
h_k	distance of ply *k* from centerline
b	chord width
k	reduced frequency
g	damping
t	time
a_∞	speed of sound

q_{∞}	freestream dynamic pressure
M_{∞}	freestream Mach number
U_f	flutter velocity
T_x, T_y, T_z	translational degree-of-freedom at x, y, z direction
R_x, R_y, R_z	rotational degree-of-freedom at x, y, z direction
$[A]$	Extensional matrix
$[B]$	Coupling matrix
$[D]$	Bending stiffness matrix
$[I]$	identity matrix
$[M]$	mass matrix
$[C]$	damping matrix
$[K]$	stiffness matrix
$[G]$	spline matrix
$\{N\}$	stress resultants
$\{M\}$	moment resultants
$[AIC(ik)]$	aerodynamic influence coefficient matrix
$[\psi]$	modal matrix
$\{\varepsilon^0\}$	centerline strains
$\{\kappa\}$	centerline curvatures
$\{\phi\}$	eigenvector or mode shape
$\{x(t)\}$	displacement vector

$\{\ddot{x}(t)\}$	acceleration vector
$\{h\}$	interpolated displacement vector at aerodynamic control point
$\{F(t)\}$	total aerodynamic force
$\{F_a(x)\}$	aerodynamic force induced by structural deformation
$\{F_e(t)\}$	external aerodynamic force
$\{\overline{q}\}$	generalized coordinates
$\{\overline{z}\}$	eigenvector of [T] matrix
$Q(ik)$	generalized aerodynamic force

CHAPTER 1

INTRODUCTION

1.1 Introduction

Aeroelastic instabilities are an important factor in the design of modern, flexible aircraft structures. At high speeds, these instabilities can exceed beyond the structural stiffness of the material resulting in structural failure. The current trend is toward the creative and innovative use of composite to delay these instabilities. On aircraft wings in particular, it will bend and twist due to the structure's interaction with the wing lift. Wing bending and twist will in turn change the local incidence of the wing and change the load distribution and stresses. The degree of load redistribution will depend on flight speed, altitude and sweep angle [1].

Two common types of aeroelastic effects that are widely researched into are flutter and divergence. At a critical speed called the divergence speed, the twisting motion may simply diverge and cause structural failure of the wing. This is a static instability. If there is coupling between the bending and twisting motion, then flutter occurs, which is a sustained harmonic oscillation. Both will render the aircraft unstable and may result in catastrophic failure. Other types of aeroelastic instabilities include buffeting and dynamic response, which are dynamic in nature while static instabilities are such as control effectiveness and aileron reversal.