



UNIVERSITI PUTRA MALAYSIA

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

DAYANG LAILA BT ABANG HAJI ABDUL MAJID

FK 2008 56

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

By

DAYANG LAILA BT. ABANG HAJI ABDUL MAJID

**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

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

By

DAYANG LAILA BT. ABANG HAJI ABDUL MAJID

June 2008

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-ply thickness were considered. The ply orientation was varied from -45° to 45° 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**

Fakulti : **Fakulti Kejuruteraan**

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 kibraran 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° to 45° 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 tersebut diubah suai dari segi gandingan kekakuan di bina dan diuji untuk kibarannya dalam ujian terowong angin. Kajian numerikal juga dijalankan menggunakan analisis struktur MSc.Nastran berserta program kibarannya ZAERO untuk memastikan sifat mekanik dan dinamik serta meramal kejadian kibarannya dan capahannya.

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. Kibarannya lentur-kilas yang terjadi didominasi oleh mod kilas, sebab itu kesannya tinggi terhadap halaju kibarannya. Kiraannya 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 kibarannya maksima. Frekuensi kibarannya dan mod kibarannya amat bergantung kepada mod-mod yang bergandingan. Selain itu, capahannya berlaku apabila sayap mirip plat ini adalah sapu ke depan.

ACKNOWLEDGEMENTS

Bismillahirrahmannirrahhim. Alhamdulillah, praise to Allah s.w.t. on the completion of this thesis.

First, I would like to express my gratitude for the wonderful support and guidance given by Prof. Ir. Dr. ShahNor Basri, my main supervisor. Also thank you to my co-supervisors, Dr. Mohamed Saleem and Dr. Prasetyo Edi. To my wonderful colleagues, guys, you are the best people I have the pleasure of working with.

Secondly, to my hubby, Hazidi Baharum, my children, family and close friends, this achievement would not have been possible without your love and constant encouragement. I love you all very much. The past three years have indeed been filled with lots of happy and sad moments, wonderful triumphs and failures. InsyaAllah, I hope all these will make me a better person.



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:

Chairman 1, PhD

Professor,
Faculty of Graduate Studies
Universiti Putra Malaysia
(Chairman)

Examiner 1, PhD,

Professor,
Faculty of Graduate Studies
Universiti Putra Malaysia
(Internal Examiner)

Examiner 2, PhD,

Professor,
Faculty of Graduate Studies
Universiti Putra Malaysia
(Internal Examiner)

Independent Examiner, PhD,

Professor,
Faculty of Graduate Studies
Universiti Putra Malaysia
(Independent Examiner)

HASANAH MOHD GHAZALI, PhD

Professor/Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia
Date:



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:

ShahNor Basri, PhD

Professor,
Faculty of Graduate Studies
Universiti Putra Malaysia
(Chairman)

Co-Supervisor, PhD,

Professor,
Faculty of Graduate Studies
Universiti Putra Malaysia
(Member)

Co-Supervisor, PhD,

Professor,
Faculty of Graduate Studies
Universiti Putra Malaysia
(Member)

AINI IDERIS, PhD

Professor/Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:



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.

DAYANG LAILA BT ABANG HJ ABD MAJID

Date:



TABLE OF CONTENTS

	Page
DEDICATION	ii
ABSTRACT	iii
ABSTRAK	v
ACKNOWLEDGEMENTS	vii
APPROVAL SHEETS	viii
DECLARATION FORM	x
LIST OF TABLES	xiv
LIST OF FIGURES	xvi
LIST OF ABBREVIATIONS	xxi
CHAPTER	
1. INTRODUCTION	1
1.1. Introduction	1
1.2. Aeroelastic tailoring	3
1.3. Tailoring of textile composites	5
1.4. Objective of research	6
1.5. Thesis outline	7
2. LITERATURE REVIEW	8
2.1. Recent development in composite technology	8
2.2. Background on textile composites	12
2.2.1. Woven fabrics	14
2.2.2. Analysis and modeling of two-dimensional fabric composites	15
2.3. Aeroelastic tailoring trend studies	17
2.4. Thin plate postflutter behaviour	30
2.5. Closure	31
3. THEORY	33
3.1. The mechanics of composite laminate	33
3.1.1 The Classical Laminated Plate Theory	34
3.2. Static analysis	40
3.3. Modal analysis	44
3.4. Aeroelastic analysis	45
3.4.1. Aeroelastic equation of motion	46
3.4.2. Unsteady aerodynamics	48
3.4.3. Flutter equation of motion	50
3.5. Closure	51



4. MATERIAL CHARACTERIZATION OF FABRIC LAMINATES	52
4.1. Textile composite structure	53
4.2. Woven laminate fabrication	56
4.2.1. Hand lay-up	57
4.3. Characterization of laminate properties	59
4.3.1. Tensile test	60
4.3.2. Static test	62
4.3.3. Modal test	64
4.4. Test results	66
4.4.1. Tensile results – determination of elastic properties	66
4.4.2. Static test results	74
4.4.3. Natural modes	80
4.5. Closure	84
5. EXPERIMENTAL SETUP	85
5.1. Test material	85
5.2. Flutter experiment set-up	88
5.2.1. UPM subsonic wind tunnel	89
5.2.2. Side-wall mount test rig	89
5.2.3. Test sample preparation	91
5.2.4. Data acquisition system	92
5.3. Wind tunnel air speed calibration	94
5.4. Wind tunnel flutter test procedure	95
5.5. Flutter results for baseline configurations	97
5.6. Limitation of experiment	103
5.7. Closure	103
6. COMPUTATIONAL ANALYSIS	105
6.1. Wing structural model	106
6.2. Modal analysis	107
6.2.1. The Lanczos solution algorithm	109
6.2.2. The Lanczos solution procedure	111
6.3. Flutter analysis	114
6.3.1. Spline matrix	115
6.3.2. Flutter solution	115
6.4. Numerical validation	120
6.4.1. Flutter validation of cantilevered aluminium plate	120
6.4.2. Flutter validation of CWR200 laminated plate	122
6.5. Closure	124
7. RESULTS AND DISCUSSION	125
7.1. Effects of ply orientation on composite stiffness	125



7.1.1. Tailored laminates	126
7.1.2. Single orientation laminates	131
7.1.3. Untailored laminates with varying sweep angles	134
7.2. Effects of ply orientation on normal modes	135
7.2.1. Tailored laminates	136
7.2.1.1 Natural frequencies	136
7.2.1.2 Structural mode shapes	139
7.2.2. Single orientation laminates	156
7.2.2.1 Natural frequencies	156
7.2.2.2 Structural mode shapes	158
7.2.3. Untailored laminates with varying sweep angles	161
7.2.3.1 Natural frequencies	161
7.2.3.2 Structural mode shapes	163
7.3. Flutter results and analysis	166
7.3.1 Flutter results of tailored laminates	167
7.3.2 Flutter results of single orientation laminates	174
7.3.3 Flutter results of swept laminates	176
7.3.4 Flutter mode shapes	177
7.3.4.1 Tailored laminates	178
7.3.4.2 Single orientation laminates	183
7.3.4.3 Untailored laminates with varying sweep angles	184
7.3.5 Discussion on the optimization of flutter in the present work	184
7.4. Closure	193
8. CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK	194
8.1 Conclusion	194
8.2 Recommendations for future work	197
REFERENCES	199
APPENDICES	205
BIODATA OF STUDENT	244



LIST OF TABLES

Table		Page
2.1	Application potential of textile reinforced composite materials for Aircraft structures	13
3.1	Illustrations of the coupling terms A_{16} , B_{16} , B_{11} , B_{12} , B_{66} for composite	37
4.1	CWR600 and CWR200 Specifications	57
4.2	Items required for hand lay-up process	58
4.3	Tensile test parameters	61
4.4	List of items required for static test	62
4.5	Al 6061 properties	64
4.6	Equipment used in modal testing	65
4.7	Results for specimens with 0^0 plies aligned to the direction of loading	69
4.8	Results for specimens with 90^0 plies aligned to the direction of loading	70
4.9	Results for specimens with 45^0 plies aligned to the direction of loading	70
4.10	Results for specimens with 0^0 plies aligned to the direction of loading	72
4.11	Results for specimens with 90^0 plies aligned to the direction of loading	72
4.12	Results for specimens with 45^0 plies aligned to the direction of loading	72
4.13	Elastic properties of CWR laminates	73
4.14	Comparison of static test results from theory and experiment for Al 6061	76
4.15	Comparison of static test results from theory and experiment for CWR600 laminate	76
4.16	Comparison of static test results from theory and experiment for CWR200 laminate	77
4.17	Comparisons of first five natural frequencies for Al 6061	81
4.18	Comparison of first five modes for CWR600	83



4.19	Comparison of first five modes for CWR200	83
5.1	Laminate layups with varying ply orientations at zero sweep	87
5.2	Laminate configurations with varying sweep angles	88
5.3	Flutter results for Al 6061	99
5.4	Flutter results for CWR200 laminates	101
5.5	Flutter results for CWR600 laminates	101
6.1	Comparison of methods of real eigenvalue extraction	108
6.2	Flutter comparison for Al 6061	121
6.3	Flutter comparison for CWR200 laminate	123
7.1	Stiffness values for case 1 to case 8 configurations	128
7.2	Stiffness values for single orientation laminate configurations	131
7.3	Comparison of stiffness with the order of the ply in the laminate	133
7.4	Stiffness values for swept laminate configurations	134
7.5	Type of mode shapes for the first five modes	140
7.6	Summary of flutter results for case 1 to 4	169
7.7	Summary of flutter results for case 5 to 8	170
7.8	Summary of flutter results for single orientation laminates	175
7.9	Summary of flutter results for swept laminates	177
7.10	Values of $V_f(\alpha)$ and $f_v(\alpha)$ for experiment and numerical	191



LIST OF FIGURES

Figure		Page
3.1	Unidirectional material and laminate coordinate system	34
3.2	Coupled deflection shapes	39
3.3	Sign conventions used for beam analysis	41
3.4	Cantilevered flat plate configuration	45
3.5	An idealized wing	46
3.6	Aeroelastic feedback diagram	47
4.1	Flow chart of research methodology	52
4.2	Schematic illustration of the hierarchy of fibres, yarns and fabrics in textile processes	54
4.3	Comparison of basic fabric structures	54
4.4	Common weaves in composite materials	55
4.5	Actual structure of CWR200 woven cloth	57
4.6	Lay-up sequence of woven composite laminate	58
4.7	CWR200 and CWR600 laminates after hand lay-up process	59
4.8	Instron Universal Tensile Machine	60
4.9	Sample set-up to the universal tester	61
4.10	Static test set-up	63
4.11	Impact testing	65
4.12	Typical load-displacement curve for CWR200 glass/epoxy laminate	67
4.13	Stress-strain curve with 0 degree aligned to the direction of loading	68
4.14	Lateral versus axial strain for sample no.: a) 1; b) 2; c) 3; d) 4; e) 5; f) 6; g) 7 and h) 8	68

4.15	Typical load-displacement curve for CWR600 glass/epoxy laminate	71
4.16	Bending strain vs load for Al 6061	77
4.17	Tip deflection vs load for Al 6061	78
4.18	Bending strain vs load for CWR600 laminate	78
4.19	Tip deflection vs load for CWR600 laminate	79
4.20	Bending strain vs load for CWR200 laminate	79
4.21	Tip deflection vs load for CWR200 laminate	80
4.22	Sample of FRF for CWR600	82
4.23	Sample of FRF for CWR200	82
5.1	Plate layout and direction of fibre orientation	86
5.2	Side-wall mount for flutter test sample	90
5.3	The side-wall mount attached to one side of the wind tunnel	91
5.4	Test sample instrumented with strain gage	92
5.5	The complete data acquisition set-up	93
5.6	Calibration test results: wind tunnel air speed versus motor rpm	95
5.7	The flutter wind tunnel testing setup	96
5.8	Laminate test sample mounted to the side-wall of wind tunnel	97
5.9	Time history plot for Al 6061	98
5.10	Time history plot at flutter onset for Al 6061	98
5.11	Typical time history plot for CWR laminates	100
5.12	Time history at flutter onset for CWR200 laminate	100
5.13	Time history at flutter onset for CWR600 laminate	101
6.1	Laminate definition conventions	106
6.2	Structural finite element model	107



6.3	Outer level of the Lanczos procedure	112
6.4	Inner level of the Lanczos procedure	113
6.5	ZAERO Main Program Flow Chart	118
6.6	g-method Flutter Solution Flow Chart	119
6.7	Damping vs velocity for Al 6061	121
6.8	Frequency vs velocity for Al 6061	121
6.9	Damping vs velocity for CWR200 laminate	123
6.10	Frequency vs velocity for CWR200 laminate	123
7.1	E_{11} variations with outer ply orientation for a) case 1 to case 4 and b) case 5 to case 8	129
7.2	GJ variations with outer ply orientation for a) case 1 to case 4 and b) case 5 to case 8	129
7.3	D_{16} variations with outer ply orientation for a) case 1 to case 4 and b) case 5 to case 8	130
7.4	D_{16} variations with outer ply orientation from -45^0 to 45^0	130
7.5	E_{11} variations with outer ply orientation for single orientation laminates	132
7.6	GJ variations with outer ply orientation for single orientation laminates	132
7.7	D_{16} variations with outer ply orientation for single orientation laminates	133
7.8	E_{11} variations with outer ply orientation for swept configurations	135
7.9	GJ variations with outer ply orientation for swept configurations	135
7.10	Variations of natural frequencies of a) mode 1; b) mode 2; c) mode 3; d) mode 4 and e) mode 5	137
7.11	Structural mode shapes for case 1	140
7.12	Structural mode shapes for case 2	142
7.13	Structural mode shapes for case 3	144



7.14	Structural mode shapes for case 4	146
7.15	Structural mode shapes for case 5	148
7.16	Structural mode shapes for case 6	150
7.17	Structural mode shapes for case 7	152
7.18	Structural mode shapes for case 8	154
7.19	Variations of natural frequencies of a) mode 1; b) mode 2; c) mode 3; d) mode 4 and e) mode 5	157
7.20	Structural mode shapes for single orientation laminates	158
7.21	Variations of natural frequencies of a) mode 1; b) mode 2; c) mode 3; d) mode 4 and e) mode 5	162
7.22	Structural mode shapes for swept laminates	163
7.23	Flutter speed versus outer ply angle for a) case 1; b) case 5; c) case 2; d) case 6; e) case 3; f) case 7; g) case 4 and h) case 8	171
7.24	Flutter frequency versus outer ply angle for a) case 1; b) case 5; c) case 2; d) case 6; e) case 3; f) case 7; g) case 4 and h) case 8	172
7.25	Flutter speeds of single orientation laminates	175
7.26	Flutter frequencies of single orientation laminates	176
7.27	Flutter mode shapes for case 1	179
7.28	Flutter mode shapes for case 2	179
7.29	Flutter mode shapes for case 3	180
7.30	Flutter mode shapes for case 4	180
7.31	Flutter mode shapes for case 5	181
7.32	Flutter mode shapes for case 6	181
7.33	Flutter mode shapes for case 7	182
7.34	Flutter mode shapes for case 8	182
7.35	Flutter mode shapes for single orientation laminates	183



7.36	Flutter mode shapes for swept laminates	184
7.37	Stiffness (Nm^2) and flutter speed (m/s) variations with outer ply orientation for case 1 to 4	188
7.38	Stiffness (Nm^2) and flutter speed (m/s) variations with outer ply orientation for case 5 to 8	190
7.39	Stiffness (Nm^2) and flutter speed (m/s) variations with single orientation laminates	190



LIST OF ABBREVIATIONS

E_{11}	Longitudinal elastic modulus
E_{22}	Transverse elastic modulus
G_{12}	Major shear modulus
C_p	pressure coefficient
γ_{12}	Major Poisson's ratio
γ_{21}	Minor Poisson's ratio
ω	circular natural frequency
ω_f	flutter frequency
$\hat{\phi}$	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

$\{\ddot{\mathbf{x}}(t)\}$	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
$\{\bar{q}\}$	generalized coordinates
$\{\bar{z}\}$	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.

