STRUCTURAL DESIGN IMPROVEMENT OF UNMANNED AERIAL VEHICLE WING

GUNASEGARAN A/L KANESAN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Mechanical)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

FEBRUARY 2014

Specially dedicated to

My beloved family

My supportive friends…

ACKNOWLEDGEMENTS

Though only my name appears on the cover of this thesis, a great many people have contributed to its production. I owe my gratitude to all those people who have made this thesis possible and because of whom my graduate experience has been one that I will cherish forever. My deepest gratitude is to my advisors, Assoc. Prof. Ainullotfi Abdul Latif and Assoc. Prof. Ir. Dr. Shuhaimi Mansor for their guidance and support throughout my studies. They have given me the freedom to explore on my own and support when my steps faltered. Their insightful comments and constructive criticisms at different stages of my research were thought-provoking and they helped me focus on my ideas.

I would like express my gratitude to Unmanned System Technology (UST) for providing me with necessary information and technical details to complete this research. Besides that, they also have provided me all the required elements to conduct the experiment. The engineers, especially Mr. Muhammad Riza Abd Rahman and Mr. Mohd Izhar Harun have been a huge help throughout this research.

Many friends have helped me throughout my study years. Their support and care helped me overcome setbacks and stay focused on my graduate study. I greatly value their friendship and I deeply appreciate their belief in me. I am also indebted to the fellow researchers from aeronautical laboratory and automotive laboratory with whom I have interacted during the course of my graduate studies. Furthermore, I would like thank technicians from aeronautical laboratory for providing me with help whenever necessary.

Most importantly, none of this would have been possible without the love and patience of my family. My family, to whom this thesis is dedicated to, has been a constant source of love, encouragement, concern, support and strength all these years. I would like to express my heart-felt gratitude to my family.

ABSTRACT

Almost all engineering systems experience strength versus weight conflict of some description. In the case of airplane wing, there are two primary requirements which must be considered during the structural design process: high strength and stiffness, and lower weight. Due to the restricted nature of technology in this field, very few design guidelines are available for design improvement of an airplane wing structure to increase its strength-to-weight ratio. The objective of this thesis is to provide guidelines for the improvement of the structural design of a composite unmanned aerial vehicle (UAV) wing with respect to weight, strength and bending stiffness, with Aludra MK-01 as a case study. The finite element method was used for the numerical analysis on the structure. Popular commercial finite element software, ABAQUS CAE, was used to model the wing structure. A detailed modelling technique for composite structure and the attachment between structures was presented in this thesis. The wing finite element model was validated using experimental results. The design improvement process on the wing structures was conducted in several modes. The variables used in the process were spar web length, spar shape and spar thicknesses. UAV wing structural weight, bending stiffness and failure index were used as the main criteria in the design improvement process. The variation of these criteria with changesin selected parameters were then plotted to observe the design trends. At the end of the research, the improved web lengths and thicknesses were obtained, as also the best combination of shapes for the spars. During the design improvement process, the failure index was found to be most sensitive towards the changes in the variable parameters compared to structural weight and bending stiffness. The design improvement guidelines presented in this thesis should facilitate the design and analysis of future UAV composite wing structures.

ABSTRAK

Hampir semua sistem kejuruteraan menghadapi konflik di antara kekuatan dengan berat. Dalam kes sayap kapal terbang, dua keperluan utama yang perlu dipertimbangkan semasa proses reka bentuk struktur adalah kekuatan dan kekakuan yang tinggi serta berat yang lebih rendah. Oleh kerana teknologi yang terhad dalam bidang ini, terdapat sangat sedikit panduan reka bentuk yang boleh diperolehi bagi meningkatkan nisbah kekuatan-terhadap-berat struktur. Objektif tesis ini ialah untuk menyediakan garis panduan untuk penambahbaikan reka bentuk struktur sayap komposit pesawat udara tanpa juruterbang (UAV), berkenaan dengan berat struktur, kekuatan dan kekakuan lenturan, menggunakan Aludra MK-01 sebagai kajian kes. Kaedah unsur terhingga telah digunakan untuk analisis berangka ke atas struktur. Perisian unsur terhingga komersial popular,ABAQUS CAE, digunakan untuk memodel struktur sayap. Satu teknik pemodelan terperinci untuk struktur komposit dan sambungan di antara struktur telah dibentangkan dalam tesis ini. Model unsur terhingga sayap telah disahkan menggunakan keputusan eksperimen. Proses penambahbaikan reka bentuk struktur sayap telah dijalankan dalam beberapa mod. Pemboleh ubah yang digunakan dalam proses ini adalah panjang web spar, bentuk spar dan ketebalan spar. Berat struktur sayap UAV, kekakuan lenturan dan indeks kegagalan telah digunakan sebagai kriteria utama dalam proses penambahbaikan reka bentuk. Perubahan kriteria tersebut terhadap perubahan parameter pembolehubah kemudiannya diplot untuk melihat trend reka bentuk. Di akhir kajian, panjang web dan ketebalan spar yang ditambahbaik telah diperolehi, begitu juga gabungan terbaik untuk bentuk spar. Semasa proses penambahbaikan, indeks kegagalan didapati paling sensitif terhadap perubahan parameter bolehubah berbanding dengan berat struktur dan kekakuan lenturan. Garis panduan penambahbaikan reka bentuk yang dibentangkan dalam tesis ini diharapkan dapat memudahkan reka bentuk dan analisis struktur komposit UAV di masa depan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

SYMBOL		DESCRIPTION	UNITS
b	-	Span length	m
$[B]$	-	Strain-displacement matrix	
c	-	Chord length	m
C_L	-	Coefficient of lift	
E	-	Elastic constants	Pa
E_b	-	Bending modulus	
ε ?	-	Normal strain	
g	-	Gravitational acceleration, 9.81	ms^{-2}
$Ix\ Iy\ Iz$	-	Moment of inertia about x, y and z axis	$kg \cdot m^2$
$Ixy\ Iyz\ Ix$	-	Moment of inertia about xy, yz and xz axis	$kg \cdot m^2$
k	-	Curvature	m^{-1}
$[K]$	-	Element stiffness matrix	
M	-	Applied moments	Nm
n	-	Load factor	

N	-	Axial load	N
$[N]$	-	Matrix of shape vector	
Q	-	Stiffness coefficient	
z	-	Distance from centre line	m
σ	-	Normal stress	Pa
τ	-	Shear stress	Pa
ν	-	Poisson ratio	ms^{-2}
γ	-	Shear strain	

LIST OF ABBREVIATIONS

BCAR	-	British Civil Airworthiness Requirement
CAA	-	Civil Aviation Authority
CAD	-	Computer Aided Design
CAE	-	Computer Aided Engineering
CLPT	-	Classical Laminated Plate Theory
DLM	-	Doublet Lattice Method
FAA	-	Federal Aviation Administration
FAR	-	Federal Aviation Regulation
FE	-	Finite Element
FEA	-	Finite Element Analysis
FEM	-	Finite Element Method
FPF	-	First Ply Failure
FSDT	-	First Order Shear Deformation Theory
HALE	-	High Altitude Long Endurance
ICAO	-	International Civil Aviation Organization

INBD	-	Inboard
JAR	-	Joint Aviation Requirements
MALE	-	Medium Altitude Long Endurance
MDO	-	Multi-disciplinary Optimization
NACA	-	National Advisory Committee for Aeronautics
NSGA	-	Non-dominated Sorting Generic Algorithm
OUTBD	-	Outboard
UAV	-	Unmanned Aerial Vehicle

LIST OF APPENDIX

CHAPTER 1

INTRODUCTION

1.1 An introduction to UAVs and composite structures

Unmanned Aerial Vehicle (UAV) is a pilotless aircraft controlled by a ground unit from a control room. The research and development in UAVs started back in early years during the First World War, but serious interest in their value as operational force multiplier has only awakened in the last quarter of the past century. One of main reasons leading towards UAV's interest is the possibility to utilize relatively non-expensive airplanes when the human presence on board is not necessary or when the mission involves long operational time and severe risks [1].

Composite materials are the materials consist of two or more separate phases with multidirectional properties. The greatest advantage of composite materials is their higher strength and stiffness combined with low weight compared to other isotropic or unidirectional materials [2]. The advancement in the structures and materials especially the introduction of composite materials used for UAV construction are one of the great factor contributing to continuous development of UAV industry.

1.2 Background of the problem

Almost all engineering systems experience strength versus weight conflict of some description. There are two primary functional requirements must be considered during the design process of an aircraft wing [3]. The first requirement is high strength and stiffness. The lift created by the pressure difference used to carry the airplane and it will be acting upon the airplane wing. The lift translates into stresses on the wings [3]. The wing must be designed to sustain the stresses created during the flight.

The second requirement is the lesser weight for wing structure. The airplane with light weight structure creates more room for payload. The cost in terms of fuel is reduced since lesser fuel is needed to operate light weight aircraft. The major problem in airplane structural design is to strike the balance between these two requirements [3]. The designer’s attempt to achieve adequate structural strength and minimum material utilization with minimum cost is a major challenge in aircraft structural design.

In aircraft design, lesser weight comes second to sufficient strength. The balancing between the strength and weight of an airplane can be represented by strength-to-weight ratio. Higher value for strength-to-weight ratio can be achieved by using composite materials. However, the design still needs to be improved in order for the strength-to-weight ratio to be optimized.

1.3 Problem statement

There is a growing demand for UAVs around the globe [4]. Due to its restricted nature of technology, very few design methodology and technological details are available [4]. There is a need for a guideline for composite UAV structural design and analysis process. Information on the dependency of weight, strength and stiffness with different types of structures and their configuration is required to enlighten further and future design processes.

In order to obtain the guidelines for design and analysis, a structural model is required as the case study. In this study, Aludra MK-01 was used as the case study. Aludra MK-01 is an unmanned aerial vehicle fully designed and developed in Malaysia. It was developed by Unmanned Systems Technology (UST) Sdn. Bhd. It is currently being used by Malaysian Armed Forces in Semporna (Sabah, Malaysia). Aludra MK-01 has been in use for reconnaissance purposes along the Malaysia-Indonesia and Malaysia-Philippines borders.

The design process of Aludra MK-01 is iterative. Since its first design and development, it had been modified several times to improve its strength-to-weight ratio. The wing of the UAV especially, has been consistently modified to achieve the improved strength-to-weight ratio. The iterative design process was conducted mostly according to the experience of the designers and engineers, but there are no definitive design guidelines available for the process. Developing a design guideline which can act as the methodology for this iterative design process of Aludra MK-01 is essential to improve the work quality in terms of time consumption and to ease the future design process.

Figure 1.1 Aludra MK01

1.4 Research objective

The objective of the research was to provide guidelines for the improvement of the structural design of a composite UAV wing with respect to weight, strength and bending stiffness, with Aludra MK-01 as a case study.

1.5 Research scope

Several scopes were set in order to achieve the research objective. The scopes are:

i. A study on structural design and configuration of a current UAV was conducted and the structure of Aludra MK-01 wing was used as a case study for this research.
ii. A validated finite element structural model of the current UAV wing was developed and validated by using experimental results.
iii. A thorough re-designing process was conducted on the current design and the new designs were subjected to finite element analysis.
iv. The trends and changing patterns of weight, strength and bending stiffness with respect to varied spar parameters were obtained and can be used for the design improvement of other similar UAV's.

1.6 Thesis outline

The thesis of this research is divided into 6 chapters. Chapter 1 outlines the introduction on the research, overview to the research problem, problem statements, objective, scopes and outline if the thesis.

Chapter 2 discusses the literature review of this research. It starts with the compilation on previous researches conducted on wing design and optimization. It was followed by requirements and considerations for UAV structural design. Wing optimization methodologies were discussed in the following section. The discussion on composite materials and the mechanics of composite material were also added in this chapter. In addition to that, the discussion on finite element modelling and analysis were given in the following section.

Chapter 3 focuses on a brief explanation of the methodology employed in this research. It was further illustrated in a flow chart with short explanations. In Chapter 4, the work conducted related to this research were presented. It includes the work on modelling, experimental work and design improvement process.

Chapter 5 presents the results obtained in this research. The results for validation process and design improvement process were presented in this chapter. The conclusion and recommendations were presented in Chapter 6.

REFERENCES

[1] Accardo, A.F., Ricci, F., Basso, P. Design and Development of a Low Altitude Unmanned Aerial Vehicle. *22nd International Congress of Aeronautical Sciences ICAS.* 2000. Harrogate, UK.

[2] Yong-Bin, P., Khanh-Hung, N., Jin-Hwe, K., Jin-Ho, C., 2011. Structural Analysis of a Composite Target-drone. *International Journal of Aeronautical & Space Science*. 2011. vol. (12): 84-91.

[3] Peirson, B. The Use of Lightweight Composites in Satisfying the Unique Structural Requirements of Aircraft Design. 2005. Grand Valley State University.

[4] Mazhar, F., Khan, A.M. Structural Design of a UAV Wing Using Finite Element Method. *51st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*. 2010. Orlando, Florida. AIAA-2010-3099.

[5] Goraj, Z., Frydrychewicz, A., Switkiewicz, R., Hernik, B., Gadomski, J., Goetzendorf-Grabowski, Figat, M., St Suchodolski, Chajec, W. High altitude long endurance unmanned aerial vehicle of a new generation–a design challenge for a low cost, reliable and high performance aircraft. *Bulletin of Polish Academy of Sciences, Technical Sciences*. 2004. vol.(52).

[6] Gadomski, J., Hernik, B., and Goraj, Z. Analysis and optimisation of a MALE UAV loaded structure. *Aircraft Engineering & Aerospace Technology*. 2006. vol. (78/2): 120-131.

[7] Tischler, V. A., Venkayya, V. B., and Bharatram, G. Design optimization of airframe structures. *Journal of Aerospace Engineering*. 1997. Vol. (10/3): 111-118.

[8] Lee, M. K., Cho, C. M., and Jang, S. Y. HALE UAV Composite Wing Structure Design. *Advanced Materials Research*. 2010. Vol. (123): 105-108.

[9] Chase, N. Optimization of Laminated Composite Aircraft Structure. *Red Cedar Technology*. 2011. AB-2034, rev. 9.11,

[10] Jin, P., Song, B., and Zhong, X. Structure Optimization of Large Composite Wing Box with Parallel Genetic Algorithm. *Journal of Aircraft*. 2011. Vol. (48/6): 2145-2148.

[11] Rajagopal, S. and Ganguli, R. Multidisciplinary Design Optimization of Long Endurance Unmanned Aerial Vehicle Wing. *Computer Modeling in Engineering & Science (CMES).*2011. Vol.(81/1): 1-34.

[12] Neubauer, M., Günther, G., and Füllhas, K. Structural Design Aspects and Criteria for Military UAV. *European Aeronautic Defence And Space (Eads) Munich (Germany).* 2007

[13] Federal Aviation Regulations. *Federal Aviation Administration*. 1990. Washington, DC, 1.

[14] Kundu, A. J. *Aircraft Design*. 1st ed. Cambridge University Press, United States of America. 2010

[15] Cruz, J. R., and Drela, M. Structural design consideration and load determination for human-powered aircraft. *21st Organisation Scientifique et Technique du Vol à Voile Conference*, 1989 Wiener Neustald, Austria.

[16] Barlow, D. A., Scott, M. L., and Clayton, G. A new approach to design optimization of aircraft box structure configurations using finite element methods. *33rd International SAMPE Technical Conference*. 2001. Seattle, Washington. vol. (33): 222-233.

[17] Rispler, A., and Raju, J. Optimization of an Aircraft Control Surface. In *ANSYS Conference.* 2001.

[18] Krog, L., Tucker, A., and Rollema, G. Application of topology, sizing and shape optimization methods to optimal design of aircraft components. *In Proc. 3rd Altair UK HyperWorks Users Conference.* 2002

[19] Krog, L., Tucker, A., Kemp, M., and Boyd, R. Topology optimization of aircraft wing box ribs. *In Proc. of the 10th AIAA/ISSMO MAO Conference,* 2004. Albany.

[20] Brecher, C., Klein, W., and Seiler, M. Parametric Optimization of Structural Components Considering Geometrical Restrictions, *IV European Congress of Computational Mechanics (ECCM).* 2010. Paris.

[21] Raju, J., Rispler, A., and Qi, B. Case study of an aircraft spoiler, *33rd International SAMPE Technical Conference*. 5-8 November 2001, Seattle, Washington.

[22] Rajbhandari, S. P., and Scott, M. L. (2001). Optimum design of fiber reinforced aircraft control surface by finite element methods, *33rd International SAMPE Technical Conference*. 5-8 November 2001, Seattle, Washington.

[23] Altenbach, H., Altenbach, J. W., and Kissing, W. *Mechanics of composite structural elements*, 1st ed. Springer-Verlag. Berlin,Germany. 2004.

[24] Datoo, M. H. *Mechanics of fibrous composites*. 1st ed. Elsevier Science Publishers Ltd, London, UK. 1991.

[25] Kaw, A. K. *Mechanics of composite materials*, 2nd ed. CRC Press, Taylor & Francis Group, Florida. 2006.

[26] Kassapoglou, C. *Design and Analysis of Composite Structures: With Applications to Aerospace Structures*, 1st ed. John Wiley & Sons Inc, New York. 2011.

[27] Cinemáticos, C., Barschke, M., Uribe, D., Ruiz, O. E., Jensen, J., and López, C. Finite Element Modeling of Composite Materials using Kinematic Constraints. *Ingeniería y Ciencia*, 2009. vol. (5/10): 133-153.

[28] Daniel, I. M., and Ishai, O. *Engineering mechanics of composite materials*, Vol 3. Oxford University Press, New York. 1994.

[29] Kollár, L. P., and Springer, G. S. *Mechanics of composite structures*, Cambridge University Press, UK. 2003.

[30] Baker, A. A. A., Dutton, S., Kelly, D., and Kelly, D. W. *Composite materials for aircraft structures*. AIAA. 2004

[31] Hibbeler, R. C. and Fan, S. C. *Mechanics of Materials*, 7th ed. Prentice Hall, Jurong, Singapore. 2008.

[32] Rand, O., Rovenski, V., and Rovenskii, V. Y. *Analytical methods in anisotropic elasticity: with symbolic computational tools*, Springer, Boston. 2005.

[33] Hashemi, S., Kinloch, A. J., and Williams, J. G. Mechanics and mechanisms of delamination in a poly (ether sulphone)—fibre composite. *Composites Science and Technology*, 1990. Vol. (37/4): 429-462

[34] Becker, A.A. and Baker, R.C. *An introductory guide to finite element analysis*. Professional Engineering, London. 2004.

[35] Szabó, B., and Babuška, I. Introduction *to Finite Element Analysis: Formulation, Verification and Validation*, Wiley Publication, West Sussex, UK. 2011.

[36] Weck, O. D. and Kim I. Y. *Finite Element Method. Engineering Design and Rapid Prototyping*, Massachusetts Institute of Technology. 2005.

[37] Hughes, T. J. R. *The finite element method: linear static and dynamic finite element analysis*. DoverPublications.com. 2012.

[38] Ochoa, O. O., and Reddy, J. N. *Finite element analysis of composite laminates*, Vol 7. Springer Publication. 1992.

[39] Reddy, J. N. *Energy and variational methods in applied mechanics*, Wiley Publication, New York. 1984.

[40] Reddy, J. N. *An introduction to the finite element method*, 2nd ed. McGraw Hill Publication, New York. 1993.

[41] Ostergaard, M. G., Ibbotson, A. R., Le Roux, O., and Prior, A. M. Virtual testing of aircraft structures. *CEAS Aeronautical Journal*. 2011. vol. (1): 83-103.

[42] Dassault System. *ABAQUS Analysis User's Manual Version 6.9EF-1*, Vèlizy-Villacoublay, France.

[43] Peery, D. J. and Azar, J. J. *Aircraft structures*, 2nd ed. McGraw Hill College. 1982.

[44] Nurhaniza, M., Arifin, M.K.A., Ali, A., Mustapha, F., Noraini, A.W. Finite element analysis of composites materials for aerospace applications. *In IOP Conference Series: Materials Science and Engineering.* 2010. vol. (11)

[45] Autio, M., Parviainen, H., Pramila, A. Accuracy of the finite element method in analyzing laminated plate and pipe structures. *Mechanics of composite materials*. 1992. Vol. (28/3): 236-245.

[46] Buehrle, R. D., Fleming, G. A., Pappa, R. S., and Grosveld, F. W. Finite element model development and validation for aircraft fuselage structures. *In Proceedings of the 18th International Modal Analysis Conference*. 2000. San Antonio, Texas.

[47] Cardozo, S. D., Awruch, A. M., and Gomes, H. M. Optimization of laminated composite plates and shells using genetic algorithms, neural networks and finite elements. *Latin American Journal of Solids and Structures*. 2011 vol. (8): 413-427.

[48] Fung, Y.C., An Introduction to the Theory of Aeroelasticity, Dover Publications Inc, New York, 1993.