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IMPACT OF AEROELASTIC TAILORING ON FLUTTER PERFORMANCE OF VARIABLE RIBS' ORIENTATION FOR DIFFERENT WING BOX MODEL PLANFORMS

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By

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For over the past decades, the basic layout of the wing-box configuration was found relatively similar and has not been drastically changed. Nevertheless, with recent advancement in additive manufacturing technology, a much complex structural design can now be manufactured with an efficiency that cannot be acquired by the conventional manufacturing process. From the conducted literature reviews, the variable ribs' orientation concept turns out to be one of the possible options whereby several previous studies have shown that significant improvement in aeroelastic characteristics can be acquired without any increment in weight. Nevertheless, the previous works were limited to an equally ribs spacing as well as for a certain type of wing-box planforms. Hence, the current effort is to provide a much wider overview on this concept by considering a various type of wing-box planforms including the case of increasing rib's spacing. Three variants of wing-box planforms were considered in the current work, namely untapered-unswept, untapered-sweptback, and tapered-sweptback configurations. In addition, an equal and increasing rib's spacing arrangement for a total of 10 and 13 ribs were also taken into account. A programming routine was developed and integrated with the finite element solver, hence allowing the parametric study to be conducted in a much systematically manner. Finite element solutions of flutter analysis and normal mode analysis have been employed, with the flutter speed parameter serves as a sole cost function for the parametric investigation. Further insight was also made with respect to the variation in modal characteristics as well as the distribution in strain energy. The finding shows that the variable ribs' orientation concept enables significant impact to any modes that incorporate with torsional characteristic, regardless of whether it is dominant or subdominant in torsional shape. As a result, the frequency gap between the flutter modes can be altered hence enables the possibility to further delay the flutter speed. Significant improvement in flutter speed was acquired within a range of 91%-93% for

untapered-unswept cases, 78%-92% for untapered-sweptback cases and 56%-78% for tapered-sweptback cases when compared to their respective baseline wing-box planforms. In addition, it was also found that for all the considered cases, the optimal rib's orientations were characterized by a zigzag profile.

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

KESAN PENYESUAIAN AEROKEKENYALAN TERHADAP PRESTASI KIBARAN BAGI ORIENTASI RUSUK BOLEH UBAH UNTUK PELBAGAI PLANFORM MODEL KOTAK SAYAP

Oleh

CHAN YING NEE

Mei 2021

Pengerusi : Prof.Madya Mohammad Yazdi Harmin, PhD
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Selama lebih beberapa dekad yang lalu, susun atur asas konfigurasi kotak sayap adalah serupa dan tidak berubah secara drastik. Walaubagaimanapun, dengan kemajuan terkini dalam teknologi pembuatan aditif, rekabentuk struktur yang lebih kompleks kini dapat dihasilkan dengan kecekapan yang tidak dapat diperolehi melalui proses pembuatan konvensional. Daripada tinjauan literatur yang dilakukan, konsep orientasi rusuk boleh ubah menjadi salah satu pilihan yang mungkin di mana sebilangan kajian sebelumnya telah menunjukkan peningkatan yang ketara dalam ciri aerokekenyalan dapat diperolehi tanpa peningkatan dalam berat. Walaubagaimanapun, kajian tersebut terbatas bagi jarak rusuk yang sama dan juga bagi bentuk pelan sayap-kotak tertentu. Oleh itu, usaha semasa adalah untuk mendapatkan gambaran yang lebih meluas mengenai konsep ini dengan mempertimbangkan pelbagai jenis bentuk pelan kotak sayap dan juga bagi kes peningkatan jarak rusuk. Tiga varian bentuk pelan kotak sayap telah dipertimbangkan, iaitu konfigurasi “tidak tirus-tidak terentang”, “tidak tirus-terentang ke belakang”, dan “tirus-terentang ke belakang”. Selain itu susunan jarak rusuk yang sama dan meningkat bagi sejumlah 10 dan 13 rusuk juga diambil kira. Rutin pengaturcaraan dibangunkan dan disepadukan dengan penyelesaian unsur terhingga bagi membolehkan kajian dijalankan secara sistematik. Penyelesaian elemen terhingga iaitu analisis kibaran dan mod normal digunakan dengan parameter halaju kibaran berfungsi sebagai fungsi kos tunggal untuk penyiasatan parametrik. Perincian lebih lanjut juga dibuat berkenaan perubahan pada ciri-ciri modal dan taburan tenaga terikan. Hasil kajian menunjukkan bahawa konsep orientasi rusuk boleh ubah memungkinkan kesan yang signifikan bagi sebarang mod yang mempunyai ciri kilasan, tidak kira sama ada ia dominan atau subdominan dalam bentuk kilasan. Kesan daripada ini, jurang frekuensi antara mod kibaran dapat diubah dan memungkinkan untuk menundakan lagi kelajuan kibaran. Peningkatan yang ketara dalam kelajuan kibaran diperolehi dalam julat 91% -93% untuk kes “tidak tirus-tidak terentang”, 78% -92% untuk kes “tidak tirus-

terentang ke belakang” dan 56% -78% untuk kes “tirus-terentang ke belakang” apabila dibandingkan dengan konfigurasi dasar masing-masing. Di samping itu, didapati bagi semua kes yang dipertimbangkan, orientasi rusuk yang optimum dicirikan oleh profil zigzag.

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I certify that a Thesis Examination Committee has met on (date of viva voce) to conduct the final examination of Chan Ying Nee on his thesis entitled “Impact of Aeroelastic Tailoring on Flutter Performance of Variable Ribs’ Orientation for Different Wing Box Model Planforms” in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the degree of Master of Science.

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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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LIST OF ABBREVIATIONS

$[AIC_I]$	Imaginary Part of Aerodynamic Influence Coefficient
$[AIC_R]$	Real Part of Aerodynamic Influence Coefficient
BDF	Bulk Data File
b	Half of Chord
C_r	Root Chord
C_t	Tip Chord
DLM	Doublet Lattice Method
FE	Finite Element
FGM	Functionally Graded Material
f	Frequency
$[K]$	Stiffness Matrix
k	Reduced Frequency
$[M]$	Mass Matrix
NASA	National Aeronautics and Space Administration
P	Eigenvector of the System
$[u]$	Generalized Coordinate
V	Velocity
Λ	Sweep Angle
λ	Eigenvalue of the System
ζ	Damping Ratio
$\{\emptyset\}$	Eigenvector or Mode Shape
θ_r	Rib Orientation Angle
ρ	Density
ω	Natural Frequency

CHAPTER 1

INTRODUCTION

1.1 Background

Since the first flying machine by the Wright brothers back in 1902, the wing design has been evolving significantly whereby advancement in aerodynamic shape, and material technology play an important role in idealizing nowadays design of the wing. Conventionally, the internal structures of an aircraft wing are mainly consisting of spars, ribs and stingers as shown in Figure 1.1 with the wing-box is represented by the structural center between the leading and trailing spars and basically it is almost similar for all the types of aircraft.

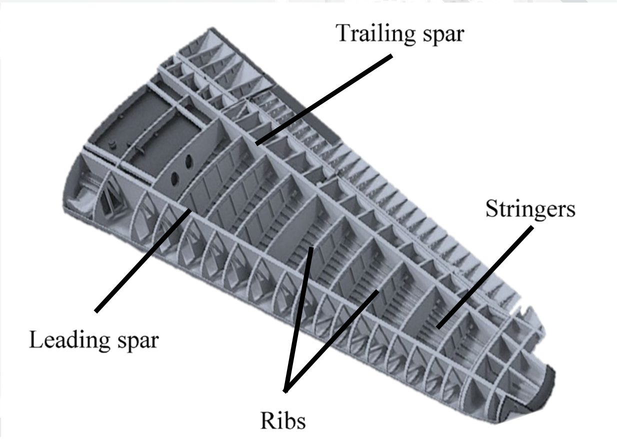

Figure 1.1: Internal wing structure and wing box [1]

The key function of the wing box is to provide sufficient strength to the wing in order to withstand both static and dynamic aeroelastic conditions during the flight. With regards to static aeroelastic condition, the deflection of the wing occurs as a result of lift force that are generated over the wing due to the pressure difference between the top and bottom surfaces as the airflow passing over it. This force leads to the deflection of the wing in terms of bending and twisting displacement. On the other hand, for the dynamic aeroelastic condition, it is mainly due to the bending and torsional modes of an aeroelastic system including their interaction and coupling characteristics. These static and dynamic aeroelastic conditions could respectively lead into a divergence and flutter instabilities which are among the three most common aeroelastic phenomena instead of reversal instability.

In most of the cases, the flutter instability occurs earlier than any other types of aeroelastic instability [2] and it is considered as one the critical flight conditions when deriving the safety envelope of the aircraft. Besides, the flight flutter testing is part of the certification process that is mandatory to be conducted in order to ensure the design is free from the flutter instability [3]. Hence, there are much research effort that seeking possible solution to further delay the flutter instability which is one of the driven notions in aircraft design.

Considerable research effort has been devoted to modifying the internal structures of wing-box configuration in order to improve the performance of the wing as well as to seek possibility in weight reduction. Moreover, with recent introduction of disruptive technologies such as additive manufacturing of metal structure, provide the way for complex wing-box designs to be manufactured without significant impact in weight and cost. Hence this permits a number of innovation efforts to be performed in venturing a new concept of wing box model such as; curvilinear rib, spar and stringer [4, 5]; material and thickness grading on spar and rib [6, 7, 8]; and variable ribs' orientation [2, 9]. From these studies, the findings show that significant improvement in flutter speed could be acquired due to the alteration of bending-torsional modes characteristic offered by the innovative wing-box design. Hence, this allows the flutter instability to be further delayed as well as offering possible reduction in weight.

1.2 Problem Statement

Previous studies [2, 5, 9, 10, 11, 12] have shown that the variable ribs' orientation concept turns out to be one of the possible solutions for an innovative topology wing-box design, whereby significant improvement in flutter speed can be acquired without any weight penalty. Nevertheless, the studies were limited to an equally ribs spacing as well as for certain types of wing-box planforms. Hence, the current work is a continuation from the previous work [11] with the effort to seek further understanding on this concept. Three baseline wing box planforms of (1) untapered and unswept wing (2) untapered and sweptback wing (3) tapered and sweptback were considered, including an equal and increasing rib's spacing arrangement cases. These parametric variables were considered in order to allow a much wider overview on this concept to be drawn with respect to flutter and modal characteristics. It should be noted that, the selected wing-box planforms were following the notion of other innovative wing-box design studies such as in untapered-sweptback model [9, 13] and tapered-sweptback configuration of NASA common research model [14, 15].

1.3 Aim and Objectives

The primary aim of the study is to enable a much wider investigation on the effect of variable ribs' orientation with respect to flutter performance. Three wing-box planforms were considered namely (1) untapered and unswept wing (2) untapered and sweptback wing (3) tapered and sweptback. In addition, effects of number of ribs and ribs spacing were also considered in this work. This aim is idealized via the following objectives:

1. To conduct a parametric study of three different wing-box planform designs by varying the number of ribs, rib's spacing and the orientation angle of the selected single rib
2. To evaluate and compare the flutter and modal characteristics of the various considered wing-box planform designs

1.4 Research Questions

1. How to deal with the parametric study that have a number of parametric cases efficiently? (Objective 1)
2. What types of finite element analysis that need to be employed for the investigation of the study? (Objective 1)
3. What are the effects of variable ribs orientation with respect to its modal properties? (Objective 2)
4. What are the optimal ribs' configuration for all the considered wing planforms and cases? (Objective 2)
5. What are the effects of variable ribs orientation with respect to its flutter instability? (Objective 2)

1.5 Scope of Work and Limitation

Numerous parametric studies had been conducted by other researchers for flutter improvement on various type of wing-box planform for innovative topology wing-box design, such as untapered-sweptback model [9, 13], tapered-sweptback configuration of NASA common research model [14, 15], and other wing configuration [16]. Hence, following this trend, three baseline wing box planforms of (1) untapered and unswept wing (2) untapered and sweptback wing (3) tapered and sweptback are considered in this work. All the considered baseline wing-box planforms were referred and projected from the wind tunnel wing model of unswept rectangular straight wing developed by previous research [2]. The maximum sweep angle of 35° and taper ratio of 0.23 were referring to the wing-box parameter of the NASA Common Research Model [17], which is a representative of a widebody commercial transport aircraft.

This study was limited to the low subsonic region where the compressibility effect and nonlinearity of flow are not considered. The aeroelastic model is formed by the linear structure which coupled to a two-dimensional computed aerodynamic panel of doublet lattice method. The method is an extension of the steady Vortex-Lattice method to unsteady flow [18]. In general, the free stream speed varies from 5m/s to 100m/s whereby the flutter speed was expected to occur between this range. Since the analysis was conducted at the sea level condition only, hence the Mach number and Reynolds number will be depending on the variation of the free stream speed.

The overall weight was made constant for all the parametric wing-box configurations by altering the thickness of the rib. The study only highlighted on the investigation of varying ribs' orientation with respect to flutter instability since the divergence instability occurs later than flutter in all cases as stated from the previous study [2]. It should be noted as well that the buckling effect are not accounted in this study.

1.6 Arrangement of Thesis

Chapter 1 provides general overview of the conventional configuration and current research progress on internal wing structure which lead into the derivation of the problem statement, objectives, research questions including scope of work and limitation.

Chapter 2 encompasses the literature review that are related to the proposed study on the variable ribs' orientation concept. An underlying principle of structural dynamics and aeroelasticity was also covered in this chapter.

Chapter 3 provides description on the parametric consideration of variable ribs' orientation concept including the simulation's procedure of normal mode and flutter analyses.

Chapter 4 presents the results. for all the parametric consideration of variable ribs' orientation concept. An assessment was made with respect to their modal properties and flutter performance.

Chapter 5 concludes the important findings of the study including recommendation for future work

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