GEOMETRICAL NONLINEAR STATIC AEROELASTIC ANALYSIS OF HIGH ASPECT RATIO WING BASED ON FLUID STRUCTURE INTERACTION

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MASTER OF SCIENCE

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ABSTRACT

In recent years, the utilization of High Aspect Ratio (HAR) wings, particularly in High Altitude Long Endurance (HALE) applications, has significantly increased. HAR wings play a crucial role in reducing induced drag and enhancing fuel efficiency. However, HAR wings exhibit complex geometrical nonlinear behaviour, posing challenges for optimal aircraft design. Traditionally, researchers have explored methods to analyze geometrical nonlinearities through Fluid Structure Interaction (FSI) analysis. However, most works have predominantly focused on low aspect ratio wings, neglecting the complexities associated with HAR wings. Consequently, a critical research gap exists in understanding the unique challenges posed by HAR wings in the context of FSI analysis. This study addresses this gap by evaluating the effectiveness of FSI approaches in the context of HAR wings using ANSYS software with three different domain sizes (100 % size domain, reducing 20 % domain size and reducing 40 % domain size). The results from the analysis were then validated with the experimental result. The finding showed that domain size (reduced by 20 %) was slightly near to the experimental result with maximum percentage difference of 12.28 % at effective angle of attack, AoA 1° using one-way FSI. In terms of FSI competency approach, one-way FSI analysis exhibits maximum percentage difference of 12.28 % at AoA 1°. Meanwhile, two-way FSI analysis closely approximates experimental data, exhibiting a maximum percentage error of 3.61 %. Based on this analysis, a two-way FSI analysis was employed to investigate the aerodynamic performance of the HAR wing. The analysis of the HAR wing aerodynamic performance included evaluating lift coefficient, drag coefficient and lift-to-drag (L/D) ratios. The lift coefficients for aspect ratios AR-12, AR-14 and AR-16 were determined to be 0.6591, 0.744 and 0.799

respectively. Conversely, the drag coefficients showed values of 0.384, 0.3581 and 0.334 for the similar aspect ratios. Meanwhile, the L/D ratios exhibited an increasing trend, measuring 1.734, 2.08 and 2.391 respectively. Hence, these results highlighted that the HAR wing with aspect ratio AR-16 demonstrates higher aerodynamic performance compared to both AR-14 and AR-12 configurations. This finding underscores the potential of optimizing the HAR wing design to enhance fuel efficiency in practical applications as well as to improve the aircraft performance.

ABSTRAK

Kebelakangan ini, penggunaan sayap bernisbah tinggi (HAR), terutamanya dalam aplikasi *High Altitude Long Endurance* (HALE), telah meningkat dengan ketara. Sayap HAR memainkan peranan penting dalam mengurangkan daya seret yang diinduksi dan meningkatkan kecekapan bahan api. Walau bagaimanapun, sayap HAR menunjukkan tingkah laku ketidaklinearan geometri yang kompleks, meningkatkan cabaran dalam reka bentuk pesawat. Secara tradisional, para penyelidik telah menerokai kaedah untuk menganalisis ketidaklinearan geometri melalui analisis interaksi berstruktur bendalir (FSI). Walau bagaimanapun, kebanyakan kajian lebih tertumpu kepada sayap bernisbah rendah dan mengabaikan kompleksiti sayap HAR. Oleh itu, terdapat jurang kajian dalam memahami cabaran yang dibawa oleh sayap HAR dalam konteks analisis menggunakan FSI. Kajian ini bertujuan untuk memenuhi jurang kajian dengan menilai keberkesanan pendekatan FSI dalam konteks sayap HAR menggunakan perisian ANSYS dengan tiga (3) pilihan saiz domain yang berbeza. Pilihan pertama dengan 100 % saiz domain, pilihan kedua dengan pengurangan sebanyak 20 % daripada pilihan pertama dan pilihan ketiga dengan pengurangan sebanyak 40 % daripada pilihan pertama. Keputusan daripada analisis hasilnya dibandingkan dengan hasil eksperimen. Dapatan menunjukkan bahawa pilihan kedua saiz domain (dikurangkan sebanyak 20 %) hampir mendekati hasil eksperimen dengan perbezaan peratus maksimum sebanyak 12.28 % pada sudut serangan berkesan, AoA 1° menggunakan FSI satu hala. Dari segi kecekapan pendekatan FSI, analisis FSI satu hala menunjukkan peratus perbezaan maksimum sebanyak 12.28 % pada AoA 1°. Sementara itu, analisis FSI dua hala menhampiri data eksperimen, dengan peratus perbezaan maksimum sebanyak 3.61 % pada AoA 1°. Walau bagaimanapun, analisis FSI dua hala memerlukan masa pengiraan yang lebih banyak, dengan peningkatan

sebanyak 40 % berbanding analisis FSI satu hala. Berdasarkan analisis ini, FSI dua hala digunakan untuk menyelidik prestasi aerodinamik sayap HAR. Walaupun lebih memakan masa sebanyak 40% berbanding FSI satu hala, pendekatan ini dipilih kerana model sayap yang tidak rumit dan tidak memerlukan masa pengiraan yang banyak. Analisis prestasi aerodinamik sayap HAR termasuk *lift coefficient*, *drag coefficient* dan *lift-to-drag (L/D) ratio* memberikan penemuan penting. Nilai *lift coefficient*, untuk nisbah aspek AR-12, AR-14 dan AR-16 adalah sebanyak 0.6591, 0.744 dan 0.799. Sebaliknya, nilai untuk *drag coefficient* menunjukkan nilai 0.384, 0.3581 dan 0.334 untuk nisbah aspek yang sama. Di samping itu, *lift-to-drag (L/D) ratio* menunjukkan trend peningkatan dengan nilai 1.734, 2.08 dan 2.391. Hasil kajian mendedahkan bahawa sayap HAR iaitu AR-16 mempunyai prestasi aerodinamik yang lebih tinggi berbanding AR-14 dan AR-12. Oleh itu, hasil kajian ini akan menyumbang secara ketara dalam membangunkan reka bentuk sayap HAR dengan penggunaan bahan api yang efektif.

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APPROVAL

The Examination Committee has met on **15 March 2024** to conduct the final examination of **Ainaa Nabilah binti Mohd Nazri** on her degree thesis entitled **'Geometrical Nonlinear Static Aeroelastic Analysis of High Aspect Ratio Wing based on Fluid Structure Interaction'.**

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LIST OF ABBREVIATIONS

AR	-	Aspect Ratio
AV	-	AeroVironment
CCD	-	Charge Couple Device
CFD	-	Computational Fluid Dynamic
ERAST	-	Environmental Research Aircraft and Sensor Technology
FEA	-	Finite Element Analysis
FSI	-	Fluid Structure Interaction
HALE	-	High-Altitude Long Endurance
HAPS	-	High-Altitude Pseudo Satellite
HAR	-	High Aspect Ratio
HP	-	Helios Prototype
ISR	-	Intelligence, Surveillance and Reconnaissance
L/D	-	Lift-to-Drag Ratio
LAR	-	Low Aspect Ratio
MAR	-	Medium Aspect Ratio
PMRF	-	Pacific Missile Range Facility
RANS	-	Reynolds-Averaged Navier-Stokes
SAR	-	Search and Rescue
SMC	-	Standard Mean Chord
SPT	-	Stereo Pattern Tracking
TSFC	-	Thrust Specific Fuel Consumption
UAV	-	Unmanned Aerial Vehicle
UPNM	-	Universiti Pertahanan Nasional Malaysia
US	-	United State
UVLM	-	Unsteady Vortex-Lattice Model
VMD	-	Videogrammetric Model Deformation

LIST OF SYMBOLS

α_{eff}	-	Effective angle of attacks
α_i	-	Induced angle of attacks
A	-	Wing area
b	-	Wing span
c	-	Wing chord
C_D	-	Drag coefficient
C_{Di}	-	Induced drag coefficient
C_{DO}	-	Profile drag coefficient
C_L	-	Lift coefficient
D	-	Drag
δ	-	Deformation
e	-	Span coefficient
E	-	Total energy per unit mass
f	-	Fluid
L	-	Lift
p	-	Static pressure
ρ	-	Density
q_i	-	Heat flux
R	-	Solver
s	-	Structural
t_n	-	Time
$\tau_{ij.turbulent}$	-	Reynold stress tensor
V	-	Velocity
W_f	-	Final weight
W_i	-	Initial weight

CHAPTER 1

INTRODUCTION

1.1 Background

Over the past decade, there has been a noticeable surge in demand for the development of Unmanned Aerial Vehicles (UAVs) among aircraft designers and technologists. UAVs have gained significant interest owing to the technologies across a wide range of industries such as the agricultural sector, Search and Rescue (SAR), as well as commercial and military sectors [1]. There are a few common types of UAVs encompassing fixed-wing, multi-rotor, Vertical Take-Off and Landing (VTOL) and solar power UAVs. Each UAV type serves distinct purposes and applications. Among these classifications, fixed-wing UAVs hold prominence due to the endurance and ability to cover large areas of mission. Within the fixed-wing UAVs category, the High-Altitude Long Endurance (HALE) aircraft often draws substantial attention with its capability to fly at high altitudes for a long period. There are a few types of the HALE applications including solar-powered aircraft, High-Altitude Pseudo Satellite (HAPS) and stratospheric aircraft. HALE aircraft are widely used in the military and commercial sectors. One of the HALE UAV aircraft employed in the military service is the Northrop Grumman RQ-4 Global Hawk, which is utilized by the United States

(US) Air Force and the US Navy. This aircraft has been designed specifically to perform an array of flying operations, including weather forecast and Intelligence, Surveillance and Reconnaissance (ISR) missions [1]. In terms of the commercial sector, HALE aircraft was used for communication, SAR and environmental monitoring. To cope with long endurance and range while operating at high altitudes, aircraft designers are confronted with the crucial challenge of optimizing their designs to maximize aerodynamic performance, which can be proven by the Breguet equation as shown in Equation (1.1) [2].

$$\text{Range} = \frac{L}{D}\ \frac{V}{TSFC}\ ln\left(\frac{W_i}{W_f}\right) \tag{1.1}$$

where; L = Lift; D = Drag; V = Velocity; TSFC = Thrust specific fuel consumption; W_i = Initial weight; W_f = Final weight

This equation considers several key factors, including the aircraft's average velocity during the flight, specific fuel consumption rate, lift-to-drag (L/D) ratio and the change in weight as fuel is consumed during the flight. The equation demonstrates that higher velocities generally lead to greater range but shorter endurance. At the same time, lower specific fuel consumption and higher L/D ratio contribute to both longer range and endurance. To optimize the L/D ratio, it is vital to minimize the total drag faced by the aircraft, which depends on two main components: (a) profile drag and (b) induced drag. Profile drag is a drag from the friction and pressure between the airflow over the aircraft. Meanwhile, induced drag is an aerodynamic force that opposes the production of lift created by the wing. One of the methods to decrease the induced drag is by increasing the aspect ratio. A higher aspect ratio generates more even lift distribution and fewer wingtip vortices, resulting in less induced drag. The relation between the induced drag and aspect ratio is represented in Equation (1.2).

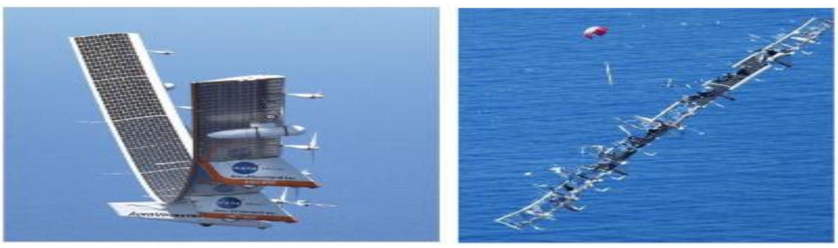
$$C_D = C_{DO} + C_{Di} = C_{DO} + \frac{(C_L)^2}{\pi . e' . AR} \tag{1.2}$$

where C_{DO} is the profile drag coefficient, C_{Di} is the induced drag coefficient, C_L is the lift coefficient, e is the span coefficient factor and *AR* is the aspect ratio of the wing. This equation shows that the induced drag, C_{Di} is inversely proportional to the aspect ratio. The reduction in induced drag, C_{Di} subsequently enhances the L/D ratio of the HAR wing, hence improving its aerodynamic performance [3], [4]. Additionally, the reduction of the drag directly contributes to fuel saving as it minimizes the energy to generate lift. Thus, researchers have proposed the use of a High Aspect Ratio (HAR) wing for the HALE aircraft application for high altitude and long endurance missions [5], [6].

Aspect ratio is defined as the ratio between the wingspan to its chord. The aspect ratio of the constant chord wing can be determined using Equation (1.3), where *b* represents the wingspan and *c* is the wing chord. As for the wing with an inconsistent chord, the *AR* can be determined by the same equation where the wing area defined by *A* and *SMC* is the standard mean chord.

$$\text{Aspect Ratio}, AR = \frac{b}{c} = \frac{b^2}{A} = \frac{b}{SMC} \tag{1.3}$$

Generally, the aspect ratio can be categorized into three categories: Low Aspect Ratio (LAR), Medium Aspect Ratio (MAR) and High Aspect Ratio (HAR). The range of aspect ratio for the LAR wing is between AR-2 to AR-6, the MAR wing is between AR-7 to AR-10 and the HAR wing starts from AR-11 and above The HAR wing configuration is commonly employed in HALE aircraft owing to its ability to generate a higher (L/D) ratio compared to other wing aspect ratios. However, increasing the aspect ratio may lead to wing deflection, potentially leading to aeroelastic issues including flutter and divergence [7]. Given the wing size and the extensive use of lightweight materials, the HAR wings are prone to large deflections, where increased structural flexibility leads to geometrical nonlinear behavior [8], [9]. Furthermore, the large deformation led to changes in dynamic behavior and aeroelastic reaction, resulting in instabilities and failure of the aircraft [10] which can be proven by the crash of NASA Helios aircraft with the aspect ratio of AR-31 on 26^{th} June 2003 in the Pacific Ocean as shown in Figure 1.1. The aircraft became unstable and exceeded the aircraft's design airspeed resulting in high dynamic pressures across the leading edge of the wing [11]. According to Noll et al. [11], [12] the cause of the failure was due to the lack of an analysis method that considered the nonlinear effect which led to a misleading analysis. Therefore, it is crucial to address the geometrical nonlinearity in the HAR wing design process.



(a) (b)

Figure 1.1 The crash of the NASA Helios aircraft (AR-31) (a) before crash and (b) after crash [12]

The design of the HAR wing remains at an immature stage due to the limited knowledge of the geometrically nonlinear aeroelastic behavior which makes it more challenging in HAR wing design [9]. In recent years, there has been a tremendous increase in research focusing on the geometrical nonlinearities of the HAR wings [6], [13 – 17]. Several techniques for geometrical nonlinearity analysis have been reported in the literature via analytical, experimental and numerical study. In terms of analytical approach, solving the geometrical nonlinearity of the HAR wing can be addressed using exact instinct beam theory, displacement-based beam theory and Euler-Bernoulli beam theory [18], [19]. However, this method can be challenging when dealing with complex wing geometry and demanding the utilization of advanced mathematical models to solve the geometrical nonlinearity [8].

Aside from that, researchers have conducted numerous experimental studies to validate numerical or analytical results of geometrical nonlinearity via wind tunnel testing [20 – 22]. Various techniques encompassing contact and non-contact methods, have been utilized to measure wing tip deflection within the wind tunnel testing. The contact method entails positioning measuring instruments on the wing's surface while the non-contact method involves measuring tip deflection without physical contact with the wing. In addition, the non-contact technique employs a Videogrammetric Model Deformation (VMD), laser and structure light scanner to monitor and record the wing's behavior and deflection during testing [21]. Nonetheless, in recent years, there has been a growing interest in the numerical approach to address the geometrical nonlinearity since wind tunnel testing is costly and time-consuming when compared to the numerical approach [23]. Numerical analysis can be performed through Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA) and Fluid-

Structure Interaction (FSI). Among these approaches, FSI analysis has attracted significant attention as a numerical method that allows comprehensive investigation of the dynamic interaction between fluid flow and structural elements. This analysis is crucial to avoid misleading analysis between the interaction of fluid flow and structure.

FSI analysis can be performed in two different approaches, namely one-way and two-way couplings [24]. One-way coupling is recommended when the wing deformation has negligible influence on the aerodynamics. In contrast, the utilization of two-way coupling is preferred when facing large wing deflection. In these cases, the utilization of the two-way coupling method is preferred as it can effectively solve the significant changes in aerodynamic characteristics that occur due to large structural deformations [24]. In recent years, the FSI methods have been employed on the HAR wing applications to study geometrical nonlinearity [25], [26]. Despite the advantages of FSI analysis, uncertainties persist regarding the comparative effectiveness of distinct FSI approaches and the establishment of clear procedure guidelines specific to FSI within HAR wing applications. Furthermore, extensive study has consistently highlighted the widespread use of FSI analysis, primarily concentrating only on the low and medium of aspect ratio wings [27 – 30] in light of the inherent complexity and high computational expenses involved when implementing the FSI analysis for HAR wing configurations. However, a gap exists in understanding the comparative effectiveness of one-way and two-way FSI analysis on the geometrical nonlinearity and the simulation setup, particularly in the context of the HAR wing application. Therefore, this study aims to bridge this gap by investigating the competence of different FSI approaches in the HAR wing application. To study the competence of

FSI approaches, one-way and two-way FSI analyzes will be performed on the HAR wing model.

1.2 Problem Statement

The High Aspect Ratio (HAR) wing is renowned in the High-Altitude Long Endurance (HALE) aircraft applications for its advantages of high lift-to-drag (L/D) ratio. Nevertheless, the HAR wing is exposed to substantial deformation resulting in geometrical nonlinearity. These large deformations significantly alter the aerodynamic performance, ultimately contributing to the failure of the aircraft [10]. Moreover, neglecting to consider the effects of these changes on aerodynamics may result in inaccurate assessments during the development phase of aircraft design [10]. The aircraft design process is inherently complex and requires a high level of precision as even small mistakes in performance forecasts can have major consequences for safety, efficiency and operational costs. Therefore, it becomes vital to conduct a comprehensive analysis on the impact of substantial wing deformation due to the geometric nonlinearity towards the aerodynamic performance.

Hence, the need for Fluid-Structure Interaction (FSI) analysis arises to analyze the interactions between the structural and aerodynamic features including the geometrically nonlinear behavior. The inclusion of geometric nonlinearity within FSI analysis places substantial computational demands, as it entails the simultaneous solution of fluid and structural domains through either one-way or two-way coupling methods [31]. Consequently, performing such analysis necessitates access to robust high-performance computational resources. Despite the benefits of FSI analysis, significant uncertainties persist concerning the comparative effectiveness of distinct FSI approaches and the development of well-defined procedural guidelines tailored to FSI within High Aspect Ratio (HAR) wing applications. Prior research has primarily revolved around low aspect ratio wing applications and techniques for examining wing deflection [27 – 30]. Nevertheless, a critical knowledge gap remains unclear regarding the relative performance of one-way and two-way methods as well as simulation setups in the context of HAR wing applications. Therefore, this study aims to fill this gap by investigating the competence of different FSI approaches concerning the selection of domain sizing, the interface for geometrical nonlinearity and the method of FSI couplings to identify the aerodynamic performance of the HAR wing model.

1.3 Objectives

The primary aim of this research is to examine the HAR wing deformation and aerodynamic performance with various aspect ratios through the Fluid-Structure Interaction (FSI) technique. This aim is identified through the following objectives:

(a) To validate the simulation results of the HAR wing deformation via the Fluid-Structure Interaction (FSI) approach against the wind tunnel experimental data at various air speeds and effective angles of attacks.

(b) To investigate the aerodynamic performance in terms of lift, drag and lift-to-drag (L/D) ratio of the HAR wing model at various ranges of aspect ratios.