INFLUENCE OF PASSIVE FLOW CONTROL METHODS ON FLOW TOPOLOGY AND STABILITY DERIVATIVES OF MULDICON WING

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DEDICATION

This thesis is dedicated to my father, who taught me that the best knowledge to have been learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task could be accomplished if it is done one step at a time.

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ABSTRACT

Sweep backward delta wings lead to flow separation and generate an effective vortex lift at high angle of attack (AOA). Despite of many studies in flow topology for the low sweep wings at a medium to higher AOA, most of them have been limited to steady-state measurements. Whereas nonlinearity in the aerodynamic stability derivatives is still not well understood and rarely reported in the literature. The aims of this study were to characterize and mitigate the unsteadiness and uncertainties of the flow at a medium to higher AOA with more consistent and predictable aerodynamic derivatives for the low sweep MULDICON wing. The experimental and Computational Fluid Dynamics methods were used to investigate the surface flow topology for the clean MULDICON wing for AOA, α = 5° to 30° with angle intervals of 5° for Re = $4.50{\times}10^5$. The wind tunnel testing involved the aerodynamic load's measurement (steady-state and dynamic) and the transient pure-yawing testing conducted at the Universiti Teknologi Malaysia Low-Speed wind Tunnel for the AOA, α = -4° to 30°, and yaw angle, β = ± 20° with angle intervals of 2°, at Re = $3.0{\times}10^5$, $3.75{\times}10^5$ and $4.5{\times}10^5$ respectively. The influence of the passive flow control methods (2-dimensional and 3-dimensional roughness heights, and vortex generators (VGs) placed at 10 % & 15 % of the mean aerodynamic chord (MAC)) were investigated at a medium to a higher AOA. The standard deviation variance data quantified the unsteadiness and uncertainties of flow topology. Analysis done suggested that the aerodynamic stability derivatives can be further improved at a medium to a higher angle of attack by improving the flow physics over the wing. A strong correlation between flow topology and pitching moment coefficient was exhibited, thus the previous computational studies for the MULDICON were validated. The aerodynamic center was found not to be fixed for the MULDICON wing and shifted forward towards the wing apex with the increase in α. For α ≥ 10°, the flow became asymmetric. Power spectral density (PSD) plots from the dynamic loading data quantified the flow separation (apex vortex, leading-edge vortex, and vortex breakdown) over the MULDICON wing and the different vortex structures detected by the several peaks in the PSD plots. The transient pure-yawing test showed that the increase in α lead to higher directional stability and oscillation was highly damped at a higher α. The transient pure-yawing test for α > 20°, indicated that there are self-sustained and self-excited oscillations. The quantification of the system's total energy at a higher AOA, i.e. for α ≥ 26° confirmed the fact that the stall occurred at α ≥ 26° where the significant total energy was associated with the system, which lead to the wing to stall. The C_{m_α} curve, the error bars, and relative standard deviation data showed that the onset of the leading-edge vortex was delayed to a higher AOA for the VGs at 10% MAC case. The C_{m_α} curve became more consistent and predictable for α = 5º to 20º. Time series data showed a small-amplitude oscillation frequency for VGs at 10% for α = 5°, 10° and 15° and no significant effects for all flow control cases at a higher AOA. Application of VGs at 10% of MAC made the stability derivatives more consistent and predictable for α = 5º to 20º for low sweep lambda configurations.º.

ABSTRAK

Sayap delta sapuan belakang mendorong kepada pemisahan aliran yang menghasilkan daya angkat vortek yang berkesan pada sudut serang yang tinggi (AOA). Walaupun terdapat banyak kajian dalam topologi aliran untuk sayap sapuan rendah pada AOA sederhana hingga lebih tinggi, kebanyakannya terhad kepada pengukuran keadaan mantap. Manakala ketaklinearan dalam derivatif kestabilan aerodinamik masih tidak difahami dengan baik dan jarang dilaporkan dalam literatur. Matlamat kajian ini adalah untuk mendapatkan ciri-ciri dan mengurangkan ketidakstabilan dan ketidakpastian aliran pada AOA sederhana hingga tinggi dengan derivatif aerodinamik yang lebih konsisten dan boleh diramal untuk sayap MULDICON sapuan rendah. Kaedah eksperimen dan simulasi digunakan untuk mengkaji topologi aliran permukaan bagi sayap MULDICON asas untuk AOA, α = 5° hingga 30° dengan selang sudut 5° untuk Re = 4.50×10^5. Ujian terowong angin yang melibatkan pengukuran beban aerodinamik (keadaan mantap dan dinamik) dan ujian rewang-tulen telah dijalankan di terowong angin Universiti Teknologi Malaysia untuk AOA, α = -4° hingga 30°, dan sudut rawang, β = ± 20° dengan jeda sudut 2°, peda Re=3.0×10^5, 3.75×10^5 hingga 4.5×10^5. Pengaruh kaedah kawalan aliran pasif (ketinggian kekasaran 2 dimensi dan 3 dimensi, dan penjana pusaran diletakkan pada 10 % & 15 % min perentas aerodinamik (MAC)) telah dikaji pada sederhana ke lebih tinggi AOA. Data varian sisihan piawai mengukur ketidakstabilan dan ketidakpastian topologi aliran. Analisis dilakukan mencadangkan bahawa derivatif kestabilan aerodinamik boleh dipertingkatkan lagi pada sudut serangan sederhana ke lebih tinggi dengan menambah baik fizik aliran di atas sayap. Korelasi yang kuat antara topologi aliran dan pekali momen anggul C_m telah dipamerkan, justeru itu kajian pengiraan simulasi sebelumnya untuk MULDICON telah disahkan. Pusat aerodinamik didapati tidak tetap untuk sayap MULDICON dan beralih ke hadapan ke arah puncak sayap dengan peningkatan α. Untuk α ≥ 10°, aliran menjadi tidak simetri. Plot PSD daripada data pemuatan dinamik mengukur pemisahan aliran (vorteks puncak, vorteks pinggir-hadapan, dan pecahan vorteks) di atas sayap MULDICON dan struktur vorteks berbeza yang dikesan oleh beberapa puncak dalam plot PSD. Manakala, ujian rewang-tulen menunjukkan bahawa peningkatan dalam α membawa kepada kestabilan berarah yang lebih tinggi dan ayunan mengalami redaman tinggi pada α yang lebih tinggi. Manakala, ujian rewang-tulen untuk α > 20°, menunjukkan bahawa terdapat ayunan mampan dan teruja sendiri berlaku. Kuantifikasi jumlah tenaga ayunan pada yang lebih tinggi AOA, iaitu, untuk α ≥ 26° mengesahkan fakta bahawa tegun berlaku pada α ≥ 26° di mana jumlah tenaga yang ketara dikaitkan dengan sistem, yang membawa sayap menjadi tegun. Lengkung C_{m_α}, bar ralat dan data sisihan piawai relatif menunjukkan bahawa permulan vorteks pinggir hadapan telah ditangguhkan ke AOA yang lebih tinggi untuk VG pada kes MAC 10%. Lengkung C_{m_α} menjadi lebih konsisten dan boleh diramal untuk α = 5º hingga 20º. Data siri masa menunjukkan frekuensi ayunan amplitud kecil untuk VG pada 10% kes MAC untuk α = 5°, 10° dan 15° dan tiada kesan ketara untuk semua kes kawalan aliran pada AOA yang lebih tinggi. Penggunaan VG pada 10% MAC menjadikan derivatif kestabilan lebih konsisten dan boleh diramal untuk α = 5º hingga 20º untuk konfigurasi lambda sapu rendah.

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LIST OF ABBREVIATIONS

UCAV	-	Unmanned Combat Aerial Vehicles
SACCON	-	Stability And Control CONfiguration
MULDICON	-	MULti-DIsciplinary CONfiguration
NATO	-	North Atlantic Treaty Organization
RTO	-	Research Technology Organization
VFE-2	-	Vortex Flow Experiment 2
NASA	-	National Aeronautics and Space Administration
AVT	-	Applied Vehicle Technology
TE		Trailing Edge
AFRL	-	Air Force Research Laboratory
CFD	-	Computational Fluid Dynamics
ElsA	-	Ensemble Logiciel pour la Simulation en Aérodynamique
DSTO	-	Défense Science and Technology Organization
NLR	-	National Aerospace Laboratory
ONERA	-	Office national d'études et de recherche aérospatiales
USAFA	-	United States Air Force Academy
IAR	-	Institute for Aerospace Research
ZDES	-	Zonal Detached Eddy Simulations
LE		Leading Edge
LRC	-	Langley Research Center
MAC	-	Mean Aerodynamic Chord
UTM-LST	-	Universiti Teknologi Malaysia Low-Speed Tunnel
ASG	-	Aerodynamic Shaping Group
BMC	-	Balance Moment Center
MRC	-	Model Reference Center
AOA	-	Angle of Attack
PSD	-	Power Spectral Density
Re		Reynolds Number

LIST OF SYMBOLS

C_L	-	Lift Coefficient
C_D	-	Drag Coefficient
C_Y	-	Side Force Coefficient
C_m	-	Pitching Moment Coefficient
C_n	-	Yaw Moment Coefficient
C_{m_α}	-	Pitching Moment Derivative (rad^{-1})
C_{n_β}	-	Yaw Moment Derivative (rad^{-1})
I_{ZZ}	-	Moment of Inertia ($kg\ m^2$)
α	-	Angle of Attack (deg)
β	-	Yaw Angle (deg)
Km	-	Reduced Frequency
Ks	-	Spring Stiffness (N/m)
b	-	Arm length (m)
C_{MAC}	-	Mean Aerodynamic Chord Length (m)
f	-	Frequency (Hz)
U	-	Wind Speed (m/s)
$\emptyset_{le}$	-	Leading Edge Sweep Angle (deg.)
$\emptyset_{te}$	-	Trailing-Edge Sweep Angle (deg.)
C_r	-	Root Chord Length of Wing (m)
C_f	-	Skin Friction coefficient
X_{MRP}	-	Moment Reference Point at wing surface (m)
S_{ref}	-	Surface Area of the MULDICON model (m^2)
k_{crit}	-	Critical Roughness Height (μm)
x	-	Boundary-Layer Run Length (m)
v	-	Kinematic Viscosity ($m^2 s^{-1}$)
$\frac{k}{l}$	-	Relative Wall Roughness
ρ	-	Density ($Kg\ m^{-3}$)
L	-	Lift Force(N)

D	-	Drag Force (N)
Fy	-	Side Force (N)
My	-	Pitching Moment (Nm)
Mz	-	Yaw moment (Nm)
Mx	-	Roll Moment (Nm)
$t_{1/2}$		Time to Half Amplitude (s)
T		Time for One Oscillation (s)
f_d	-	Damped Frequency (Hz)
f_{MO}	-	Model Oscillating Frequency (Hz)
Q	-	Dynamic Pressure (MPa)
u_*	-	Friction Velocity
τ_ω	-	Wall Shear Layer
$\triangle y$	-	Size of first cell adjacent to model (m)
μ	-	Viscosity (Pa.s)
l	-	Length of the VGs (mm)
h	-	Height of the VGs (mm)
α_{VG}	-	Incidence angle of VGs to flow
d	-	Spacing between two VGs (mm)
x_{VG}	-	Chord wise location of the VGs (mm)
t	-	Thickness of the VGs (mm)
δ	-	Boundary layer thickness (mm)

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter covers the problem background for the unsteadiness and uncertainties of the flow topology at medium to higher Angle of Attack (AOA) for the low sweep delta wing. The problem statement follows the problem background. Objectives are laid down with a specific goal to answer the problem statement. The scope of the study is briefly clarified, and the significance of the research work is also discussed.

1.2 Problem Background

When a conventional aircraft moves through air, pressure differences on the lower and upper sides generate a potential lift. Delta wings are a particular type of sweepback wings. The high sweep leading edge (LE) delta wing leads to the leading-edge vortex at a higher Angle of Attack (AOA), producing an additional vortex lift. A significant advantage of vortex lift is that it is effective at high AOA flight, over which the conventional aircraft would generally stall. The high AOA flight is frequently encountered during the flight's landing, takeoff, and combat manoeuvring phases. Delta wings satisfy all military aircraft requirements, such as high speed and super-manoeuvrability.

Delta wings are classified into a high sweep and low sweep delta wings. Highly swept delta wing has applications at supersonic speeds, whereas more recently, low sweep delta wings are used in low Reynolds number applications such as unmanned combat aerial vehicles (UCAV). The flow topology over high sweep delta wings has been extensively studied and well understood (Rockwell, 1993, Visbal, 1995). In contrast, flow over the low sweep delta wing is highly complex and nonlinear and not well understood. The recent interest in UCAVs has resulted in a need to understand further the topology of the flow over low sweep delta wings.

At low AOA, the flow over the low sweep delta wing is attached, which results in consistent and predictable pitching moment coefficients. In contrast, at moderate and higher AOA, the flow doesn't remain attached, and onset and progression of the vortex separation occur, which results in a highly complex and nonlinear flow. The unsteadiness and uncertainties of the flow topology at moderate to high AOA such as leading-edge vortex separation, vortex breakdown, and shear layer reattachment result in the highly nonlinear, fluctuating, and discontinuous pitching moment coefficient. The unsteadiness and uncertainties of the flow for low sweep delta wings at medium to higher AOA need to be mitigated. By either controlling the vortical flow or delaying the onset and progression of the vortex flow separation to higher AOA, the pitching moment coefficient is more consistent and predictable (Nangia et al., 2010, Schuette et al., 2018).

Centred on the problems related to the low sweep delta wing configurations discussed above, there is an obvious requirement to conduct further detailed research to fully understand and mitigate the unsteadiness and uncertainties of the flow topology at moderate to high AOA.

1.3 Problem Statement

The experimental and the CFD studies reveal that the low sweep lambda wing configuration experiences highly unsteady and uncertain flow over the surface of the for medium to a higher angle of attack, which makes the pitching moment coefficient highly nonlinear, fluctuating, and discontinuous (Zhang et al., 2005, McParlin et al., 2006, McLain, 2009, Cummings et al., 2010, Schütte et al., 2010, Vicroy Dan et al., 2010, Jentzsch et al., 2016, Williams et al., 2019, Liersch et al., 2020c). This indicates that the pitching moment coefficient appears to be highly sensitive to the flow topology. The recent studies predict a strong correlation between flow topology and pitching moment coefficient. Still, the correlation is not fully understood as most of the previous data is limited to steady-state measurements.

Most of the earlier research for the low sweep lambda wings was carried out to understand the unsteadiness and uncertainties of the flow topology and the correlation between the flow topology and the force and moment coefficients. Thus, the nonlinearity in the aerodynamic stability derivatives was not studied in detail and not well understood. Minimal data is available for the aerodynamic stability derivatives, especially the research work for the aerodynamic damping derivatives is very limited. Previous researchers utilized wind tunnel testing and the CFD simulations; however, the findings regarding the aerodynamic stability derivatives are not conclusive. By focusing on experimental wind tunnel transient testing, this research work will bring value to estimating the aerodynamic stability derivatives.

Most of the researchers previously had worked to understand and mitigate the flow's unsteadiness and uncertainties to make the pitching moment coefficient predictable and consistent at a medium to a higher angle of attack for the low sweep lambda wing by conducting only the CFD simulation work. However, different CFD techniques failed to predict consistent results for the nonlinear region at a medium to a higher angle of attack (Kaya et al., 2018, Nangia et al., 2019, van Rooij et al., 2018). There is a definite need to use several experimental flow visualisation and the aerodynamic load's measurements methods to fully understand the flow topology and pitching moment coefficient at medium to a higher angle of attack

As reported by Buzica et al. (2018), some of them have not published the use of passive flow control methods in previous work to mitigate the unsteadiness and uncertainties of the flow topology for low sweep lambda wings. Passive flow control methods have shown superior effects for avoiding complex flows at medium to higher AOA for the Diamond wing. With such exciting findings, it is appropriate and timely to extend their work by investigating the use of several passive flow control methods in the low sweep MULDICON wing.

All the above discussions had pointed that there is a clear need to characterize and mitigate the unsteadiness and uncertainties of the flow at a medium to higher AOA so that aerodynamic stability derivatives are more consistent and predictable for the low sweep MULDICON wing using passive flow control methods.

1.4 Research Objectives

The work aims to develop a low sweep MULDICON configuration for medium to higher AOA with more consistent and predictable aerodynamic derivatives. Based on the challenges, the specific objectives of the research are as follows:

(a) To correlate the unsteadiness and uncertainties of the flow topology and aerodynamic forces and moments at a medium to a higher angle of attack applying the experimental methods.

(b) To determine the transient aerodynamic behaviour of low sweep MULDICON configuration by estimating the aerodynamic stability derivatives, especially the aerodynamic damping derivatives using transient wind tunnel testing.

(c) The influence of several passive flow control geometries on the flow topology and aerodynamic derivatives, at a medium to a higher angle of attack.

(d) To quantify the unsteadiness and uncertainties of the flow topology using Power Spectral Densities (PSD) and self-sustained oscillation through the dynamic aerodynamic loadings and the transient pure-yawing measurements.

1.5 Research Scope

To attain the three main objectives of the research, the scope of the work is formulated as

(a) Design and fabrication of the 1:25 MULDICON AVT251 scale model. The same 1:25 MULDICON AVT251 scale model will be used for the detailed wind tunnel analysis and the computational fluid dynamics (CFD) analysis.

(b) Two types of passive flow control methods will be applied to the wind tunnel MULDICON model, i.e., the roughness heights and the vortex generators (VGs).

(c) Three types of wind tunnel testing will be conducted at Universiti Teknologi Malaysia Low-Speed Tunnel (UTM-LST) for the clean MULDICON wing and the MULDCION wing with the passive flow control methods in this research work, i.e., flow visualization, aerodynamic loads measurement, and the transient pure-yawing testing.

(d) Surface oil flow application methods will be done using wind tunnel. The oil flow visualization will be carried out for the clean MULDICON model for the angle of attack, α = 5° to 30° for Re = 4.50×105 corresponding to the speed of 30 m/s. The surface oil flow application methods will give a detailed view of the surface flow topology.

(e) A series of wind tunnel experiments will be carried out for load measurements (steady-state loading and dynamic loadings). The aerodynamic load measurements will be carried out for the clean MULDICON model and the MULDCION wing with the passive flow control methods for the angle of attack, α= -4° to 30°, yaw angle, β = ±20° for Re = 3.00×105, 3.75×105 and 4.50×105 corresponding to the speed of 20, 25 and 30 m/s. The steady-state loading will give the averaged aerodynamic coefficients & static derivatives, while the dynamic loadings will give the time series data and Power Spectral Densities (PSD).

(f) A series of wind tunnel experiments will be carried out for transient pure-yawing testing using dynamic oscillatory rig facility for the clean MULDICON model and the MULDCION wing with the passive flow control methods for the angle of attack, α = 0° to 30°, yaw angle, β = ± 10° for Re = 3.00×10^5 and 4.50×10^5 corresponding to the speed of 20, and 30 m/s. The response from the dynamic oscillatory tests predicts the aerodynamic stability derivatives C_{n_β} and C_{n_r}.

(g) In this study, CFD simulations will be performed using commercial CFD software, ANSYS version 19.0, for the clean MULDICON model for the angle of attack, α = 5° to 30° for Re = 4.50×10^5 corresponding to the speed of 30 m/s. The CFD simulations will give a detailed view of the surface flow topology.

1.6 Significance of Work

One of the potential outcomes of the research will be more consistent and predictable aerodynamic stability derivatives for low sweep lambda wings at medium to high AOA. The unsteadiness and uncertainties of the flow topology for the MULDICON wing are reduced and the aerodynamic stability derivatives are more consistent and predictable for angle of attack, α = 5° t0 20° by applying the Vortex Generators (VGs) at 10% of Mean Aerodynamic Chord (MAC). Useful knowledge about the application of the passive flow control methods will be gained and will be applicable for blunt leading-edge wings. This research will also advance the aerodynamic knowledge for the low sweep blunt leading-edge configuration. Useful knowledge will be available for the unsteady and uncertainty flow measurement at a higher AOA, particularly on the onset and progression of the leading-edge vortices and the vortex breakdown. The knowledge will be very beneficial as very little experimental data is available for the MULDICON wing configuration. Considering the issues mentioned above, the results of this research will contribute to what is currently known about the low sweep lambda wing.

1.7 Summary

This thesis consists of 6 chapters. Chapter 1 describes the general background, problem statement, objectives and scope, and significance of study of this work.

Chapter 2 describes comprehensive literature review regarding the fundamentals of vortex lift, issues related to vortex lift, aerodynamic stability derivatives, related work for low sweep UCAV configurations, passive flow control.

Methodology for the research work is presented in Chapter 3 where the wind tunnel model, passive flow control methods design, experimental test setup and instrumentation are described. Data collecting and data processing techniques are also presented. In addition, the development of CFD modelling is explained.

Chapter 4 and 5 present the results and discussions parts of this research work. Chapter 4 describes the results and discussions for the clean MULDICON wing configuration, whereas the results and discussions for MULDICON wing with the passive flow devices attached are discussed in chapter 5.

The conclusions of this research are drawn in Chapter 6. In addition, recommendations for further work will also be outlined. References and appendices that contain additional support material are attached at the end of this thesis.

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LIST OF PUBLICATIONS

Journal Papers

1. B. Haider, S. Mansor, S. Mat, and N. Nasir, "Review of Uncertainty of the Flow over Low Sweep Lambda Wing Unmanned Combat Air Vehicles (UCAV)," *Journal of Aeronautics, Astronautics and Aviation,* vol. 54, no. 1, pp. 25-48, 2022. **(Scopus Impact Factor: 0.16-Q4)**

Conference Papers

1. B. Haider, S. Mansor, S. Mat, and N. Nasir, "Wind tunnel test setup methodology for MULDICON AVT251 UCAV Configuration," *South-east Asia Workshop on Aerospace Engineering (*SAWAE2020*)*, 2021.

2. B. Haider, S. Mansor, S. Mat, W. Z. W. Omar, and N. Nasir, "Design of experiments for wind tunnel testing of 53º sweep lambda wing UCAV configuration," *Conference International Symposium on Aircraft Technology, MRO & Operations,* 2021. **(Scopus)**

3. B. Haider, S. Mansor, S. Mat, W. Z. W. Omar, and N. Nasir, "Experimental analysis for low-speed aerodynamic characteristics of MULDICON AVT251 UCAV configuration," *First International Seminar on Aeronautics & Energy (ISAE2021),* 2021.

4. B. Haider, S. Mansor, S. Mat, W. Z. W. Omar, and N. Nasir, "Effects of Transition Strip on Aerodynamic Coefficients of MULDICON Wing for Low-Speed Wind Tunnel Testing," *First International Seminar on Aeronautics & Energy (ISAE2021),* 2021.

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