LIFT CHARACTERISTIC ANALYSIS OF COANDA JET ON CURVED SURFACES WITH VARYING INCLINATION ANGLES

By

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Chair : Mohd Faisal Bin Abdul Hamid, PhD
Faculty : Engineering

With the applications of small unmanned aerial vehicles (UAVs) getting much more diverse, the need for a system that is capable of high lift force augmentation is important for longer flight endurance while possessing the versatility to perform diverse flight missions. Coanda UAV is one of the options. To address the said need, the current study explored the influence of the curved surface inclination angle on the lift augmentation performance and the Coanda jet flow behavior since the potential effects of curved surface inclination angle to lift performance are yet to be fully studied. In this study, both experimental and numerical computation approaches were employed for the analysis involving two curved surfaces with the curvature ratios of 1 and 2 with a jet velocity of 10 m/s to 30 m/s while the surface inclination angles varying in the range of 0° to 40° were analyzed through computational analysis. The experimentation used the static pressure measurement method measured through 13 static pressure tap holes to plot the static pressure distribution along the test models whereas the numerical computation utilized Computational Fluid Dynamic (CFD) method using the k-ω SST CC turbulence model to simulate the Coanda jet flow. Both analyses deal with the 2-dimensional (2D) Coanda jet flow. The experimental data gave an overview of the static pressure distribution along the curved surface on different surfaces with curvature and showed the total lift performance of curvature ratio 2 is 52% more than the curvature ratio 1. The result extracted from CFD analysis closely followed the experimental data with a percentage difference of 6%. Similar to the experiment data, the curvature ratio 2 produced 32% more lift force. The lift force generated under the effect of surface inclination angles, however, showed a fluctuating pattern and the highest generated lift force is obtained at 0° surface inclination angles valued at 5.23 N and 7.1 N for the curvature ratio 1 and 2, respectively. Nevertheless, the Coanda jet flow is capable to remain attached to the end of the surface at all surface inclination angles, and a slight increase of jet thickness of at least three times the initial jet thickness is observed at the edge of the curved surface in all inclination angles due to addition of mass flow from the entrained fluid. An increase in surface

inclination angle resulted in a thicker jet though the change is minimal. On the whole, the current study offers an analysis result on the impact of surface inclination angle on lift performance and demonstrated that designing the Coanda UAV with a greater curvature ratio and assuming a 0° surface inclination angle results in the highest generated lift force.

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

ANALISIS CIRI DAYA ANGKAT JET COANDA PADA PERMUKAAN MELEKUNG DENGAN SUDUT KECONDONGAN BERBEZA

Oleh

MUHAMMAD ALIMIN BIN MD SHAFIE

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Dengan aplikasi pesawat tanpa juruterbang (UAV) kecil yang semakin pelbagai, keperluan untuk sistem yang mampu meningkatkan daya angkat yang tinggi adalah penting untuk memanjangkan ketahanan masa penerbangan tanpa mengorbankan kebolehan melaksanakan pelbagai misi penerbangan. Coanda UAV adalah salah satu pilihan. Dalam usaha untuk menangani keperluan tersebut, kajian semasa meneroka pengaruh sudut kecondongan permukaan melengkung terhadap prestasi peningkatan daya angkat dan tingkah laku aliran jet Coanda kerana kesan potensi sudut kecondongan permukaan melengkung terhadap prestasi daya angkat masih belum sepenuhnya dikaji. Dalam kajian ini, pendekatan secara eksperimen dan komputasi berangka digunakan untuk menganalisis dua permukaan melengkung dengan nisbah kelengkungan 1 dan 2 pada kelajuan jet dari 10 m/s hingga 30 m/s sementara sudut kecondongan permukaan diubah dalam julat 0° hingga 40° untuk analisis pengiraan komputer. Eksperimen menggunakan kaedah pengukuran tekanan statik yang diukur melalui 13 lubang tekanan statik untuk mengambarkan taburan tekanan statik sepanjang model ujian manakala pengiraan komputer menggunakan kaedah Dinamik Bendalir Pengiraan (CFD) dengan model turbulensi k-ω SST CC untuk mensimulasikan aliran jet Coanda. Kedua-dua analisis berurusan dengan aliran jet Coanda 2-dimensi (2D). Data eksperimen memberikan gambaran umum tentang taburan tekanan statik sepanjang permukaan melengkung pada nisbah kelengkungan yang berbeza-beza dan menunjukkan prestasi angkat keseluruhan nisbah kelengkungan 2 adalah 52% lebih tinggi daripada nisbah kelengkungan 1. Keputusan yang diperoleh dari analisis CFD bersetuju dengan data eksperimen dengan perbezaan peratusan 6%. Sama seperti data eksperimen, nisbah kelengkungan 2 menghasilkan 32% daya angkat lebih tinggi. Daya angkat yang dihasilkan di bawah kesan sudut kecondongan permukaan, bagaimanapun, menunjukkan corak yang berubah-ubah dan daya angkat yang tertinggi diperoleh pada sudut kecondongan permukaan 0° dengan nilai 5.23 N dan 7.1 N untuk nisbah kelengkungan 1 dan 2. Walau bagaimanapun, aliran jet Coanda mampu untuk terus melekat pada hujung

permukaan pada semua sudut kecondongan dan peningkatan sedikit ketebalan jet sekurang-kurangnya tiga kali ganda ketebalan jet asal diperhatikan di bahagian hujung permukaan lengkung pada semua sudut kecondongan disebabkan oleh penambahan aliran jisim dari kesan bendalir yang terjalin. Peningkatan sudut kecondongan permukaan menghasilkan ketebalan jet yang lebih tebal walaupun perubahan ini adalah minima. Secara umum, kajian ini memberikan hasil analisis mengenai pengaruh sudut kecondongan permukaan pada prestasi angkat dan menunjukkan daya angkat yang tertinggi boleh diperoleh dengan mereka-bentuk UAV Coanda dengan nisbah kelengkungan yang lebih tinggi dan dengan menganggap sudut kecondongan permukaan 0°.

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I certify that a Thesis Examination Committee has met on 27th December 2022 to conduct the final examination of Muhammad Alimin Bin Md Shafie on his thesis entitled "Lift Characteristic Analysis Of Coanda Jet On Curved Surfaces With Varying Inclination Angles" 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 Master of Science.

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LIST OF ABBREVIATIONS

2D	2 Dimension
3D	3 Dimension
CAD	Computer-Aided Design
CAGR	Compound Annual Growth Rate
CC	Circulation Control
CFD	Computational Fluid Dynamic
CPU	Central Processing Unit
DNS	Direct Numerical Simulation
EASM	Explicit Algebraic Stress Model
FDM	Fused Deposition Modeling
FFT	Fast Fourier Transform
FVM	Finite Volume Method
HTOL	Horizontal Take-off and Landing
LES	Large-eddy simulation
PLA	Polylactic acid
RANS	Reynold averaged Navier-Stokes
SARC	Spalart-Allmaras Rotation/Curvature Correction
SIMPLE	Semi-Implicit Method for Pressure Linked Equations
SST	Shear-Stress Transport
SSTCC	Shear-Stress Transport Curvature Correction
STOL	Short Take-off and Landing
UAV	Unmanned Aerial Vehicle

CHAPTER 1

INTRODUCTION

1.1 Background

The application of unmanned aerial vehicle (UAV) is gaining more popularity in the recent decade. In 2020, the global UAV market was valued at 14.3 billion and is projected to grow with a Compound Annual Growth Rate (CAGR) of 14% by the year 2030 (Precedence Research, 2020). This promising trend is reflected in Figure 1 which forecasts the estimated global market value for the years 2021 to 2030. The projection includes the military, commercial, and recreational market sectors in the UAV industry.

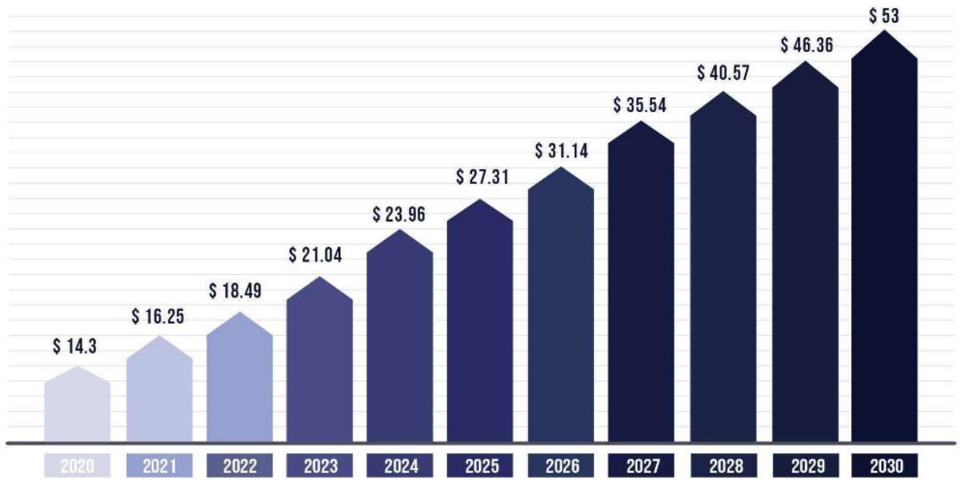

Figure 1: UAV market value forecast from 2021 – 2030 (Precedence Research, 2020)

The increasing popularity of UAVs is due to their adaptability in carrying out a range of missions and their capacity to be outfitted with a variety of sensors and cameras. These missions include reconnaissance, search and rescue, mailing and delivery, monitoring, and photography (Hassanalian et al., 2018; Saeed et al., 2018). These missions are often handed to a group of UAVs that come from the small UAV category where its applications are often in urban areas. To this end, various concepts of small UAVs have been developed to match different mission requirements and environments, either indoors or outdoors. Various methodologies have been used to distinguish these UAVs into specific classifications. The small UAVs can be characterized based on their design configurations which are the Horizontal Take Off and Landing (HTOL), Rotary wing, and Bio-inspired UAVs.

The HTOL is a type of UAV that requires space or runway for it to reach the minimum required speed to take-off or land, unlike the rotary wing UAVs which employ their propulsion system in a vertical direction to gain thrust for take-off, landing as well as hovers (Hassanalian & Abdelkefi, 2017). Finally, the Bio-inspired UAV, which is designed to emulate the flight of live things like birds and insects. This sort of UAV might be able to fit into very small spaces due to its small size, which can be as little as a few millimetres. However, the benefit is complicated by miniaturisation.

Regardless of their classes, each UAV is desired to possess high performance, especially for missions that require high flight endurance or high payload capacity. However, to achieve the said characteristics, the energy capacity carried onboard the UAV system acts as the limiting factor. This limitation can be addressed by either developing a power supply (i.e. battery) with a larger energy storage capacity or by improving the airframe design to minimize the power usage of the UAV's system to overcome the negative aerodynamic forces such as drag (Hassanalian & Abdelkefi, 2017). Unfortunately, battery miniaturization and energy capacity technology are limited to the current technological progress, even though it is largely contributing to the total weight of the UAV system (Petricca et al., 2011). Improvement on the airframe design on the other hand offers large room for optimizations largely in terms of lift-to-drag ratio (L/D), especially for the new type of UAV that is yet maturing such as the Coanda UAV.

The Coanda UAV benefits from a fluid dynamics phenomenon called the Coanda effect in its propulsion system. Figure 2 illustrates the typical design of the Coanda UAV, often characterized by its dome-shaped body geometry.

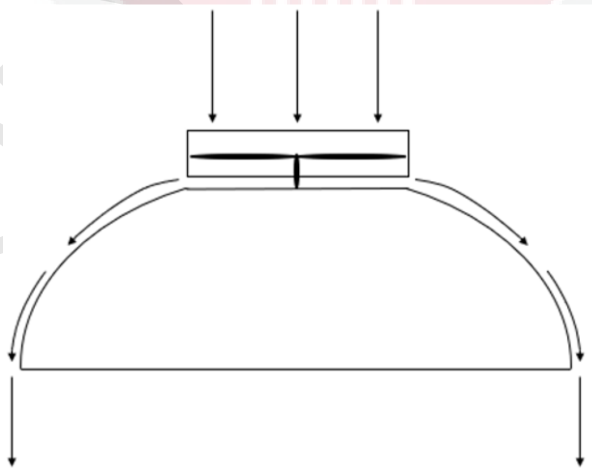

Figure 2: The schematic drawing of the Coanda UAV

With an encased rotor placed on top of the UAV, it generates lift by drawing the surrounding fluid into the shroud and ejecting it as a thin high-velocity jet tangential to the highly curved surface of the UAV. The Coanda effect ensures the jet flow follows the contour of the body geometry, hence generating lift that is not only produced by the pressure differential but also from the downward jet momentum (Hamid et al., 2018). Although the typical design of this type of UAV is referred from the design produced by Geoff Hatton in the AESIR project (Figure 3) (Hatton, 2010), Henri Coanda himself is the first inventor that develops a flying vehicle that utilized the Coanda effect in its propulsion system which is similar to the AESIR, is a saucer-shaped named Avrocar as shown in Figure 4.

Figure 3: The Coanda UAV designed by Geoff Hatton (Hatton, 2010)

Figure 4: The Avrocar (Francine et al., 2015)

Since the Coanda UAV is part of the rotatory wing class, it is much more advantageous compared to the other type of UAVs in terms of flight mission versatility due to its hover capability. Moreover, the Coanda UAV offers safe human interaction and resistance to collision especially in a tightly spaced indoor environment since its rotating component is safely enclosed inside a shroud. However, to maintain a hover flight, rotary wing UAVs demand high power usage (Bouabdallah et al., 2005; Petricca et al., 2011). Therefore, the current study is interested in enhancing the aerodynamic lift augmentation capability of the Coanda UAV to reduce the required power for the Coanda UAV to maintain hover flight, hence increasing flight endurance.

1.2 Problem Statement

The current rotary wing UAVs such as quadcopters do not perform well in forward flight due to the effect of retreating blade stall (Lorber et al., 2000). The phenomenon occurs due to the retreating side of the rotor disc experiencing a much lower relative wind velocity compared to the advancing side. Fixed-wing UAVs would not endure such issues, however, they are frequently outfitted with intricate mechanisms that add to the overall weight of the system. It also lacks the capability to hover in a fixed position due to its low thrust-to-weight ratio which makes it much less versatile for diverse missions that require fixed position monitoring over a period of time (Darvishpoor et al., 2020). As a result of these constraints, a new type of rotary wing UAV incorporating Coanda jets, the Coanda UAV has been developed as an alternative with an enclosed rotor placed inside a shroud. This reduces the effect of retreating blade stall during forward flight and makes it safe to operate in a tight space or near a human. Nevertheless, for a rotary wing UAV such as the Coanda UAV to maintain its hover flight requires a large amount of energy which in turn will reduce the flight endurance. For that reason, further study is required to address the need for enhanced lift performance for Coanda UAVs.

The established studies related to the Coanda UAV highlight the critical effects of jet parameters and surface curvature on the flow development and performance on the surface (Wessapakdee et al., 2014; Ahmed et al., 2014; Ping et al., 2010; V. Inthasuwan, 2013). Most of the presented conclusions are in agreement with each other that the most effective region to generate lift force is near the end of the curved surface (Gan et al., 2015; Wessapakdee et al., 2014). This is due to the large area of a concentrated negative region generated around it before the suction pressure declines as the flow progresses downstream due to the loss of flow momentum. This illustrates the potential effects of surface curvature and angle inclination to lift performance when the large concentrated area of negative pressure is shifted toward the center. The area of a concentrated negative region can be observed in Figure 5, which depicts the illustration of the pressure contour on the curved surface of the Coanda UAV at a normal and tilted angle. Since pressure acts normally to the curvature of the surface, the broad region of high suction pressure in the pressure contour over the curvature will not be able to harvest the lift force at full capacity. Therefore, controlling the angle of the surface curvature with regard to the incoming jet flow, θ so that the force vector is closer to the vertical direction (as illustrated in Figure 5) appears to be capable of increasing the lift produced since the lift due to the pressure differential is much predominant compared to the downward force of the jet momentum (Hamid et al., 2018). This is beneficial to UAV endurance since the system is dependent solely on the amount of energy on board.

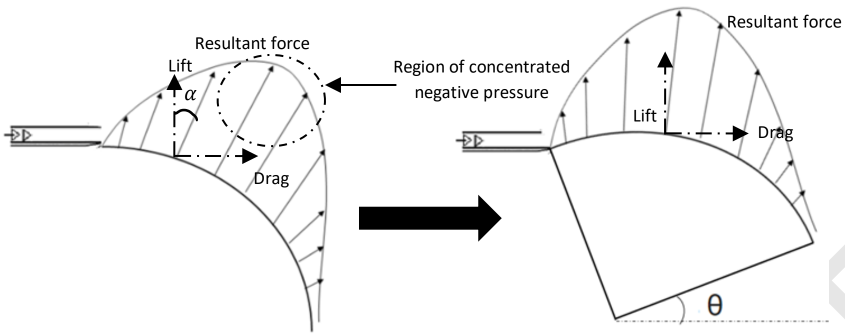

Figure 5: Schematic illustration of the pressure contour on a normal (left) and tilted (right) curved surface

However, so far, the studies on this topic are still insufficient to establish a good understanding of the effect of the surface angle on the behavior of the flow. Up to the point where this study is conducted, only a few authors are interested in this topic. The study performed by Bailey (1961) tested the influence of the surface inclination angle on a curved surface, but his investigation solely focuses on the high-speed subsonic speed application. As a result of multiple early failures in the endeavor to incorporate the Coanda effect into an aircraft design, interest progressively faded (such as the project of AVROCAR). However, in the early 2000s, as UAV use increased, the Coanda effect's popularity started to rise once more especially after the creation of the AESIR project was made public. The study carried out by Maman demonstrated that the surface inclination angle contributes positively when compared to the typical Coandá UAV as long as the rotational component is considered but the study is primarily focused on the impact of the rotational component on aerodynamic performance and only takes a 45° angle into account and does not investigate further on the contribution of surface angle inclination on the aerodynamic lift augmentation (Maman, 2019). Other authors that are interested in the potential effects of angle inclination to lift performance include Saeed and Gratton (2010) and Barlow et al. (2009). However, these studies are too fundamental and only interested in the ring wing surface acting as the deflection surface for the Coanda jet. Moreover, these studies are still only conceptual and yet to be realized in the Coanda UAV application.

Based on the mentioned studies, the current study is interested to explore the flow behavior of Coanda when it flows tangentially to a much simpler curved surface geometry under the influence of surface inclination angle, which is a much more suitable consideration for the UAV application compared to the annular airfoil. Besides that, the current study is interested to examine the impact of curved surface inclination angles on jet flow development and behavior. Moreover, moving forward the established result could serve as a guideline for choosing the right design configuration for the Coanda UAV during the preliminary design step.

1.3 Objectives

From the research gap presented in subsection 1.2, numerous questions are raised that are of interest to the current study to explore.

1. How does the distribution of pressure on the curved surface contribute to lift augmentation?

2. How does the curved surface inclination angle impact the jet flow development and behavior?

3. At what inclination angle and which curved surface geometry provide the best flow performance enhancement?

This study aims to investigate the influence of varying surface inclination angles on the overall lift augmentation performance of the Coanda jet and the flow behavior under such a setup. To carefully answer the stated questions above, a list of objectives is designed and summarized as follows.

1. To analyze the lift performance of the Coanda jet on the curved surface with varying curvature ratios through experimental analysis.

2. To analyze the lift performance of the Coanda jet on the curved surface with varying curvature ratios and inclination angles through computational simulation analysis.

1.4 Scope and Limitations

It should be noted that the current study focuses on both experimental and computational simulation approaches. The general aim of this study is to offer a preliminary investigation of the design configuration of the Coanda UAV, which involves the profile of the curved surface. In this early stage of analysis, simplification is assumed to break down the complexity of the problem. Here, only 2-dimensional flow is considered due to the symmetricity of the semi-spherical geometry of the Coanda UAV. Since the static pressure on the curved surface of the Coanda UAV is similar due to the symmetricity of the geometry at any horizontal plane, the test model can be further simplified into a quarter of the sphere. In this study, the analysis is focused more on the aerodynamic lift augmentation during the hovering flight since the rotary wing UAV uses a large amount of energy to stay afloat in a fixed position. Again, due to the symmetricity of the semi-spherical geometry, any drag force acting on the Coanda UAV is canceled out by another drag force similar in magnitude on the opposite side of the Coanda UAV. Therefore, in this analysis, the drag force is omitted.

Based on Darvishpoor et al., the application of small UAVs in the urban area is limited by the dynamic flight environment and operational constraints, resulting in its operation within a low Reynold number regime with the typical flight speed varying from 6 m/s to 20 m/s (Darvishpoor et al., 2020). However, these speeds are applicable for forward flight only and since the maximum jet velocity of a Coanda UAV is limited by the highest RPM of the motor used to drive the rotor, there is no upper limit on how far should the jet speed needed to be analyzed in this study. Hence, the upper limit of the speed obtainable by the blower used in the experiment is taken as the cap. Therefore, the current study analyses the flow with the jet velocity of 10 m/s to 30 m/s with an increment of 10 m/s.

1.5 Thesis Structure

This thesis will be decomposed in the following way. In Chapter 1, an introduction to the topic of study is presented and both objectives and scope of the study are defined. Chapter 2 will present the literature review on flow control through the Coanda jet and the previous attempts to capture the effect both experimentally and numerically. Chapter 3 defines the methodology that will be utilized to achieve the outlined objectives, which involves the experimental static pressure measurement and computational numerical analysis. Chapter 4 exhibits both experimental and numerical results, follow-up by a discussion of the qualitative and quantitative data. Finally, Chapter 5 presents the conclusion obtained from the conducted study.

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