COMPUTATIONAL FLUID DYNAMICS OF UNSTEADY AERODYNAMIC WAKE ON HELICOPTER MAIN ROTOR-HUB ASSEMBLY

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DEDICATION

I dedicated this thesis to my father, Othman Bakar who taught me knowledge best learnt the hard way and my mother, Saitom Idris who taught me that the hardest tasks can be accomplished if you just take one step at a time. My siblings Hamka, Afifi, and Haqim that always supported me even in my craziest time and not forgettingmy friends Mukah, Aiman and Gaspar who always offered me his best thoughts on opinions on my work.

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ABSTRACT

Flow field on the helicopter is intricate and has puzzled aerodynamicists for decades. Tail shake problem has become an issue since the creation of helicopters, where it has caused tremors on the structure of the helicopter, performance, occupant's comfort and interrupted the control, response and quality of the flight. It has been the continuous issues for designers and researchers in improving flight quality and better helicopter performance. However, previous researches focused on unsteady helicopter rotor hub wake at low range advance ratios merely up to 0.3 where the air load pressure was believed to be too small to influence the flow surrounding at the vicinity of tail parts. Therefore, simulation work beyond 0.3 is much required to investigate the unsteady flow characteristics at higher advance ratios. The aim of this research was to identify the aerodynamic characteristics elicited by the unsteady wake of the helicopter's main rotor hub-assembly at higher advanced ratios beyond 0.3 through observations on static and dynamic analyses. The parameters investigated were the rotational speeds of 1200, 1400 and 1600 rpm, with two, three and four main rotor blades, two different fairing configurations and four different angles of attack (α). Rotor aerodynamics was modelled using Computational Fluid Dynamics by employing sliding mesh method to account for rotor rotation and *k-w* Shear Stress Transport for turbulent modelling. The results were collected in percentage and compared with calculation that had been done through experimental works by other researchers. The data collected were pressure fluctuation, turbulent kinetic energy, turbulent intensity and drag force. Dynamic analysis focused on the power spectral density, which showed the wake amplitude formation in the frequency domain. In general, turbulent kinetic energy for four blades rotor components showed higher values as compared to two blades, three blades and fuselage components. Turbulent kinetic energy recorded maximum value from 3.0 m^2/s^2 to 4.0 m^2/s^2 fuselage and 6.4 m^2/s^2 to 10 m^2/s^2 for rotor for elliptical fairing and 6.8 m^2/s^2 to 13 m^2/s^2 and 14 m^2/s^2 to 22 m^2/s^2 for rectangular fairing. Turbulent kinetic energy and turbulent intensity were effected by the number of blades, rotational speed, angle of attack and geometry of fairings. Drag force sourced out from the fuselage created 29% to 70% while the rotor produce 30% to 45% of drag. For dynamic analysis, turbulent kinetic energy of rectangular fairing showed a high wake amplitude of 7268.5 (m^4/s^4)/Hz, while turbulent kinetic energy of elliptical fairing showed wake amplitude of 7285.3 (m^4/s^4)/Hz, which showed the effect of complex geometry on the turbulent formation. Furthermore, the simulation conducted on the actual rotor hub indicated that a rotational speed of 1200 rpm has the highest value of turbulent kinetic energy of 42.7 (m^4/s^4)/Hz without the fairing employment. Employment of fairing has proven to reduce the formation of wake frequency. The results from 1200 rpm rotational speed were successfully validated with past researchers' results in predicting the wake formation based on the frequency domain. In conclusion, the study successfully showed that the formation of unsteady wake sourced from a simplified model helicopter drawn and proved the presence of fairing does reduce the wake formation on the aft of the fuselage. Subsequently, this research proposes that three rotor blades with an elliptical fairing configuration is the best configuration with the lowest wake formation.

ABSTRAK

Medan aliran pada helikopter adalah rumit dan telah membingungkan ahli aerodinamik sekian lama. Masalah getaran pada ekor helikopter telah menjadi isu sejak penciptaannya, yang mana ia telah menyebabkan gegaran pada struktur helikopter, pengurangan prestasi, keselesaan penumpang, mengganggu kawalan, tindak balas dan kualiti penerbangan. Ia telah menjadi isu berterusan dalam menambah baik ke arah penerbangan berkualiti dan helicopter berprestasi lebih baik. Walaubagaimanapun, fokus kajian terdahulu mengenai pemutar had keracak helikopter yang tidak stabil telah dilakukan pada julat rendah nisbah mara sehingga 0.3 yang mana beban tekanan udara dipercayai terlalu kecil untuk helikopter mempengaruhi aliran sekeliling di sekitar bahagian ekor. Oleh itu, kerja simulasi melebihi 0.3 amat diperlukan untuk menyelidiki ciri aliran tidak mantap pada nisbah mara yang lebih tinggi. Tujuan penyelidikan ini adalah untuk mengenal pasti ciri-ciri aerodinamik yang terkesan disebabkan keracak tidak-tetap dari pemasangan hab pemutar utama helikopter pada nisbah lebih tinggi melebihi 0.3 melalui pemerhatian pada analisis statik dan dinamik. Parameter yang disiasat adalah kelajuan pada putaran 1200, 1400 dan 1600 rpm, dengan dua, tiga dan empat bilangan bilah pemutar utama, dua konfigurasi reraut berbeza dan empat sudut serang (α) yang berbeza. Pemutar aerodinamik dimodelkan menggunakan kaedah jejaring gelangsar untuk putaran hab pemutar dan pemodelan gelora *k-w Shear Stress Transport*. Keputusan dikumpul melalui kadar peratus dan telah dibandingkan dengan pengiraan yang dilakukan melalui kerja-kerja eksperimen oleh penyelidik lain. Bentuk data yang dikumpul adalah perubahan tekanan, gelora tenaga kinetik, keampatan gelora dan daya seretan. Analisis dinamik memberi tumpuan kepada ketumpatan spektrum kuasa, yang menunjukkan pembentukan amplitud terhadap domain frekuensi. Secara umumnya, gelora tenaga kinetik bagi komponen dengan empat bilah menunjukkan nilai yang lebih tinggi berbanding dengan dua, tiga bilah dan komponen fiuslaj. Gelora tenaga kinetik mencatatkan nilai maksimum dari 3.0 m^2/s^2 hingga 4.0 m^2/s^2 untuk fiuslaj dan 6.4 m^2/s^2 hingga 10 m^2/s^2 untuk pemutar bagi reraut elips dan 6.8 m^2/s^2 hingga 13 m^2/s^2 dan 14 m^2/s^2 hingga 22 m^2/s^2 untuk reraut segi empat tepat. Gelora tenaga kinetik dan keampatan gelora terbukti dipengaruhi oleh bilangan bilah, kelajuan putaran bilah, sudut serang dan geometri reraut. Daya seret yang diperoleh daripada fiuslaj memenuhi keputusan data yang dikumpul oleh penyelidik lain bahawa ia menghasilkan 29% hingga 70% daya seretan manakala pemutar menghasilkan 30% hingga 45% . Manakala, analisis dinamik reraut segi empat tepat untuk gelora tenaga kinetik menunjukkan amplitud yang tinggi sebanyak 7268.5 ((m^4/s^4)/Hz), bahkan reraut elips untuk gelora tenaga kinetik menunjukkan amplitud setinggi 7285.3 ((m^4/s^4)/Hz), menunjukkan kesan geometri yang rumit membantu dalam penghasilan dan pembentukan gelora. Tambahan pula, simulasi yang dilakukan pada hab bilah sebenar menunjukkan bahawa 1200 rpm mempunyai nilai gelora tenaga kinetik tertinggi iaitu 42.7 ((m^4/s^4)/Hz) tanpa pemasangan reraut. Penggunaan reraut terbukti dapat mengurangkan pembentukan kekerapan gelora. Hasil daripada kelajuan putaran 1200 rpm telah berjaya disahkan dengan penyelidik lepas dalam pengiraan pembentukan amplitud berdasarkan domain frekuensi. Kesimpulannya, kajian telah membuktikan kehadiran reraut dapat mengurangkan pembentukan keracak tidak- tetap pada fiuslaj dan mencadangkan tiga bilah pemutar reraut elips adalah model konfigurasi helikopter terbaik dengan kadar pembentukan dan penghasilan gelora terendah.

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CHAPTER 1

INTRODUCTION

1.1 Background

Helicopter is a wingless aircraft that can attain vertical flight from the gyration of overhead blades (Brain et al., 2018). Helicopter runs through revolution of blades that forming a lift (Robert, 2017). Its ability to fly in multiple directions has been admired vigorously. Flight condition and duration are crucial as thehelicopter itself (Lombardo, 1993). De Jonge (1986), stated that helicopter manoeuvre results in a number of continuous incremental load of cycles as compared to a fixed wing. Advance helicopter design continuously focuses on implementation of a better and faster helicopter. However, the intricate geometry or rotational effect does play a vital role in the production of hub drag (Raghav et al., 2013). Large eddy motion usually found in the formation of an unsteady wake, which shed downstream along the tail boom of the helicopter, usually create irregular frequency. As the unsteady wake hits the vertical tail rotor, the impact causes the formation of tail shakephenomenon. The aerodynamic interaction between a rotor and fuselage is complex and difficult problems. Understanding the component on the helicopter plays an important role in knowing the parts that involved in initiation of unsteady wake. Engine, main rotor and tail rotor are important key parts in flight formation; however, each component contributes to its own mechanical vibration. Therefore, investigation on the presence of unsteady wake will be the focus especially the unsteady wake interaction on main rotor hub assembly.

1.2 Importance of Rotor System

Helicopter is known for its specialty and uniqueness through their ability to manoeuvres in multiple directions during flight (Lombardo, 1993). However, everythingcomes with limitation. To obtain a better flight quality for a helicopter, new technology and ideas had been presented. Even though many aeronautic companies had come with various designs of helicopter with certain functionality, yet, it all comes down to blades of the rotor. Rex (2020) stated that vibrations and vibratory loads propagated through the rotor system into fuselage through rotor shaft and flexible control linkage, mechanically. Similarly, as stated by Wang (2020), to improve a helicopter ride, designers were required to minimise the vibration, which mostly originates from the rotor and interface with fuselage. De Jonge (1986) stated that it was difficult to accurately predict the rotor blade loading since it has to currently follow up with air worthiness requirements and fatigue analysis must be based on the existing measured loads. David (1986) and Brocklehurst (2013) had done a research on the characteristic of the optimum dynamic and a review paper on various design of rotor blade tip, which determined the best design and highest lift recorded. A desirable flight condition such as producing the best lift with minimum drag and fuel consumption is favourable. This project, concentrating on the main rotor hub assembly itself. There were few scholars who did a design on the main rotor hub to reduce the drag produced, for example, by Khier (2012). Khier (2012) stated that one third of the total drag on a modern conventional helicopter is attributed to the rotor hub and major contributor to the tail shake phenomenon (Cassier, 1994). Tail shake phenomenon relates to an anti-torque system, especially during forward flight, whereby, in this state, the highly unsteady main rotor wake strikes onto the tail boom and empennage, which excites a fluctuation of the lateral bending moment on the helicopter fuselage (Kowarsch et al., 2014). This high vibration level is considered to be unfavourable. Figure 1 shows the anti-torque system of the helicopter that is used to counter the torque production from the blade rotation.

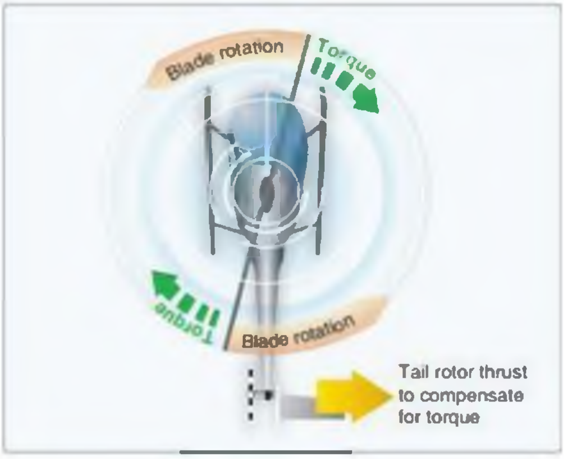

Figure 1 Anti-torque rotor produces thrust to oppose torque (FAA ,2012).

Anti-torque system or also known as tail rotor is one of the control system that was design to help counter the torque created from the blade rotation. Through the control panel, the flight crew vary the thrust located on the tail rotor to maintain the direction of flight, especially during yaw or changing heading while hovering(Federal Aviation Administration, 2012). Tail rotor acts as the mounting for a single tail rotor as it creates torque during helicopter turns, whereas the rotor blades generate yawing effect (Padfield,1996). It is stated that in achieving a static stability even in the directional mode, the yawing derivative, Cn_{β} must be a positive value whereby it will turn to its balance condition when subjected to a yawing disturbance (Nelson,1998). However, the focus of this project is to investigate the formation of an aerodynamic unsteady wake on main rotor hub which leads to the creation of tail shake phenomenon. There are two parts of the system that play crucial roles in flight and stability in unsteady wake investigation which are the main rotor and tail rotor.

1.3 Interaction of Unsteady Wake

Turbulent formation usually occurs due to disturbance of air flow surround or through an area that divert the original flow. Reduction or an increment of velocitydue to surface roughness effects the generation of turbulent. It can be visibly seen on wingtip of a fixed wing during high speed flight whereby vortices occur due to the pressure differential over the wing surfaces (IVAO, 2018). Jimenez et al. (2016) stated that fuselage is one of the main contribution of a parasite drag which supported by Raghav et al. (2013) whereby 50% to 70% of drag generated by the fuselage of a helicopter that included both the main rotor fairing and hub. The complex geometry of the main rotor hub is one of the reason for the generation of unsteady wake that been said to contribute 25% to 30% of aircraft parasite drag (Kowarsch, 2014). Kowarsch (2014) listed that without the main rotor hub cap, it reduces the parasite drag portion by 5.7%, however, in the design stage of a helicopter, the number of rotor blade is crucial since it is closely related to main rotor hub assembly. The number of blades relatively dependent in the mission and weight of the aircraft. Most helicopter with one or two passengers tends to be assembled with a single rotor blade. Robinson R22 is one of lightweight helicopter that commonly employed for surveying purposes whereby it is assembled with a single rotor blade. However, helicopter such as Chinook CH-47 is design for military mission and for heavy lifting, therefore the ideal CH-47 assembled with six rotor blades. The angle difference on rotor blades could cause the existenceof a wake turbulence. Moreover, the interference between the geometry of fairings and number of blades could lead to an increase of turbulent wake formed on the aft of a helicopter. In this paper, different number of blades and design of fairings will be used to observe the interference effects of geometry and number of blades in the formation of turbulent. Also, to prove either in the presence of hub cap or fairings, the wake frequency will be reduced. Figure 1.1shows the area that believed to be contributing to the production of unsteady wake and tail shake phenomenon.

Figure 1.1 Main rotor hub assembly (FAA, 2012).

During the forward flight, the geometry on the main-rotor-hub assembly includes the number of main-rotor blades believed to contribute to the formation of unsteady wake. Physically, the geometries of the main-rotor-hub assembly can be seen to have sharp edges and irregular surfaces that deflects the free stream flow. Refer the blades rotation into an element, which is labelled in red and black, as shown in Figure 1.2. Velocity is the best parameter used to explain and visually show the derivatives or changes that occurred during the flight. Figure 1.2 shows the adverse velocity generated alongthe main rotor blade. The analysis is based on the location of the element that moves further away from the hub with the velocity produced, also known as tip speed. During a normal rotation of blades, the red label element has higher velocity as compared to an element in black label whereby it is position closer to the centre of the main rotor hub.

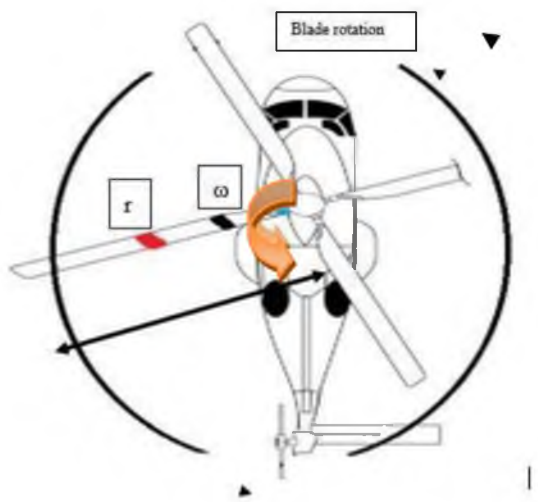

Figure 1.2 Velocity differences along the main rotor blades

Equation (1) shows the relationship between the velocity of a blade element and the distance of an element to the centre of the hub.

$$V = \omega r \quad (1)$$

Where; the V = blade velocity, (m/s)

ω = angular velocity (revolution per min)

r = distance from the centre of hub to the colour label, (m)

Equation (1) shows that the velocity is proportional to the distance from centre of the hub, r. It is proven that velocity increase as the well as the blade length increases. The speed of the tip of the blades is greater related to the speed of the blades which closer to the main rotor hub. The velocity difference causes the formation of velocity in irregular magnitude along the main-rotor blades. This produces pressure differential, which at particular pitch angle may cause the tail shake phenomenon. Figure 1.3 shows the top view of a helicopter that is assumed to be in a control system, with incompressible flow at forward flight condition. The velocity derivatives at the tip of the blades would produce higher velocity with an additional of free stream flow velocity. Stream flow increases the level of velocity as it is further way from the centre of rotation. The irregular velocities along the main-rotor blade generated are one of the causes of the uneven wake of the main rotor hub.

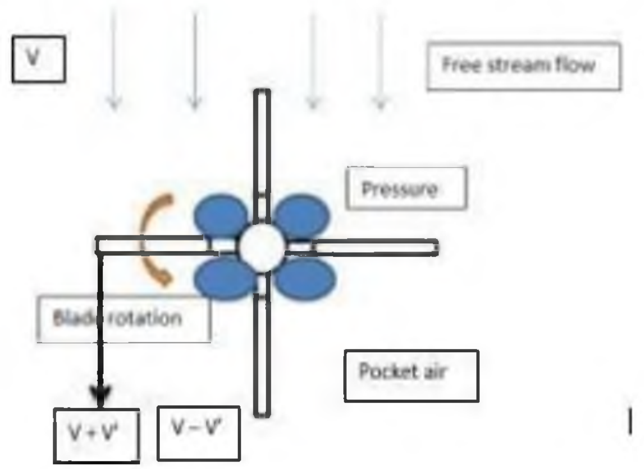

Figure 1.3 Velocity difference between the tip and the centre of the rotation.

Where,

V= Free stream flow velocity
V' = Derivative of velocity.

The adverse velocity along the rotor blades causes an adverse pressure, which leads to the formation of turbulent and wake. The cyclic load of blades generates an alternate form of adverse pressure in the form of air pocket. During forward flight, these air pocket's adverse pressure travel towards the aft post of fuselage and hit the tail rotor continuously, whereby it leads to a so-called tail shake phenomenon. Vibration typically occurs between one and two times the rotor rotational frequency (Waard &Trouve,1999). The wake of the main rotor, the rotor hub and the airframe that imposes on the tail boom, causing an excitation of low-frequency of the entire helicopter airframe (Schaeferlein et al., 2017). Figure 1.4 shows the visual formation of unsteady wake sourced out from main rotor assembly.

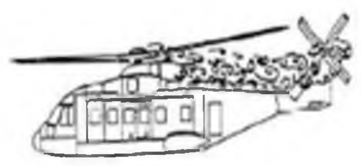

Figure 1.4 Schematic of tail shake phenomenon (Waard and Trouvé, 1999)

The unsteady wake was justified to affect the control performance and safetyof the helicopter structure. It is said to be complicated and leads to a complexity in understanding the aerodynamics itself (Hassan et al., 1999). Supported by Roesch and Dequin (1983) who stated that tail shake helicopter phenomenon caused the disturbance in performance, passenger's comfort and control quality. Interactional Aerodynamics (I/A) still remain a prolong issue for continuous investigation. This is also agreed by Schaeferlein (2017), whereby such phenomenon described a significant interaction of the rotor wake with structure of the airframe leading to the flight instability and reduction in ride comfort.

A wind tunnel is an unwieldy device that need continuous monitoring and maintenance as compared to Computational Fluid Dynamic (CFD) which is a modern instrument that helps to reduce the time and cost of a simulation. However, a validation stage through grid independent study is required. It is to comprehend the capabilities of the software and the computer itself. Without validation, it cannot be a definite result. Vertical tail and the main rotor hub interaction is said to be the consequence of tail shake phenomenon, although the researcher's hard work and a lot of effort given, yet little information of tail shake phenomenon had been made (Coton, 2009). Coton

(2009) said it was due to most data which were kept sensitive and private from most researchers.

1.4 Problem statement

The rotor hub system is one of the primary contributors to the helicopter parasite drag and inherent limiters to maximise the helicopter forward-flight speed (Reich et Al., 2016). Previous conducted study stated that one third of the total drag was generated from the rotor hub and this statement achieved from the analysis conducted on a modern conventional helicopter (Khier, 2012). Supported by Schaeferlein (2017), that rotor hub fairing, engine exhaust, cowling, the shape, position and dynamics of the tail boom play a key role in the characteristics of the tail shake phenomenon. Minimalising the production of drag is very much desired and an essential step in developing an operative, effective helicopters. However, the main rotor hub assembly believed to be the foremost contributor in tail shake phenomenon (Cassier, 1994). Interactional Aerodynamics (A/I) is complex even after experiencing and conducting many works, yet it is still hard to confidently predict the result without any flight test of a new design helicopter (Waard & Trouvé, 1999). Due to sensitivity issues, most helicopter manufacturer tended to keep the A/I data away from most researchers and reduces the chances of understanding the complexity of tail shake phenomenon.

Variation of time makes unsteady flow to be difficult and complicated as compared to a steady flow (Brock et al., 1972). In maintenance of an aircraft, some parts are required to undergo periodic maintenance based on the system cyclic. Through a continuous hours of flying, vibration is not something yet to be avoided by any mechanical system. Through unsteady wake formation source from the main rotor hub, it will create a tremor on the helicopter's tail boom that generates continuous vibration which leads to poor control performance and responsive quality of the helicopter. Excessive vibration and additional of external forces reported to be one of the reason of any helicopter crashed incident. Wake is divided into near and far wake which comprised trailed and shed vorticity which later on created vortex (Xu Guo et

Al., 2002). The pulsation frequency plays the main part in the helicopter crash incident. The low inducedvelocity of the main rotor as well as the additional descent rate leads to a strong interaction between the main rotor wake and tail boom (Schaeferlein et al., 2017). A subtle frequency existed as the rotor blades rotation been disrupted, however, with presence of outward forces, an intermediate vibration could be generated leading to disengagement of loose components on helicopter. A high frequency vibration can be detected especially when the tail rotor, tail drive cable and shaft, tail fan shaft vibrates equally or beyond the speed of tail rotor. In any circumstance, whereby the main rotor hub assembly wake coincides with the natural frequency on the tail section, a robust intensification would occur which leads to an impulsive structural failure that may transpire due to fatigueproblems. Addition of drag can be detected from the tail shake phenomenon that leads to poor handling and comfort. Moreover, the stability characteristic such as yawing and pitching can be affected (Ishak, 2012). By using the Computational Fluid Dynamics (CFD), an investigation on unsteady flow of air at constant velocity, various rotational speeds, and in different pitch angle, would help in understanding the effects of the unsteady wake produced from the main rotor hub assembly. It is important to perceive the outcome of the unstable flow under selected flight parameters. study Previous study researcher on the low range advance ratios of up to 0.3. However, the air load pressure is believed to be quite small for both the low and high pitching positions indicating that the wake generated is too small to influence the flow surrounds in the vicinity of tail parts (Leishman et al., 1996). Obviously, higher advance ratio works are highly demanded and this paper focuses on investigating the effects of high advance ratio towards the wake formation.

1.5 Objectives

1) To investigate the unsteady aerodynamic load characteristics triggered by the unsteady wake of the helicopter's main rotor-hub assembly through numerical simulation.
2) To evaluate the static and dynamic analyses of unsteady wake of main rotor-hub assembly of a simplified and real rotor models for different flight configurations.

1.6 Scopes of Study

The following are the scopes that will be covered:

1. Develop a simplified three-dimensional model of the main-rotor-hub helicopter for unsteady wake analysis.
2. Simulations on the actual helicopter model by using CFD software with various helicopter configurations and flight parameters.
3. Flight parameters and configurations that shall be studied:

   i) Advance ratio / rotational speed
   ii) Number of main rotor blades
   iii) Configurations
   iv) Angle of attack (α)
4. CFD results will be validated with experimental results conducted by other researchers.

From the selected flight configurations, this paper will be able to observe the formation of adverse pressure gradient surrounding the simplified and real rotor model. Quantified the amount of turbulent, pressure and drag generated and compared the effects of stream flow due to complex geometry and employment of fairing on the after wake for static and dynamic analyses.

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LIST OF PUBLICATIONS

Conference Proceeding

1) Othman, N., Ishak, I.S. and Dahalan, M.N., Numerical Studies on Turbulence Modelling of Symmetrical Aerofoil. *Sharing Visions and Solutions for Better Future*, p.192.

Indexed Journal

1) Othman, N., Ishak, I.S. and Dahalan, M.N. (2021) ‘Static Analysis of Unsteady Aerodynamics Wake of Simplified Helicopter Model via Simulation Work’, Journal of Advanced Research in Fluid Mechanics and Thermal Sciences. (Accepted)