UNIVERSITI PUTRA MALAYSIA

*EFFECT OF SURFACE ROUGHNESS ON HELICOPTER MAIN ROTOR BLADE*

WAN NORHAFIZAN BIN WAN ROHIZAN

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# EFFECT OF SURFACE ROUGHNESS ON HELICOPTER MAIN ROTOR BLADE

By

**WAN NORHAFIZAN BIN WAN ROHIZAN**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science**

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the Degree of Master of Science

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**April 2017**

**Chair: Assoc. Prof. Azmin Shakrine bin Mohd Rafie, PhD**
**Faculty: Engineering**

This study describes the effect of surface roughness when applied on helicopter main rotor blade. The study was performed in wind tunnel using scaled helicopter model to study the aerodynamic characteristic in vertical flight condition. This is to show the feasibility of surface roughness for rotary wing applications. The requirement for helicopter main rotor blades are high thrust and low power requirement. Smooth profile of main rotor blade is modified by applying surface roughness on the upper and lower camber in transition and turbulent boundary layer region; starting from 25% of chord length and gradually extended to trailing edge (TE). The analysis following the research shows that with right application of roughness will result in lower power requirement. The aerodynamic efficiency is enhanced at lower and upper pitch level between 7% to 69%. However, this came at the expense of reduced thrust at middle collective pitch level between 11% to 45%. Surface roughness found to have insignificant effect on rotor power requirement (only 2% to 5% difference). At upper range of collective pitch level, surface roughness is seen to delay the stall angle as well as increasing the lift in the stall region. Meanwhile for aerodynamic efficiency, thrust-to-power ratio shows less steep graph and peak ratio were pushed to higher pitch level. This indicates wider operating envelope and more predictable flight profile. All these results may provide foundation for further research to further optimisation of surface roughness effect for rotary wing aircraft.

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

**KESAN KEKASARAN PERMUKAAN PADA BILAH ROTOR UTAMA HELIKOPTER**

Oleh

**WAN NORHAFIZAN BIN WAN ROHIZAN**

**April 2017**

**Pengerusi: Prof. Madya Azmin Shakrine bin Mohd Rafie, PhD**
**Fakulti: Kejuruteraan**

Kajian ini menerangkan kesan kekasaran permukaan apabila diaplikasikan pada bilah rotor utama helikopter. Kajian dijalankan dalam terowong angin menggunakan model skala helicopter bagi mengkaji ciri-ciri aerodinamik dalam keadaan penerbangan menegak. Ini bagi membuktikan kesesuaian kekasaran permukaan bagi aplikasi sayap putar. Profil asal bilah rotor diubah dengan meletakkan permukaan kasar di bahagian atas dan bawah, mulai daripada 25% *chord length* dan beransur-ansur ditambah sehingga ke *Trailing Edge* (TE). Analisis daripada eksperimen tersebut menunjukkan: Dengan aplikasi yang betul akan memberikan keperluan kuasa yang lebih rendah; Keberkesanan aerodinamik lebih baik dapat dicapai pada julat dongakan bawah dan tinggi dengan penambahbaikan antara 7% hingga 69%. Namun, pemnambahbaikan ini datang dengan pengurangan tujah di julat pertengahan antara 11% hingga 45%. Kekasaran permukaan didapati mempunyai kesan yang tidak signifikan kepada keperluan kuasa rotor (hanya perbezaan antara 2% hingga 5%). Di julat atas, kekasaran permukaan diperamati meningkatkan sudut pegun di samping meningkatkan tujah di zon pegun. Manakala bagi keberkesanan aerodinamik, nisbah tujah-kepada-kuasa menunjukkan graf yang kurang curam dan nisbah maksimum berada di sudut dongakan yang lebih tinggi. Keadaan ini menunjukkan julat operasi yang lebih lebar dan profil penerbangan yang lebih mudah dijangka. Semua hasil kajian ini boleh menjadi asas untuk kajian seterusnya bagi lebih optimisasi kesan kekasaran permukaan untuk pesawat sayap putar.

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I certify that a Thesis Examination Committee has met on 7 April 2017 to conduct the final examination of Wan Norhafizan bin Wan Rohizan on his thesis entitled "Effect of Surface Roughness on Helicopter Main Rotor Blade" 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.

Members of the Thesis Examination Committee were as follows:

**Md Amzari bin Md Zhahir, PhD**
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
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**Fairuz Izzuddin bin Romli, PhD**
Senior Lecturer
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Professor
Universiti Sains Malaysia
Malaysia
(External Examiner)

**NOR AINI AB. SHUKOR, PhD**
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 6 July 2017

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

**Azmin Shakrine bin Mohd Rafie, PhD**
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

**Mohamad Yazdi bin Harmin, PhD**
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
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I hereby confirm that:

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Name of Chairman of Supervisory Committee: Assoc. Prof Dr. Azmin Shakrine bin Mohd Rafie

Signature: ______________________
Name of Member of Supervisory Committee: Dr. Mohamad Yazdi bin Harmin

## TABLE OF CONTENTS

## LIST OF TABLES

# LIST OF FIGURES

## LIST OF NOMENCLATURE

| | |
|---|---|
| Re | Reynolds Number |
| CFD | Computational Fluid Dynamics |
| TE | Trailing Edge |
| VG | Vortex Generator |
| LE | Leading Edge |
| $\alpha$ | Angle of Attack |
| $U$ | Relative Wind |
| $\theta$ | Pitch Angle |
| $\rho$ | Air Density |
| $A$ | Rotor Disc Area |
| $C_T$ | Coefficient of Thrust |
| $C_P$ | Coefficient of Power |
| $V_T$ | Tip Speed of Rotor Blade |
| $s$ | Rotor Solidity |
| $N$ | Number of Blades |
| $c$ | Chord Length |
| $R$ | Rotor Swept Radius |
| I | Current |
| V | Voltage |
| P | Power |
| $C_L$ | Coefficient of Lift |
| $C_D$ | Coefficient of Drag |
| $\omega$ | Angular Speed |
| $\mu$ | Dynamic Viscosity |

# CHAPTER 1

# INTRODUCTION

The advent of helicopter is considered one of the most important milestones in aviation. Even though the development started later and not much publicised compared to the development of fixed wing aircraft, the versatility of helicopter makes it a choice among civilian and military operators. It is also observed that aerodynamics of helicopter is largely influenced by rotor blade aerodynamics, and aerodynamic design of its airframe has lesser influence on flight performance compared to fixed wing aircraft. Therefore, this study is focused on helicopter rotor blades in order to enhance flight performance.

## 1.1 Background

Helicopter is a type of rotorcraft (also known as rotary wing aircraft) that uses rotating wings (known as blades) to fly. As mentioned by Johnson (2013), the rotor blades rotate depicting a disk in horizontal (or almost horizontal) plane. A helicopter with its rotating blades can generate aerodynamic forces via its motion relative to the air. Given this feature (which is unique to a rotorcraft), these forces can be produced even though the velocity of the airframe is zero, in contradiction of fixed-wing aircraft in which the airframe needs translational velocity to sustain flight (Johnson, 2013).

According to Seddon and Newman (2011), the history of rotary-winged flight can be traced from 400 B.C. with a toy known as Chinese top or bamboo-copter (Figure 1.1). It was constructed with a shaft attached to wings inclined to the rotation plane normal to the shaft. When spun between the hands and released, it generated thrust which allow it to fly for a short time. Even though simple, it provided inspiration for invention of helicopters.

**Figure 1.1: Chinese Bamboo-copter**
(Source: kaleidoscope.cultural-china.com/en/144Kaleidoscope1053.html)

A famous artist and inventor Leonardo da Vinci conceived his design of a helicopter (Figure 1.2). Similar to many of his ideas, the design never left the drawing board, but the drawings and notes charted exactly how a helicopter would operate. With the purpose of compressing air to obtain flight, the helical screw on his design formed a basis on how a helicopter rotor blade would be.

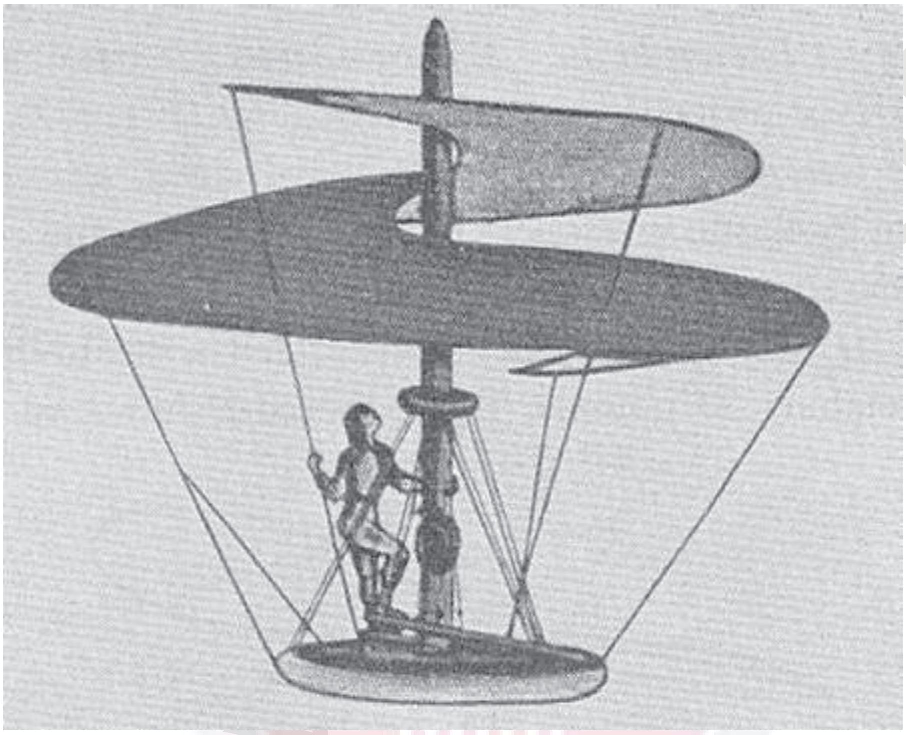

**Figure 1.2: Leonardo da Vinci's "Helicopter"**
(Source: http://www.aerospaceweb.org/design/helicopter/history.shtml)

Meanwhile, Sir George Cayley wrote an aeronautical paper which laid the foundation for future helicopter development (Seddon and Newman, 2011). He envisioned an air vehicle consisting of two pairs of contra-rotating rotors arranged coaxially to generate lifting thrust. The forward propulsion of this so-called "aerial carriage" was provided by two propellers mounted at the rear. This design was the sign of many features of modern rotary-winged craft. This awkward design (Figure 1.3) was an improvement compared to other contemporary projects; however due to unavailability of suitable propulsion, the project never materialised.

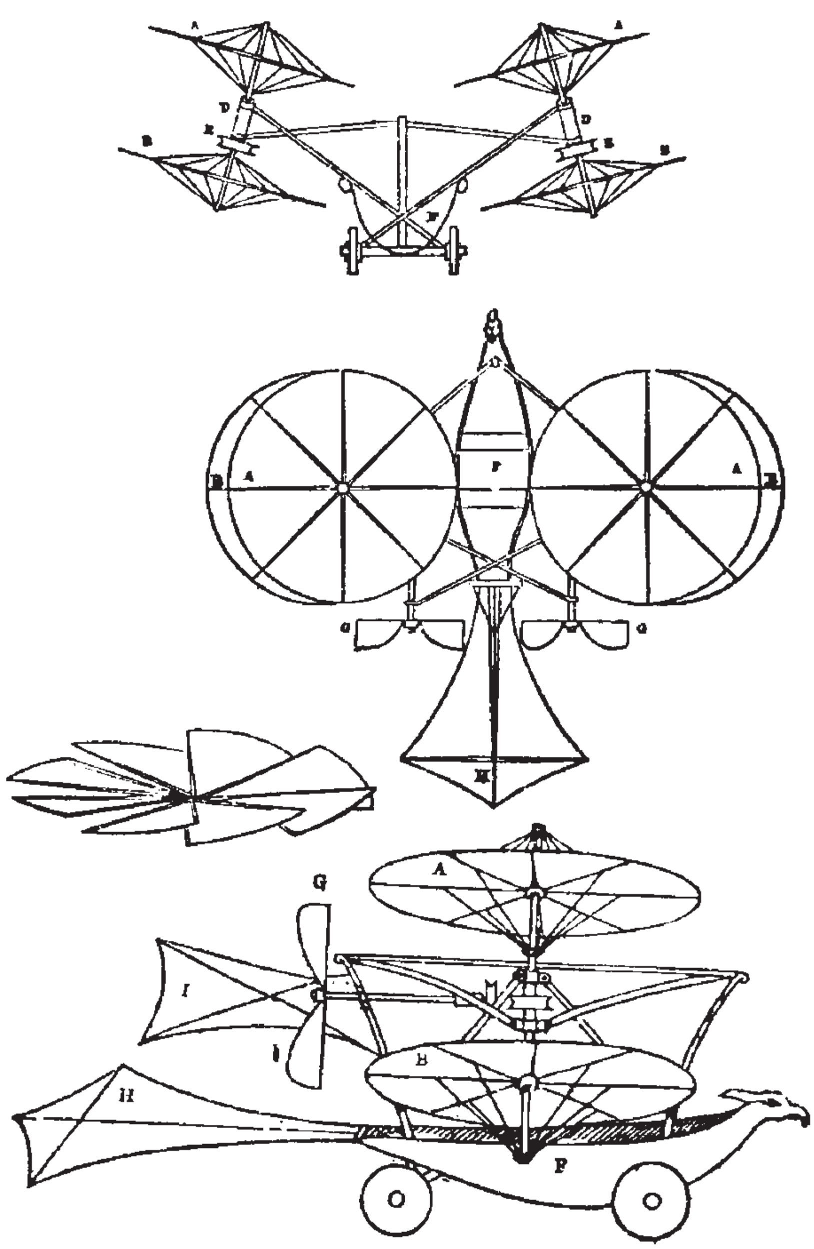

**Figure 1.3: Sir George Cayley's "Aerial Carriage"**
(Source: http://www.aviastar.org/helicopters_eng/cayley.php)

American inventor, Thomas Alva Edison was facing the same problem that Cayley and other aircraft experimenters had; which was lack of suitable propulsion (www.aviastar.org/history). In 1880, he examined the thrust vs. power performance. He tested on various designs of rotor blades in order to find out those with the best lifting power. With only electric motor at his disposal (since internal combustion engines did not yet exist), he found it as unsuitable for the purpose. With this in mind, he shifted his focus to the engine instead. He was thinking of one with small weight with a good amount of horsepower. In a notable attempt, he used gun cotton in the cylinder of an engine fired with a spark. He attained good results, but at the expense of near-fatal injury to him and one of his colleagues.

This incident forced him to abandon his helicopter experiments and focused on more pressing work. Nevertheless, his work provided estimation of the required power-to-weight ratio for a workable helicopter to be achieved (Seddon and Newman, 2011). He concluded, no helicopter would be able to fly until engines with power to weight ratio of 3 to 4 lb/hp were available (Johnson, 2013). In parallel with this finding, he also confirmed that the most suitable propulsion means for helicopter is the one with high power-to-weight ratio.

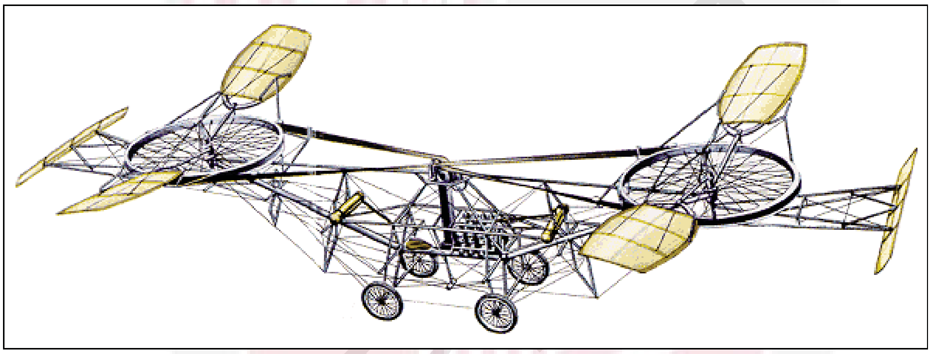

**Figure 1.4: Paul Cornu's "Cornu Helicopter"**
(Source: http://www.aviastar.org/helicopters_eng/cornu.php)

Meanwhile in 1906, a Frenchman, Paul Cornu pioneered first free flight of helicopter. His twin-rotored helicopter (Figure 1.4) rose to between 1 and 5 feet of altitude for a period of 20 seconds. This is considered a significant milestone, since the flight controls entirely achieved from the aircraft without any interference or attachment from the ground, hence giving the distinction of first free flight of helicopter. Since then progressive developments have been made until the birth of Focke-Wulf 61 as first operational helicopter in 1936. This is later followed by Sikorsky's R-4 helicopter which became the first mass-produced helicopter in 1942. Since then helicopter has evolved into multiple type of configurations; from its earlier designs of more than one main rotor, to single main rotor with anti-torque tail rotor arrangement, tandem rotors (Figure 1.5), compound helicopter (Figure 1.6), tiltrotor (Figure 1.7) and coaxial helicopter (Figure 1.8).

**Figure 1.5: Boeing CH-47 Chinook**
(Source: http://www.militaryfactory.com/aircraft/detail.asp?aircraft_id=56)

**Figure 1.6: Airbus Helicopters' X3**
(Source: http://www.militaryfactory.com/aircraft/detail.asp?aircraft_id=880)

**Figure 1.7: Bell-Boeing V-22 Osprey**
(Source: US Navy)

**Figure 1.8: Kamov Ka-27 "Helix"**
(Source: US Navy)

The first true turboshaft engines developed for helicopter was built by French firm Turbomeca in 1948, with the creation of a turboshaft engine code-named

"782". Originally developed as auxiliary power unit, it was soon adopted to aircraft propulsion, and settled down as a niche power plant for turboshaft driven helicopters back in the 1950s. However, in 1951, Charles Kaman with his K-225 synchropter modified to receive newly-developed Boeing T50 turboshaft engine became the first ever turboshaft-powered helicopter to fly (www.faa.gov).

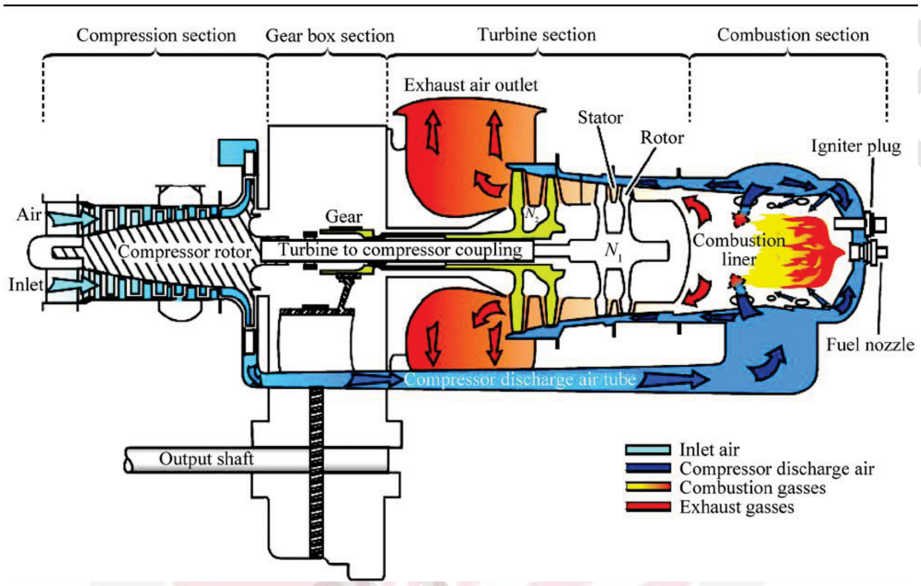


**Figure 1.9: Turboshaft Gas Turbine Schematics**
(Source: Nkoi et al, 2013)

Turboshaft engines (Figure 1.9) is considered an important leap in helicopter development. With high power-to-weight ratio, turboshaft engines allowing helicopter to have lighter weight while at the same time having significant higher lift capability. This also translates into the benefit of higher payload.

Because helicopters use rotating blades to generate thrust required for flight, this allows helicopter to hover and have vertical flight (including vertical take-off and landing) capability, in addition to forward and lateral flight. Due to this unique feature, it can operate at areas with limited runway or at isolated or congested areas. Therefore, despite having significantly slower speed than fixed wing aircraft, it is regarded as more versatile than fixed-wing aircrafts; and often tasked to perform missions that other types of aircraft were incapable, or for tasks which require close contact with ground such as medical transport, vertical replenishment or aerial firefighting.

For military use, the function of helicopter evolved significantly for 40 years ago. Not only restricted to troop or logistical transport like before, it evolved into a formidable combat platform and able to perform its own offensive manoeuvre or assisting friendly forces such as anti-tank fire support or in case of shipborne helicopters; assisting in identifying hostile contacts and providing guidance for missile fired from a friendly platform to a target located beyond the horizon, a capability known as Over-The-Horizon-Targeting (OTHT).

## 1.2 Helicopter Rotor Blade

As mentioned by Leishman (2000), a helicopter rotor provides three basic functions; to generate vertical thrust for vertical flight, to generate propulsive force for forward flight, and generating forces and moments for attitude and position control of a helicopter. Unlike fixed wing aircraft where these functions are split, the helicopter rotor must provide all three within single control on the pilot.

The aerodynamics often regarded as more complex than fixed wing, largely due to wakes trailed from each blade. As for fixed wing aircraft, tip vortices will stream away from the aircraft. However, for a helicopter in forward flight, the tip vortices can remain near to the rotor and following rotor blades for several rotor revolutions. These tip vortices can cause fluctuating airloads which can cause excessive rotor vibrations and noise.

During early days of helicopter development, blade airfoil profile was not given priority because of other many technical issues to solve. Although National Advisory Committee on Aeronautics (NACA; precursor to National Aeronautics and Space Administration (NASA)) developed some airfoils dedicated for helicopter in the 1940s, it was only in the middle of 1960s that specially tailored type of airfoil sections for helicopter were widely used by manufacturers (Leishman, 2006).

With regard to rotor blade design, the selection of airfoil type is proven to be more complex than fixed wing because the angle of attack and Mach number vary continuously throughout the spanwise of rotor blade and one airfoil profile cannot satisfy the different aerodynamic requirements. In addition, the complexity of rotor control mechanism makes it difficult to embed any moving-type high lifting device (such as adjustable slot and flap) on the rotor blade as opposed to fixed wing. Given the intricacy of the system, it is obvious that any active based flow control method is impossible to be devised. This causes the design of rotor blade remain basically solid, something unchanged for the past century since the early development of helicopter.

While most airfoil designs are built around 2-D flow, the complex flow at the rotor tip requires 3-D flow consideration as well. Given this, plus severe operating conditions and typically unsteady flow environment on helicopter meaning that rotor blade must be tested in wind tunnel to fully and accurately appraise the aerodynamic performance.

### 1.3 Problem Statement

Due to complexity of the helicopter main rotor mechanism, there is little or no advancement in active flow control method and currently it is impractical to implement such approach. Therefore, passive control flow is seen more viable to be applied. While previous research has been done on the application of surface roughness as passive control flow method, those researches were focused on fixed wing applications and in two-dimensional flow conditions. Given this, there is an opportunity to explore the applications of surface roughness for rotary wing applications. Generally, main criteria for helicopter rotor blade is high thrust with low power requirement.

### 1.4 Objective

The research goals are to come up with improvised surface roughness on helicopter rotor blades, which will enhance the flight performance and power consumption. Specifically, the objectives are as follow:

a. To perform wind tunnel experiment on helicopter main rotor blade using scaled helicopter model to study and find the aerodynamic characteristic in vertical flight condition.

b. To evaluate the effect of surface roughness on helicopter main rotor blade and observe the thrust and power characteristics when surface roughness is applied.

### 1.5 Scope

The report will cover the result of applied surface roughness on helicopter main rotor blade. For rotary wing aerodynamics, the areas of interest are the thrust and power which correspond to lift and drag for fixed wing. This experiment will focus entirely on vertical flight condition, since it is a most complex flight regime for a helicopter. It involves constant correction input which takes toll on power provided, therefore vertical flight (particularly hover condition) is considered as high power consuming flight regime. Therefore, any improvement in vertical flight will subsequently enhance flight performance in other flight conditions.

The limitation of the research is the restricted power supply to the rotor, with maximum power supplied between 44W – 49W. This restricts rotational speed output between 600rpm – 900rpm, equal to linear speed between 20m/s – 40m/s at the rotor tip. Due to this nature, the Reynolds Number (Re) due to flow through the rotor blade will be between $3.7 \times 10^4$ and $5.4 \times 10^4$. This region is considered as transitional flow region as mentioned by McArthur (2008). The limitation is also on blades' collective control mechanism, since the rotational speed variates with pitch level. In addition, no frontal airflow will be used in this research.

## 1.6 Thesis Layout

The layout will be as follows: introduction is provided in Chapter 1 which includes a background in helicopter development and also issues regarding helicopter main rotor blade.

Chapter 2 will cover the literature review for this thesis, which consists of previous research work in related area, as well as theories relevant to the study.

In Chapter 3, the methodology of the study is described and the setup of the experiment will be discussed. This also covers an overview of the wind tunnel, apparatus and the model. Furthermore, the measurement techniques will also be described.

Chapter 4 will give the results and analysis from the experiment. Finally, the conclusion and recommendation will be covered in Chapter 5.

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