Effect of surface roughness on helicopter main rotor blade

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Abstract. This paper describes the effect of surface roughness when applied on helicopter main rotor blade. The aim is to prove that surface roughness can be used as a simple and inexpensive method to achieve better flight performance such as enhanced thrust and/or reduced power requirement. The research was done experimentally, using scaled model of Eurocopter AS350 Ecureuil. Smooth profile of the main rotor blade was 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 extending up to the trailing edge (TE). This study was conducted with the conditions of a vertical flight (particularly in hover condition) since this is a high power-consuming flight regime for helicopter. The experiment resulted in lower power requirement but at the expense of reduced thrust at the middle collective pitch level. At upper range of the collective pitch level, surface roughness was seen to delay the stall angle as well as increase the lift in the stall region. Meanwhile, at lower pitch level, there was an increase in thrust-to-power ratio.

1. Introduction
Given the complexity of the helicopter main rotor mechanism, it is practically impossible to have any active high-lift devices installed on the main rotor blade. Therefore, the blades remain basically solid, a design which is unchanged since the advent of helicopter despite the fact that many researches have been done to achieve improvement in flight performance. The desired improvement includes enhanced thrust (for better flight performance) and lower power requirement (for extended flight duration).

2. Literature review
Looking at previous research works, it is clear that surface modifications can enhance aerodynamic performance considerably as discovered by Reuss [1]. Surface modifications energise the flow by creating vortices, which makes the flow remains attached to the surface and hence delaying boundary layer separation. Meanwhile, the research by Srivastav [2] shows that surface roughness can reduce the drag drastically and improve lift. This can be efficient at high angles of attack and also can increase the stall angle to some extent. Based on the work done by Dhilliban et al., surface modifications on lower surface gives better aerodynamic efficiency than on the upper surface [3]. A research by Noonan et al. using slotted airfoil tips found that at high coefficient of lift, the slotted airfoil profile gave lower coefficient of torque and high figure of merit [4]. In 2012, Jensen [5] conducted a study using airfoil
flap model with vortex generator (VG) and cylinder. He found that, while VG showed notable increase in effects at low angles of attack, the pattern then declined near the stall angle. Furthermore, the use of cylinder showed improvement across the range and performed better than VG.

While all previous works were based on computational, 2-dimensional and in fixed wing condition, no notable work has been done for helicopter main rotor blades. Therefore, this research will explore the effect of surface roughness when applied to the main rotor blades. The values to be observed are the coefficient of thrust \( C_T \) and coefficient of power \( C_P \). It is decided to place the roughness starting from 25% of chord length away from leading edge (LE) and extending up to the trailing edge. This is done since this region is conceived to be where the flow separation will occur, forming transition and turbulent boundary layer region. In addition, Matheis found that adding roughness at LE resulted in drastic loss of aerodynamic performance due to premature flow transition that was caused by the roughness [6]. A study on NACA 0012 profile also showed a lower lift coefficient and a higher drag coefficient when roughness was placed at LE [7]. Moreover, another research found that the presence of roughness at LE of the wind turbine blades caused an early TE turbulent separation, hence reducing its aerodynamic efficiency [8].

According to Johnson [9] and Leishman [10], \( C_T \) and \( C_P \) are defined as in Equation 1 and Equation 2, respectively, in which \( V_T \) is the tip speed of rotor blade.

\[
C_T = \frac{T}{\frac{1}{2} \rho V_T^2 A} \quad (1) \quad C_P = \frac{P}{\frac{1}{2} \rho V_T^2 A} \quad (2)
\]

As cited by Seddon and Newman[11], the rotor solidity is defined as ratio of blade area to disc area, known as \( s \) or sometimes \( \sigma \), given by Equation 3. This ratio is unique to the rotary wing aerodynamic calculations and will be used later to determine the actual \( C_T \) and \( C_P \).

\[
s = \frac{N c R}{A} = \frac{N c R}{\pi R^2} = \frac{N c}{\pi R} \quad (3)
\]

where \( N = \) number of blades, \( c = \) chord length and \( R = \) rotor swept radius.

3. Methodology

This research was done experimentally using an open circuit wind tunnel and a scaled down helicopter model. Although the test was performed using the wind tunnel, no frontal air flow was involved. Instead, only the test section is used, where the helicopter model was mounted on the six-component balance to see the effects in vertical flight.

3.1. Experimental setup

For the experimental model, the Eurocopter AS350 helicopter model (see Figure 1) was chosen since it was available off-the-shelf and can be readily used. The wind tunnel used for the experiment was the OWLT-1000 of Aerodynamic and Fluid Mechanics Lab, Faculty of Engineering, UPM with the test section of 1.0 m × 1.0 m × 1.0 m in dimension. The model was mounted in the wind tunnel and on the electronic six-component balance to measure the thrust and power. The mean rotational speed was measured using multi-range tachometer (see Figure 2) at all collective pitch levels. The measurements were taken in vertical direction at the root of rotor blade. The tachometer displayed different rotational speed at each pitch level. The blade pitch angle was determined visually. The operating parameter of helicopter model is tabulated in Table 1.

The surface roughness profile was prepared using sand paper strip and applied to the main rotor blade surface using double sided adhesive tape. Experimental analysis for smooth surface (baseline) was performed first before applying the surface roughness on the rotor blade. After that, the surface roughness was applied from the tip to near the root, starting from 25% of chord length and extended up until the trailing edge on the upper surface and lower surface (see Figure 3, Figure 4, Figure 5, Figure 6 and Figure 7).
Table 1. Helicopter model operating parameter

| Collective Pitch | Blade Pitch Orientation (+ve/-ve) | Rotational Speed | Linear Speed (m/s) |
|------------------|-----------------------------------|------------------|-------------------|
|                  |                                    | rpm              | rad/s             |                   |
| -2               | -ve                               | 729.60           | 76.40             | 28.27             |
| -1               | -ve                               | 926.60           | 97.03             | 35.90             |
| 0                | 0                                 | 890.00           | 93.20             | 34.48             |
| 1                | +ve                               | 839.40           | 87.90             | 32.52             |
| 2                | +ve                               | 754.46           | 79.01             | 29.23             |
| 3                | +ve                               | 651.90           | 68.27             | 25.26             |

Figure 1. Helicopter model mounted on six-component balance

Figure 2. Multi-range tachometer

Figure 3. Roughness at upper surface covering 25% of airfoil and located 25% from the leading edge

Figure 4. Roughness at lower surface covering 25% of airfoil and located 25% from the leading edge

Figure 5. Roughness at upper surface covering 50% of airfoil and located 25% from the leading edge

Figure 6. Roughness at upper surface covering 75% of airfoil and located 25% from the leading edge
In order to get continuous power supply and subsequently consistent result, a direct power supply of maximum around 45W was used. The readings from six-component balance and power converter were recorded and computed into a simple Excel spreadsheet to determine the values of $C_T$ and $C_P$. Because the rotor solidity ratio, $s$ is instrumental in influencing the experimental results, it was also included in the calculation.

4. Results and discussion

The results for the research are presented in three plots: $C_T/s$ vs. collective pitch, $C_P/s$ vs. collective pitch and $C_T/C_P$ ratio vs. collective pitch. Consistency analysis was also conducted, with repeatability within 1% to 5% for rotor power requirement. However, significant variations recorded for $C_T/s$ value, with deviation up to 0.11 N (which translated to 86% value deviation from average) due to presence of resonance during experimental run.

4.1. Thrust force

Figure 8 shows the $C_T/s$ values at different collective pitch levels for four different roughness models (baseline, 25%, 50% and 75%). Since the thrust was positive (upward) at zero pitch level, it was concluded that the main rotor blade profile was asymmetrical. At lower pitch (-2 and -1), the effect of surface roughness was insignificant, with deviation of only 0.01 in $C_T/s$ value between all roughness condition. At middle range (0 until 2), baseline surface performed better than those with surface roughness. This is also the range where the difference of baseline model against roughness models started to show, where the deviation in $C_T/s$ value increased from 0.02 – 0.03 between all models. Only at the maximum pitch level (3), the baseline model showed a decline in $C_T/s$ value because it had exceeded the stall angle. At this pitch level, all cases of surface roughness outperformed the baseline condition by showing a higher $C_T/s$ value with increment between 23% to 53% than the baseline and without any indication of stalling. One notable pattern could be seen where for all cases with surface roughness, the graphs show an increasing pattern even though at maximum pitch level.

From the graph, it is deduced that stall angle for all cases of applied surface roughness is higher than that of the baseline model. However, those higher values of $C_T/s$ at high collective pitch range come at the expense of lower $C_T/s$ values at middle pitch range. At negative pitch range, the difference
was smaller and deemed insignificant even though all roughness models showed slightly higher $C_T/s$ value, which suggests that higher positive thrust is achieved. Due to limitation of the model’s control mechanism, the stall angle for other conditions cannot be determined. Nevertheless, from the result, it is shown that for both fixed wing and rotary wing, surface roughness is beneficial at higher angles of attack and can push stall angle to be higher to some extent.

4.2. Power requirement

Figure 9 shows the plot of $C_P/s$ versus collective pitch level. The minimum $C_P/s$ values were observed to be in the range between -1 and 0 pitch levels for all roughness models. The baseline recorded the lowest reading. Meanwhile, for other cases, the minimum $C_T/s$ increased as roughness size increased, with increment between 1.05% to 8.06% compared to the baseline model.
The graphs show identical pattern for all roughness condition: as the blade pitch increases, the rotor power requirement also increases until it reaches the maximum blade pitch angle, regardless of the blade pitch orientation. From the graph as well, generally the power requirement for all roughness condition showed a higher reading than the baseline condition. This is due to higher power required to overcome resistance from the rougher surface conditions. However, an exception is for 25% roughness condition, which consistently showed lower power requirement than the baseline model in mid-range (at pitch level 0 until 2). Therefore, in case of lower power requirement becoming the priority, 25% roughness condition should be considered.

Given small values of $C_P/s$, a slight change will give a large difference in percentage as mentioned earlier. Nevertheless, throughout all roughness conditions, only small deviations recorded for $C_P/s$ with the difference was between 2% to 5% at all pitch level (with exception of -2 level due to cut-in power required to rotate the blades from standstill). This was parallel with the power consumed during the test where it showed very consistent pattern. 40 W to 45 W of power was expended at any blade pitch level, with the average figure of 42.12W. The only exception was at -2 level, where the difference in $C_P/s$ value across all roughness ranges were more significant (i.e. 12.48%) because of cut-in power mentioned above. Therefore, it is determined that surface roughness effect is insignificant and has little impact on the rotor power requirement.

4.3. Thrust to power ratio

$C_T/C_P$ ratio curve provides a view on the thrust generated in proportion to the power required at a particular pitch level, while at the same time gives the optimum operating angle of an airfoil. It also shows the aerodynamic efficiency of the airfoil. As shown in Figure 10, the roughness models were deemed effective at negative pitch level (-2 and -1) and high pitch (level 3). However, it comes at the expense of lower $C_T/C_P$ ratio at the middle range (0 to 2) where the baseline model gave a better performance. When the operating angle was pushed at higher pitch level and at maximum pitch (3), the improvement was 50% higher than the baseline model (whereas for baseline model, $C_T/C_P$ ratio started to drop beyond pitch level 2). Between the three roughness models, the 75% roughness showed the highest aerodynamic efficiency where it outdid other models beginning from level -1 up to 3. It also outperformed other roughness models in average of between 14% - 21% across the pitch ranges.

![Figure 10. $C_T/C_P$ Ratio vs. Collective Pitch Level](image-url)
Interpreting the graph, it shows that with surface roughness applied, the operating envelope of the helicopter becomes wider (with more useful blade pitch range). With aerodynamic efficiency of the rotor blade is spread more evenly and improving at certain pitch level, it enables pilot to operate the helicopter to maximum pitch level without any risk of stalling the aircraft. In addition, given the graphs for all roughness models are less steep than that of the baseline, surface roughness gives more predictable flight profile that can contribute towards safer helicopter operation. It is also evident that the $C_T/C_P$ ratio graph largely influenced by $C_T/s$ vs collective pitch graph (refer to Figure 8).

5. Conclusion
Experimental work was conducted to understand the effect of surface roughness on helicopter main rotor blade. Surface roughness has a significant impact on thrust and power coefficients. Baseline model with smooth surface shows the lowest minimum drag coefficient. Meanwhile, in general, the increase of surface roughness will lead to increasing minimum drag coefficient value. For thrust, it is seen that surface roughness improves the coefficient of lift at lower and higher pitch levels, but it performs at middle range compared to the baseline. Subsequently, for thrust/power ratio, the same pattern is also observed. From here, it is clear that surface roughness is beneficial for certain range of operations. As a type of passive flow control method, it suffers from inability to adapt accordingly to flow condition. Nevertheless, this experiment proves that surface roughness gives higher stall angle and consequently widens helicopter operating envelope to the maximum without the risk of stall. Apart from giving a better flight performance in high angles of attack and full power, the surface roughness can give more predictable flight profile that contributes to safer helicopter operations. This surface roughness can be made as a controllable one, which will eliminate the use of active-based high lifting devices. Simply by using the surface roughness, the thrust and power values can be manipulated according to the required preference. This will enhance the vertical flight performance and have great impact on sophisticated military-purpose helicopter where manoeuvrability and endurance are of paramount importance.

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