Aerodynamic Prediction of Rotor in Forward Flight using Blade Element Theory

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Abstract. This paper is focusing on analysis of angle of attack and lift distribution along the helicopter blade in forward flight conditions and the effects of increasing helicopter’s speed. The Blade Element Theory (BET) is used throughout this study. The result was in good agreement with the existing data. From the analysis, the angle of attack and lift at retreating side is low compared with advancing side and by increasing the helicopter’s speed, the reverse flow area widen. This analysis will assist researchers on blade modification for the sake of improving aerodynamic characteristic of the helicopter blade as well as stability and performance of the helicopter.

1. Introduction
Helicopter is a unique flying vehicle that is designed to perform various maneuvering flight such hovering, forward and backward, sideward and vertical translation. These capabilities make helicopter very popular in air patrolling, search and rescue (SAR), transportation to rural places and offshore platform which the takeoff and landing space is often limited.

For a single rotor type of helicopter, the main rotor is the main component that produces lift and propulsive forces. The tail rotor generates a thrust to counteract the fuselage torque arising from the rotation of the main rotor and is mainly used for the directional (yaw) motion control of the helicopter. During flight, the rotor is spinning at a constant rotor rotational speed. The change in the collective and cyclic pitch angles input by the pilot will change the aerodynamic loads of the rotor hence changing the translation motion of the helicopter. In hover flight, the main rotor experiences equivalent collective and cyclic pitch inputs to stays afloat in equilibrium. However, in forward flight maneuver, the forward speed causes the rotor to experience high and low air speed regions at both sides of the rotor which complicates analysis compared to hovering flight.

There are several methods that can be used to analyze the aerodynamic characteristics of helicopter blade such as Momentum Theory [1,2,6], Blade Element Theory (BET) [1,2,6] and Vortex Method [1,2,6]. Among above mentioned methods, BET is a widely used to provide prediction of the rotor
aerodynamics forces such as rotor thrust, lift and drag coefficient, induced velocity and rotor disk loading at each element along the blade either in the advancing or retreating side [1,6]. Additionally, dynamic coefficients such as lateral and longitudinal flapping coefficients, pitching, sectional blade angle of attack, collective pitch and rotor coning angles acting on the blade also can be obtained using BET. Other advantages of BET is that the method is relatively simple for predicting the performance of a rotor and the results of the analysis are reasonable accurate.

The lift generation between advancing and retreating side of the blade is different between each other during forward flight where the advancing blade experience significant lift increase compared to the retreating side. The advancing side encounters increased velocity due to combination of the rotational velocity of the rotor and the helicopter’s forward speed but the retreating blade experiences a decreased velocity [Fig. 1]. To overcome the dissymmetrical of lift problem in forward flight, pilot have to control the blade cyclic pitch input to the main rotor blade in order to control the angle of attack of each the main rotor blade. The angle of attack at retreating blade side must be increased due to its lower relative velocity while at the advancing side, the blade must operate at lower angle of attack due to the higher velocity profile. If the angle of attack of the retreating blade become too large, then the retreating blade will stall which results in a loss of overall lift from the rotor and this would restrict the forward speed of the helicopter [3, 4, 5].

![Figure 1. Velocities distribute on the helicopter blade [6].](image.png)

The present work will explore the implementation of BET for predicting the aerodynamics performance for a rotor blade in forward flight condition. The angle of attack and lift distributions at the advancing and retreating side of the rotor will be investigating under increasing helicopter’s forward speed in order to understand the effect of increasing forward speed towards reverse flow area.
2. Methodology

2.1. Theoretical Background

In this paper, BET is used throughout this analysis. In BET, each blade section is assumed acts as a quasi-2D airfoil to produce aerodynamic forces. Figure 2 shows the velocity components and angle of attack occur at the blade element on the helicopter blade. In forward flight, a function of the radial station, r and the azimuth position, ψ is used to analyze the angle of attack and increment of lift at the element. Furthermore, the blade flapping motion, blade feathering motion and velocity of the blade are also taken into account in this analysis to obtain angle of attack at various element of the blade.

![Aerodynamic environment at a typical blade element](image)

The angle of attack along the blade radial and the azimuth position is shown in Eq. 1.

\[
\alpha_r = \theta + \tan^{-1}\left( \frac{U_p}{U_T} \right)
\]  

(1)

where \( U_T \) is the tangential velocity (Eq.2), \( U_p \) is the perpendicular velocity (Eq.3), and \( \theta \) is blade pitch. The calculation of tangential and perpendicular velocity are given as follows:

\[
U_T(r, \psi) = \Omega r + \mu \Omega R \sin \psi
\]  

(2)

\[
U_p(r, \psi) = (V \alpha_i - v) - r \frac{\partial \beta}{\partial t} - \mu \Omega R \beta \cos \psi
\]  

(3)

where \( V \alpha_i \) is the component of forward speed that is parallel to the rotor shaft and local induced velocity, \( v \) is used for this analysis is shown in Eq.4 and Eq.5 respectively.

\[
v = v_i \left( 1 + \frac{r}{R} \cos \psi \right)
\]  

(4)

\[
v_i = \frac{\Omega R C_f}{\mu} \frac{1}{2}
\]  

(5)
The helicopter blade pitch (or feathering) motion, and blade flapping as the function of blade azimuth, can be described as the Fourier series in Eq. 6 and Eq. 7 respectively [2,6].

\[
\theta(r, \psi) = \theta_0 + \frac{r}{R} \theta_w - A_1 \cos \psi - B_1 \sin \psi \\
\beta(\psi) = a_0 - \sum_{n=1}^{\infty} \left( a_{n\alpha} \cos n \psi - b_{n\beta} \sin n \psi \right) \tag{6}
\]

where \(\theta_0\) is collective pitch, \(\theta_w\) is twist angle, \(A_1\) is lateral cyclic, \(B_1\) is longitudinal cyclic, \(a_{n\alpha}\) is rotor coning angle, \(a_{n\beta}\) is longitudinal flapping and lateral flapping is \(b_{n\beta}\). The angle of attack along the blade radial and the azimuth position is simplified in Eq. 8 [6].

\[
\alpha_r = \frac{1}{r + \mu \sin \psi} \left\{ \theta_0 + \frac{r}{R} - \left( A_1 - b_{\beta} \right) \cos \psi - \left( B_1 + a_{\alpha} \right) \sin \psi \right\} - \frac{v}{\Omega R} \left( 1 + \frac{r}{R} \cos \psi \right) \\
+ \mu \left\{ \alpha_{\text{tip}} + \left( \theta_0 + \frac{r}{R} \right) \sin \psi - \left( A_1 - b_{\beta} \right) \sin \psi \cos \psi \right\} \\
- \left( B_1 + a_{\alpha} \right) \sin^2 \psi \tag{7}
\]

The increment of lift on each blade element along the blade and around the azimuth is computed by using Eq. 9.

\[
\frac{\Delta L}{\Delta r} = \frac{1}{2} \rho U_1^2 a \alpha_r c \tag{8}
\]

### 2.2. Blade Data and Parameter

In BET, the angle of attack and the lift on the entire blade is the integration of the angle of attack and lift on all the blade elements from the center of the rotor to the tip. The rotor blade from Prouty’s example helicopter [6] are used in our analysis where the blade was divided into 50 equally spaced elements and azimuth range, \(\psi\) at 7.2° for each movement of blade (Fig.3). The analysis of this paper is based on the data from Prouty’s example helicopter given in Table 1.
5

3. Result and Discussion
Throughout this paper, the analysis is done based on the Prouty’s data from his example helicopter. In order to ensure that the analysis is done properly and accurately, the computed distribution of angle of attack along the helicopter main rotor blade in forward flight condition are compared with establish findings from Prouty analysis [6]. The result of that analysis in Fig. 4 shows that the computed
analysis are in good agreement with the Prouty’s diagram. From Fig. 4(b), the analysis gives evidence that the area at advancing side region (y/R > 0) contains of low angle of attack while at retreating side (y/R < 0 region), the analysis produces high angle of attack and a reverse flow area. Reverse flow area is the area with no lift and indicates that the airflow is moving across the trailing edge toward the leading edge of the blade. The reverse flow area can also be identified by observing rotation area with significantly high angle of attack value.

(a) Angle of attack distribution from Prouty’s analysis at V=60m/s [6].

(b) Computed analysis

Figure 4. Angle of attack and reverse flow area comparison. (a) Prouty’s diagram (b) the computed analysis.
The retreating side area produces less lift forces along the blade compared to advancing side. To evaluate this condition, the movement of the blade rotation in 1-2-3 position sequence (counter clockwise) is considered as shown in Fig. 5. The analysis considers 3 azimuth angles at $\psi = 43.2^\circ$, $\psi = 223.2^\circ$, $\psi = 93.6^\circ$, $\psi = 273.6^\circ$, and $\psi = 136.8^\circ$, $\psi = 316.8^\circ$. The data from Fig. 4(b) and the lift coefficient for NACA0012 at different Mach numbers from Paul [7] are used in this analysis in order to obtain the lift distribution along the Blade A and B.

Fig. 6 shows the angle of attack and lift distribution along Blade A and B at position 1, 2 and 3. From Fig 6(a), general trend for all azimuth angles shows that high angle of attack occurs at retreating side (Blade A) compared with advancing side (Blade B). The azimuth $\psi = 223.2^\circ$ (Position 1) of Blade A contains the highest angle of attack, which is about $11.3^\circ$ located at the $37\%$ of Blade A from the hub of rotor. While for Blade B $\psi = 43.2^\circ$ (position 1) the highest angle of attack is around $6.3^\circ$. Position 2 and 3 have the similar curve of angle of attack compared to Position 1. The negative angle of attack at inboard of the Blade A at retreating side is the reverse flow area where the angle of attack value is increasing at the inboard of the blade from $r/R=0.2$ (Position 1) to $r/R=0.4$ (Position 3). At the advancing side (Blade B at azimuth $\psi = 43.2^\circ$, $\psi = 93.6^\circ$, and $\psi = 136.8^\circ$) in Fig. 6(a), the high angle of attack occurs at inboard of the blade and it gradually decreases from root to tip of the blade. This reduction is due to the blade twist effect.

From Fig.6(b), for the triple positions of rotation, the advancing blade side have an extra lift $\frac{\Delta L}{\Delta r}$ compared to retreating side. This extra lift affects the helicopter forward motion and have the tendency to roll the helicopter to the left at the retreating blade side. As a matter of fact, the pilot should take care of extra lift by controlling the rotor of the helicopter manually by using cyclic pitch input in order to stabilize the blade and to avoid the unwanted rolling motion to the retreating blade side.
Figure 6. Angle of attack and lift distribution for Blade A and B. (a) Angle of attack distribution (b) Lift distribution
Figure 7. Comparison of distribution angle of attack of the blade for forward speed at $V=60\text{m/s}$ and $V=80\text{m/s}$.

Figure 7 show the distribution of angle of attack when the helicopter speed increases about 33.33% from $V = 60\text{ m/s}$. From Figure 6, the diameter of reverse flow area at retreating side for $V = 80\text{ m/s}$ increases two times of reverse flow region diameter for $V = 60\text{ m/s}$. The distribution of angle of attack differs for each speed due to the increased speed of the helicopter. This indicates that the lift for the retreating side of the rotor is decreasing when the speed of the helicopter increases. To ensure safety, every helicopter normally have their limit of speed, VNE (Velocity Never Exceed) to avoid the build-up of reverse flow area and significant low lift at retreating blade. This two factors are very important indicator to researchers in order to improve the blade aerodynamic performance and also the overall helicopter performance.

4. Conclusions
In this paper, the result of the angle of attack and lift distribution along the main rotor blade when helicopter in forward flight condition obtained using Blade Element Theory (BET) is presented. The Prouty example helicopter data is validated to ensure the angle of attack and lift distribution along the blade is done properly and accurately. Good agreement of angle of attack between BET data and angle of attack diagram is achieved. Based on the findings, high angle of attack occurs at the advancing side of the rotor starting from the inboard position of the blade and gradually decrease from root to tip of the blade. Meanwhile, the highest angle of attack and reverse flow area occur at the retreating side. Thus, the results show that the lift of retreating side is lower compared to advancing blade, hence cause the helicopter to roll to the retreating side. Increasing the helicopter speed effect the angle of attack and lift distribution along the blade. The reverse flow area region also increases as the helicopter move at a faster speed.

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