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Assessing helicopter main rotor blade critical area using blade element theory in the cases of forward speed and blade collective pitch angle increments

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Abstract

The critical area on the main rotor blade when a helicopter is in forward flight conditions was assessed in this research using Blade Element Theory program. Two cases have been analyzed in this studied which are the effects of increasing forward speed and blade collective pitch angle. The Blade Element Theory was used throughout in the research. The validation of the Blade Element Theory program showed that the computed results were in good agreement with published data of Prouty's. Furthermore, it was evident that in forward flight, the retreating blade experiences high angle of attack and low lift, in contrast to the advancing blade. The increment of the helicopter speed affected the lift distribution along the blade and also the reverse flow area at retreating blade. The increment of collective pitch angle changes the angle of attack distribution and lift of the rotor blade. In addition, it is proven that to ensure safety, every helicopter has its limit of speed called Velocity Never Exceed.

1. Introduction

Helicopter is a unique vehicle that is designed to perform at various flight manoeuvres such as hovering as well as forward, rearward, sideward and vertical translations. Helicopters do not require a runway for take-off and landing and are also able to land almost everywhere. Thus, helicopters are a versatile mode of vehicle and are extensively used for missions such as air patrol, search and rescue (SAR), medical rescue missions, high-risk military missions, transportation to rural places or offshore missions and other missions of high risks. For conventional helicopter configuration, the main rotor blade is the important component to produce both the lift and the propulsive force simultaneously for the helicopter. To fly the helicopter, the pilot has to control the main rotor blade using all three controllers such as collective pitch control, cyclic pitch control and pedal concurrently to ensure the main rotor blade creates enough lift to complete the flight routine. The function of the collective pitch control is to adjust the lift and thrust of the main rotor blade by

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increasing/decreasing the pitch angle, which consequently makes the helicopter moves in a vertical direction. To control the cyclic pitch, a joystick is used to manage the pitch angle of the main rotor blade in order to move the helicopter forward, sideward and backward. Lastly, the pedal functions to control the fuselage by countering the torque and gyroscopic effect caused by the main rotor blade. During the flight, the main rotor blade spins at a constant rotational speed. The change in collective and cyclic pitch angles alters the aerodynamic loads of the main rotor, hence, modifying the motion of the helicopter. During a hover, the main rotor experiences equivalent collective and cyclic pitch inputs to stay afloat in equilibrium. However, in a forward flight maneuverer, the forward speed causes the rotor to experience high and low airspeed regions on both sides of the rotor, which makes an analysis of the flight more complicated compared to that of a hover flight [1-5].

Nevertheless, the main rotor blade in forward flight condition is in the situation that contributes most to the occurrence of helicopter accidents as compared to that in any other conditions of flight. In forward flight, the distribution of the velocities occur on the main rotor blade were illustrated in figure 1. There are two conditions happened to the main rotor blade in forward flight which are called advancing blade side which this blade is moving in the same direction as the helicopter and retreating blade side is the blade is moving in the opposite side of the helicopter.

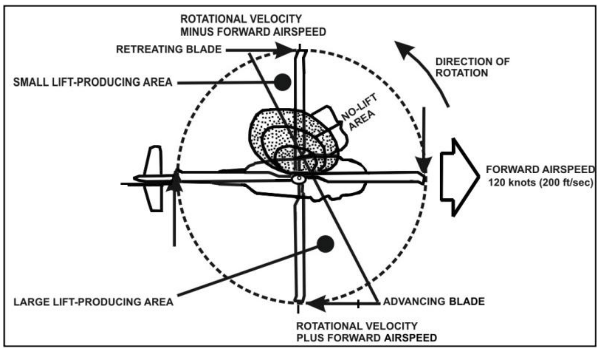


Figure 1. Velocities distributed on the main rotor blade of the helicopter in forward flight conditions [6].

Based on figure 1, the retreating blade is more critical blade compared to the advancing blade because it contains a smaller area to produces an equal amount of the lift to that the larger area of the advancing blade. To balance lift both blades, the angle of attack for the retreating blade needs to be increased due to its lower relative velocity, while at advancing blade, the blade must operate at lower angle of attack due to the higher relative velocity. If the retreating blade of the angle of attack become too large, the blade will stall which results in a loss of overall lift from the rotor. This phenomenon is very dangerous to the helicopter because the helicopter will pitch up and roll to the retreating side if it is not properly handled in these situations, thus, causing a crash. An addition, this stall of the rotor blade limits the forward speed of the helicopter, V_{NE} (Velocity Never Exceed) [7]. Consequently, the need to improve forward flights clearly has high demands and remains a major research topic in the rotorcraft industry for addressing rotor aerodynamics is to enhance the performance of the helicopter [8-11]. The focus of this paper is to determine the critical area on the main rotor blade when helicopter in forward flight condition using developed Blade Element Theory Program. There are two cases have been studied for this analysis which are effect of increasing forward speed and the effect of increasing the collective pitch angle.

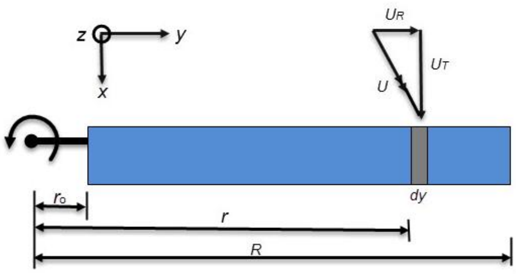
2. Methodology

2.1. Theoretical Background

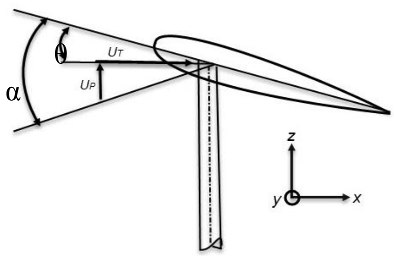
There are several arguments that support the choice of Blade Element Theory over

Momentum Theory as well Vortex Methods in order to analyse the aerodynamic characteristics of the main rotor blade. In fact, the Blade Element Theory is relatively simple in the analysis of rotor performance, yet it provides reasonably accurate results. It is robust in the sense that it is applicable not only to predict the aerodynamic forces represented by, for instance, lift, drag and thrust coefficients, as well as induced velocity and rotor disk loading for each rotor blade's element [1-4], but also the dynamic coefficients which include those of pitching, longitudinal, and lateral flapping. Furthermore, the theory, which is used in this research, is also useful in determining both rotor coning angle and sectional blade angle of attack.

We used a function of the radial station *r* and that of the azimuth position ψ, the blade velocity, the blade feathering and flapping motions in the prediction of angle of attack as well as lift addition at each helicopter blade element. For each element, the angle of attack and the components of velocity are shown in Figure 2. Note that blade sections are assumed in Blade Element Theory to be quasi-2D airfoils.



(a) Components of velocity at blade element



(b) Blade element angle of attack

Figure 2. Aerodynamic environment at a canonical blade element [1-4].

The relation between angle of attack with respect to the blade radial and the azimuth position is expressed in equation (1).

$$\alpha_r = \theta + \tan^{-1}\left(\frac{U_P}{U_T}\right) \qquad (1)$$

where U_T represents the tangential velocity to the leading edge of the airfoil, U_P is the perpendicular velocity to the blade quarter chord line and lies in a plane that contains the rotor shaft, and θ is blade pitch. The detail of the velocities for the helicopter blade is shown in figure 3 and figure 4.

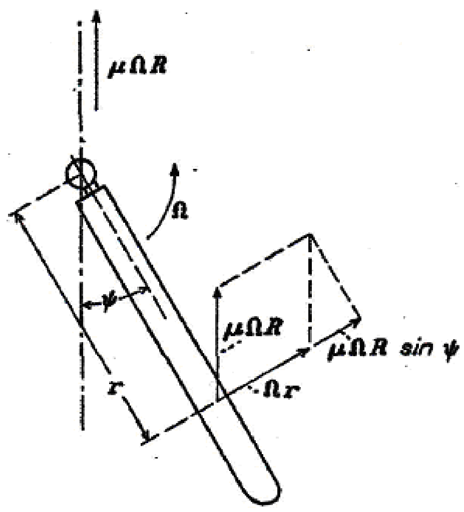


Figure 3. Velocities at the blade in the plane of the disk [2].

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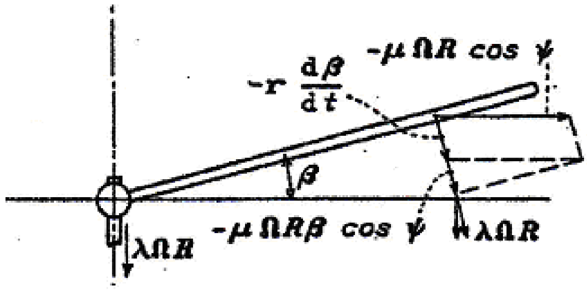

Figure 4. Velocities at the blade in the plane of flapping containing rotor axis and blade [2].

The following shows the tangential and perpendicular velocities calculation, based on figure 3 and 4:

$$U_T(r,\psi) = \Omega r + \mu\Omega R \sin\psi \quad (2)$$

$$U_P(r,\psi) = (V\alpha_s - v) - r\frac{\partial\beta}{\partial t} - \mu\Omega R\beta\cos\psi \quad (3)$$

$$U_R(r,\psi) = V\cos\psi + (V\alpha_s - v)\beta \quad (4)$$

where $V\alpha_s$ is the forward speed component which is parallel to the rotor shaft. Both $V\alpha_s$ and the local induced velocity, v are expressed in equation (5) and equation (6), respectively.

$$v = v_1\left(1 + \frac{r}{R}\cos\psi\right) \quad (5)$$

$$v_1 = \frac{\Omega R}{\mu}\frac{C_T}{2} \quad (6)$$

The Fourier series in equation (7) and equation (8) describe the helicopter blade pitch, $\theta(r,\psi)$ and blade flapping as the function of blade azimuth, $\beta(\psi)$, respectively [1-4].

$$\theta(r,\psi) = \theta_0 + \frac{r}{R}\theta_{tw} - A_1\cos\psi - B_1\sin\psi \quad (7)$$

$$\beta(\psi) = a_0 - \sum_{n=1}^{\infty}\left(a_{ns}\cos n\psi - b_{ns}\sin n\psi \right) \quad (8)$$

where θ_0 is collective pitch, θ_{tw} is twist angle, A_1 is lateral cyclic, B_1 is longitudinal cyclic, a_o is rotor coning angle, a_{ns} is longitudinal flapping and lateral flapping is b_{ns}.

Thus, all the equation are combined to analyse the angle of attack at each element of rotor blade. The angle of attack along the blade radial and the azimuth position is simplified in equation (9) [4].

$$\alpha_r = \frac{1}{\frac{r}{R} + \mu\sin\psi}\left\{ \begin{aligned} &\frac{r}{R}\left[\theta_0 + \theta_1\frac{r}{R} - (A_1 - b_{1s})\cos\psi - (B_1 + a_{1s})\sin\psi\right] - \frac{v}{\Omega R}\left(1 + \frac{r}{R}\cos\psi\right) \\ &+ \mu\left[\begin{aligned} &\alpha_{TTP} + \left(\theta_0 + \theta_1\frac{r}{R}\right)\sin\psi - a_0\cos\psi - (A_1 - b_{1s})\sin\psi\cos\psi \\ &-(B_1 + a_{1s})\sin^2\psi \end{aligned}\right] \end{aligned} \right\} \quad (9)$$

2.2. Blade Element Theory Program, the Data and Parameter

In this research, a program using such theory is developed using C programming language in order to analyse all the corresponding equations systematically. This program is also designed to generate and analyse the helicopter aerodynamics and characteristics of the main rotor blade. The data from Prouty's example helicopter on which the analysis in this paper is based is given in table 1. The rotor blades from Prouty's example helicopter are used in this Blade Element Theory program where each blade is divided into 50 equally spaced elements and azimuth range, ψ for each movement of blade with the spacing of 7.2° as shown in figure 5. Note that in Blade Element Theory, the angle of attack and the lift on the entire blade is the integration of those on all the blade elements from the center of the rotor to the tip.

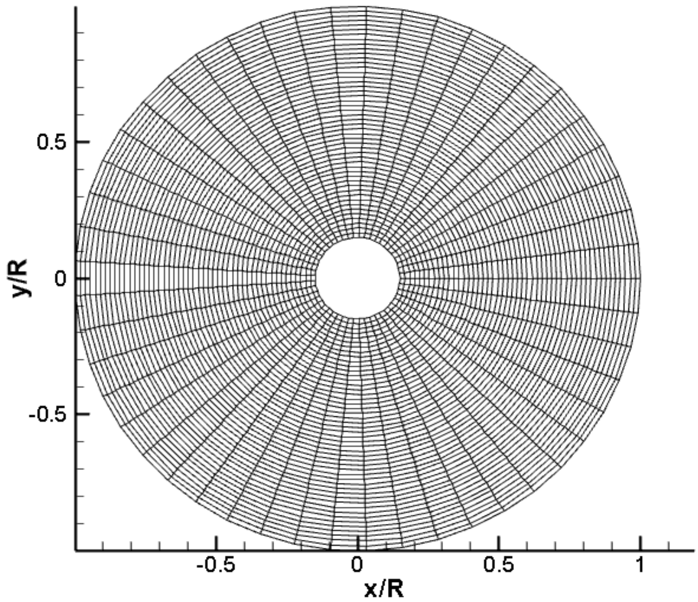

Figure 5. Equally spaced azimuth angle spacing (ψ = 7.2° each) is used in the division of 50 elements along the span of the blade in the meshing of the blade movement area.

Table 1. Blade parameter and Prouty's data used for analysis.

Blade Parameter	
Blade number	2
Blade radial section	50
Blade Azimuth section	7.2°
Sample Data [4]	
Airfoil	NACA 0012
Radius of blade, R	9.144 m
Chord, c	0.61 m
Blade cutout ratio, ro	0.15
Tip speed, ΩR	197 m/s
Speed, V	59.16 m/s
Tip speed ratio, μ	0.3
Collective pitch, θo	15.8°
Lateral cyclic, A_1	-2.3°
Longitudinal cyclic, B_1	4.9°
Coning angle, ao	4.3°
Angle of tip path plane, $aTPP$	-3.7°
Twist angle, θtw	-10°

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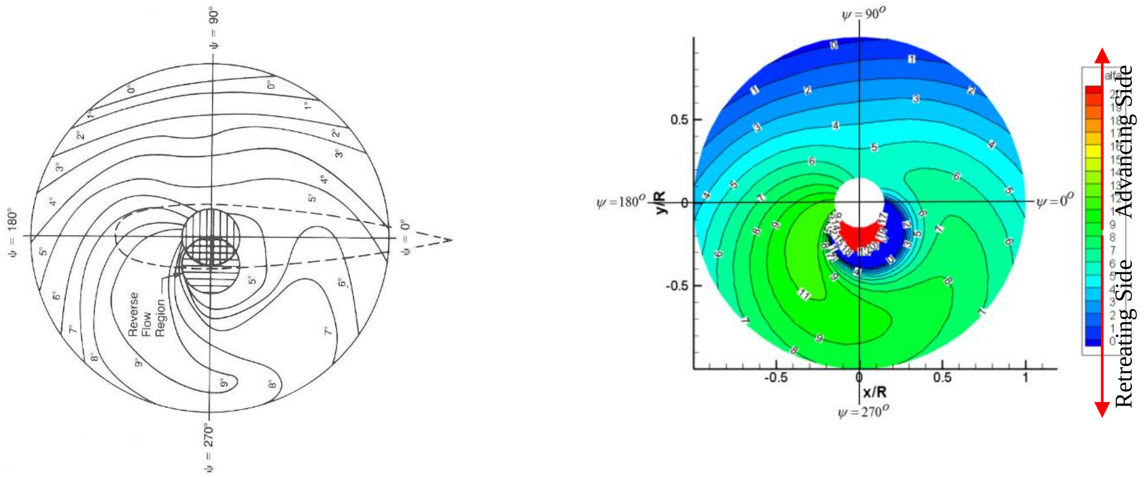
3. Results and Discussion

In this research, the analysis was done based on the data obtained from Prouty's helicopter. There are two cases which have been analysed using the Blade Element Theory program:

Case a: The effect of increasing forward speed of helicopter, *V* from 59.16 m/s (Prouty's helicopter speed) to 100 m/s
Case b: The effect of increasing the collective pitch angle, θ_0 from 15.8^o (Prouty's collective pitch angle) to 25^o

3.1. Validation of Blade Element Theory Program

The analysis of flow over the main rotor blade results in the important information on the region in which the reverse flow occurs. In such region, the lift is not detected due to the air flows in the opposite direction (i.e. from the trailing to the leading edges). The details of the results as given in figure 6 are obviously in a good agreement with Prouty's diagram. The advancing (y/R > 0) and retreating side (*y/R* < 0) regions are those corresponding to low and high angle of attacks, respectively [1-4]. The analysis therefore proved the accuracy of the Blade Element Theory method used in the case of helicopter forward flight condition.



(a) The distribution of angle of attack from Prouty's analysis at *V*=59.16 m/s [4].

(b) Computed analysis

Figure 6. Angle of attacks distribution and reverse flow area comparison. (a) Prouty's diagram (b) the computed analysis.

3.2. Case a: The effect of increasing forward speed of helicopter, V from 59.16m/s (Prouty's helicopter speed) to 100m/s

The effect of increasing the helicopter speed is important to understand its limitations, V_{NE}, to observe the effect and to determine the critical area at the blade. In this research, the three speeds of the helicopter were chosen, namely *V*=59.16m/s (Prouty's helicopter speed), 80m/s and 100m/s. It is important to note that each helicopter has Velocity Never Exceed, V_{NE} parameter. The parameter represents the speed limit beyond which the retreating blade's reverse flow would build up causing significant degradation of lift. Knowing V_{NE} would contribute to the flight safety. Furthermore, it serves as a guide in further improving a helicopter and its blades aerodynamic performance.

We investigated the relationship between the helicopter speed and dimension of the reverse flow region in order to ensure that the helicopter speed considered in subsequent

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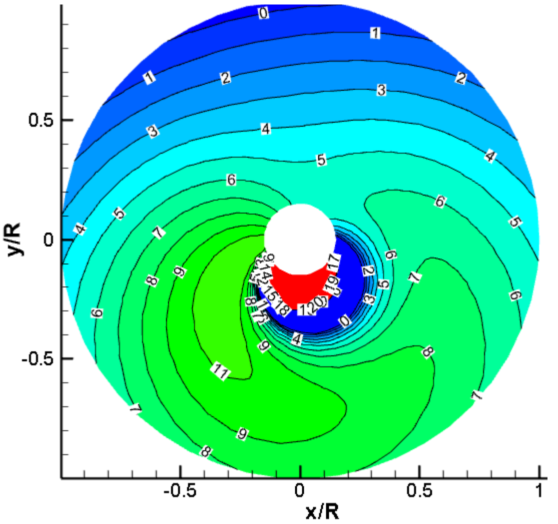
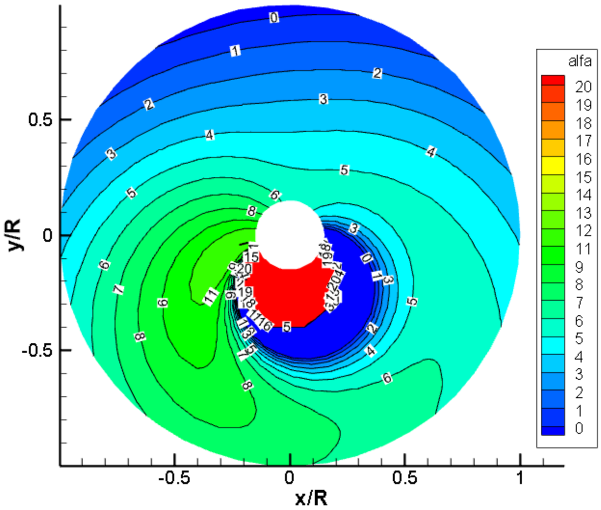
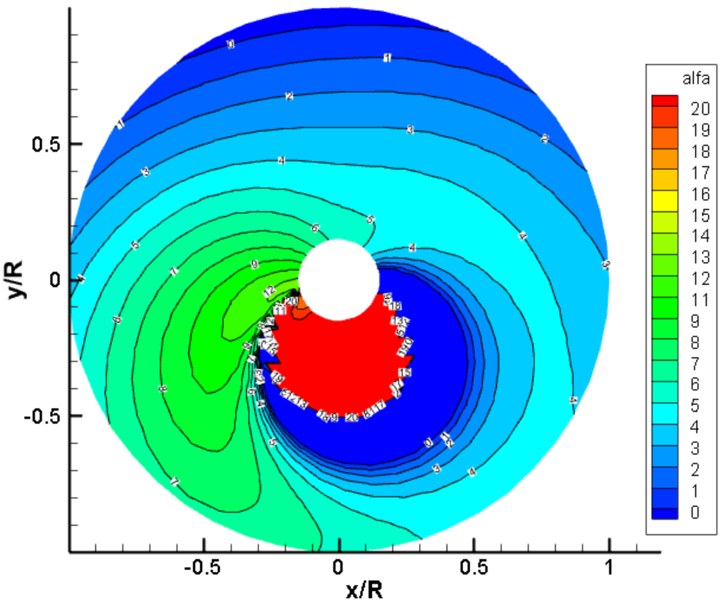
stages of this research did not exceed V_{NE}. It is clear that the increment in the reverse flow region' size is due to the increment of the speed, where the largest reverse flow region is found to occur at V = 100 m/s. This can be seen in figure 7. Further information regarding the variation of angle of attack with respect to the helicopter speeds, which indicates the decrement in the lift at the retreating blade with the increment of the speed, is shown in figure 8.



(a) V = 59.16 m/s



(b) V = 80 m/s



(c) V = 100 m/s

Figure 7. The effect of increasing forward speed of helicopter: Comparison the angle of attack distribution of the helicopter blade for forward speed at V =59.16m/s, V =80m/s and V =100m/s.

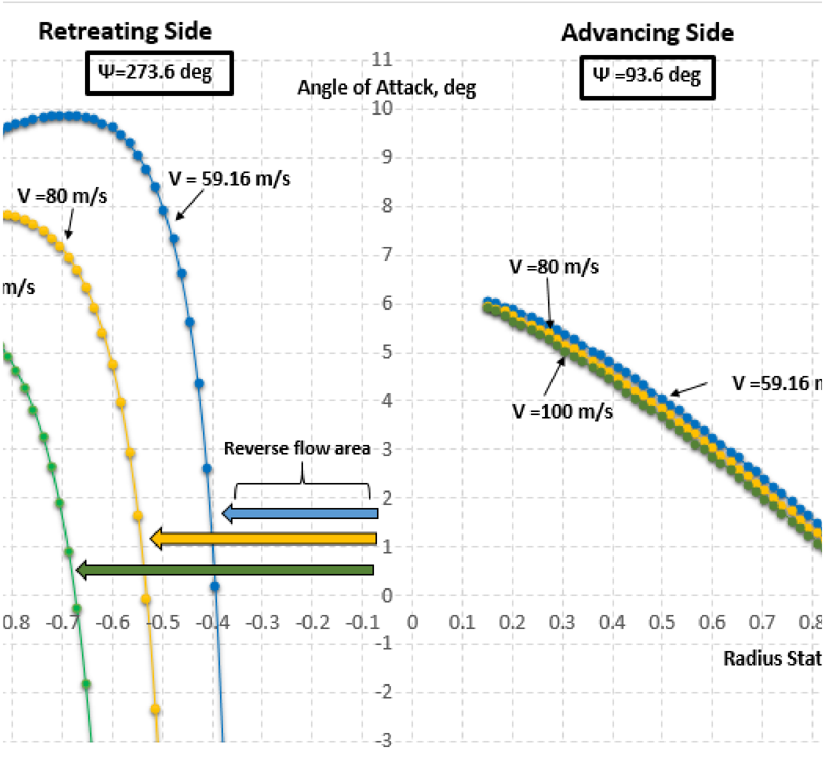


Figure 8. The angle of attack distribution for forward speed, *V*=59.16m/s, 80m/s and 100m/s at azimuth, ψ = 93.6° and 273.6°.

3.3. *Case b: The effect of increasing the collective pitch angle, θo from 15.8° (Prouty's collective pitch angle) to 25°*

The importance of understanding the effect of collective pitch angle, *θo* is to define the changes of the contour of the angle of attack and also the increment of reverse flow area when the pilot changes the collective pitch angle using the collective pitch stick, which is to control the thrust of the helicopter main rotor. For this case, the forward speed is set to *V* =59.16m/s (Prouty's helicopter speed) and collective pitch is changed from 15.8° (Prouty's collective pitch angle) to 25°. From the investigation from figure 9, the increment of collective pitch angle causes the contour of the angle of attack to change from lower to the highest angle of attacks for both sides of the blade (advancing and retreating side) but the size of the reverse flow area still remains. Other than that, the retreating side is still in the critical area, which contains a higher angle of attack and reverse flow area (no lift) compared to the advancing side. Figure 10 clearly shows the angle of attacks distribution along the main rotor blade and reverse flow area at forward speed which Prouty's helicopter speed is at *V*=59.16 m/s. Based Figure 10, the limitation of the collective pitch angle is 15.8 degrees due to the stall angle of Prouty's airfoil (NACA0012) at 12 degrees. Any increment of the collective pitch angle did not affect the size of the reverse flow area and it remains at the size of *r/R*=0.4. From figure 10 also, it is indicated that increasing collective pitch angle causes the blade to have a critical lower lift because most of the blade contains high angle of attacks at the stall angle at the advancing and retreating side. It also explains the reason that the collective pitch has a limited angle.

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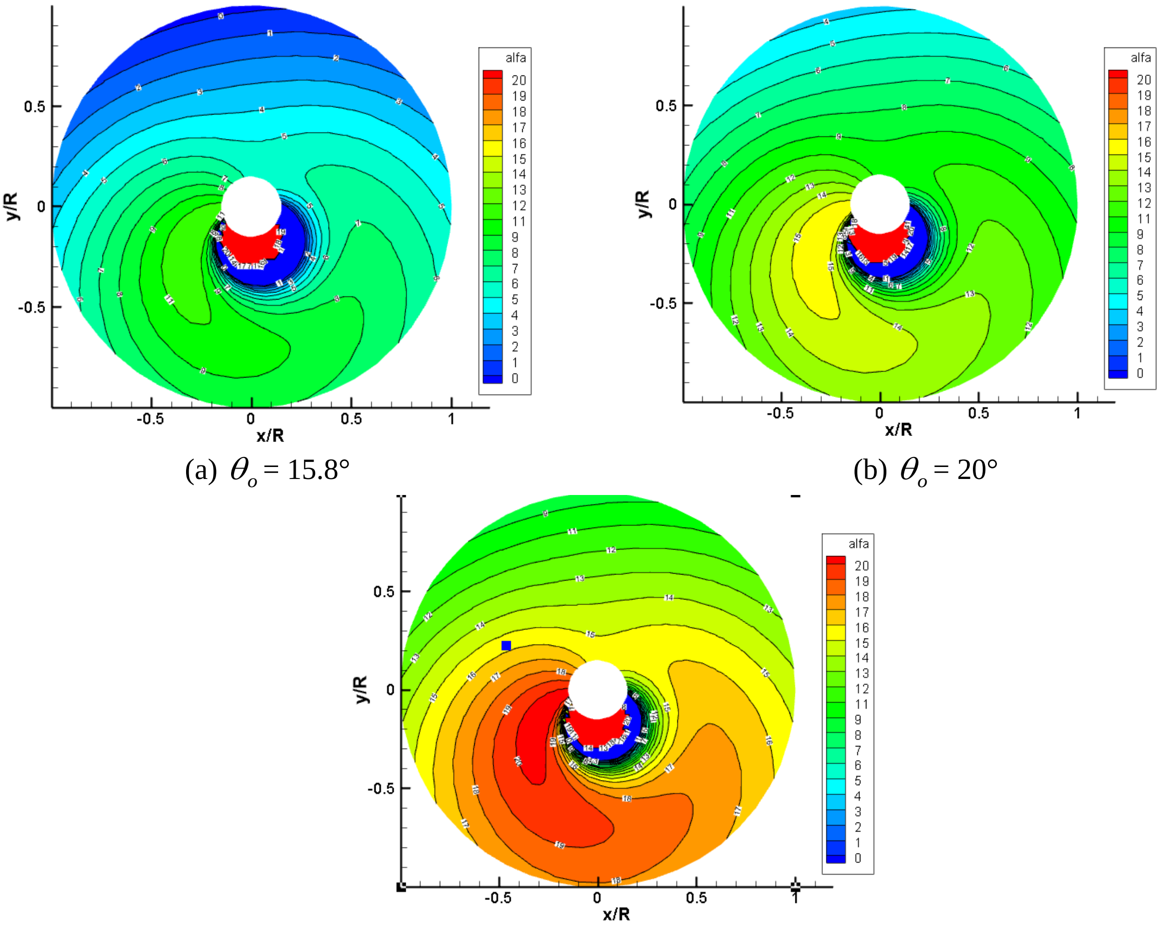

(a) $\theta_o = 15.8°$ (b) $\theta_o = 20°$

(c) $\theta_o = 25°$

Figure 9. Effect of increasing the collective pitch from 15.8° to 25° at forward speed, V =59.16 m/s.

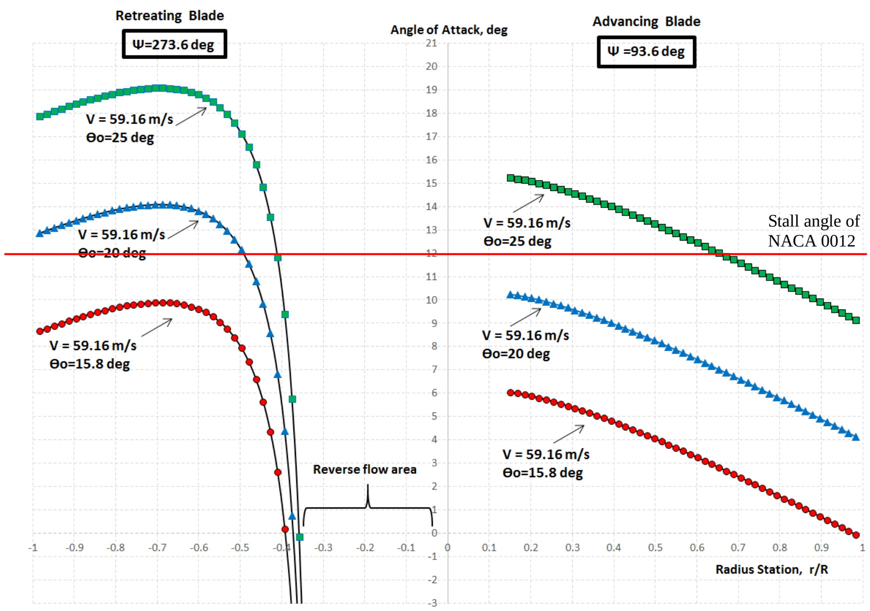

Figure 10. The angle of attack distribution for forward speed V = 59.16m/s in increment of the collective pitch angle at azimuth, ψ = 93.6° and 273.6°.

4. Conclusions

In this paper, the results which are based on two cases corresponding to the effect of increasing forward speed of the helicopter and the effect of increasing the collective pitch angle using Blade Element Theory Program are presented. This work is aimed to assess the critical area on the main rotor blade when a helicopter is in forward flight conditions. The blade parameter and data of Prouty's example helicopter have been used in this study. The computed angle of attacks distribution along the main rotor blade from Blade Element Theory Program has been validated against Prouty's diagram. Good agreement of angle of attack between Blade Element Theory data and the diagram was achieved. Based on the findings, the advancing side contains low angle of attack to produce the lift. However, high angle of attack and reverse flow area which area with no lift occur at the retreating side. From the findings also, the increasing of helicopter speed affects the angle of attack and lift distribution along the blade. The reverse flow area at retreating blade will increase as the helicopter move at faster speed. An addition, it shows that the lift at retreating blade is decreased when helicopter speed is increased and to ensure safety, all helicopters has its limit of speed, called Velocity Never Exceed (V_{NE}). Increasing collective pitch angle causes both rotor blades to have a critical lower lift because most parts of the blade are at stall angle. However, the size of reverse flow area at retreating blade remains. Thus, it can be concluded based on the Blade Element Theory Program that the most critical area on the main rotor blade when helicopter in forward flight condition is retreating blade. This factor is very important indicator to researchers in order to improve aerodynamic performance of the blade and the helicopter.

5. Acknowledgement:

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