The effect of the aerofoil thickness on the performance of the MAV scale cycloidal rotor

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ABSTRACT

The numerical simulations for cycloidal propellers based on five aerofoils with different thickness are presented in this paper. The CFD simulation is based on sliding mesh and URANS. The results of CFD simulation indicates that all test cases share similar flow pattern. There are leading edge vortex and trailing-edge vortex due to blade dynamic stall. Interaction between the vortices shed from upstream blade and the downstream blade can be observed. There is variation of blade relative inflow velocity due to downwash in the cycloidal rotor cage. These factors result in large fluctuations of the aerodynamics forces on the blade. The comparison of the forces and flow pattern indicates that the thickness and leading edge radius of the aerofoil can significantly influent the flow pattern and hence the performance of the cycloidal propeller.
NOMENCLATURE

AOA angle-of-attack

\( a_o \) acceleration of the moving frame

\( a \) absolute acceleration

\( a_r \) relative acceleration

\( g \) gravitational acceleration

\( C \) blade chord length

\( C_n \) radial force coefficient of a blade

\( C_t \) tangent force coefficient of a blade

\( C_r \) thrust coefficient of the cycloidal rotor

\( D \) diameter of the cycloidal propeller

\( F_v \) vertical force of the cycloidal propeller

\( F_h \) horizontal force (side force) of the cycloidal propeller

\( p \) pressure

\( r' \) absolute radius vector of a point

\( T \) thrust of the cycloidal propeller. It is the resultant force of \( F_v \) and \( F_h \)

\( L/D \) lift to drag ratio of the blade

\( V \) absolute velocity

\( V_e \) transportation velocity

\( V_o \) velocity of the moving frame

\( V_r \) relative velocity

\( V_y \) vertical velocity component

\( x \) \( x \) co-ordinate of a point

\( y \) \( y \) co-ordinate of a point

\( z \) \( z \) co-ordinate of a point

\( \alpha \) blade pitch angle

\( \epsilon \) angular acceleration of the moving frame

\( \theta \) azimuth angle of the cycloidal rotor

\( \Lambda \) blade aspect ratio

\( \rho \) density of the air

\( \tau_{ij} \) viscous-stress

\( \phi \) offset angle of thrust

\( \omega_s \) rotation speed of the moving frame

\( \Omega \) rotation speed of the cycloidal propeller

1.0 INTRODUCTION

Cyclogyro or cyclocopter is a type of rotorcraft which flies by cycloidal propellers. The cycloidal propeller is a kind of rotor whose blades rotate around an axis parallel to the rotor shaft. The pitch angle of each blade is varied by an eccentric. If the position of the eccentric varies, the magnitude and the direction of the thrust will be instantly changed. Therefore cycloidal propeller can provide omni-directional vectored thrust. With this feature, the cyclogyro may be capable of hovering at any pitch angle, or taking off and landing at many difficult places such as walls, tree branches, cliff or even roof ceiling. The cyclogyro could perch on those places and the engines can be shut off. The endurance of the mission can be significantly extended. Therefore cyclogyro can be a very good choice for perch and observe missions.
The cyclogyro has been studied since the early 20th century. However, only within the recent decade, there are major progresses for cyclogyro. Gil Iosilevskii and Yuval Levy performed experiment and CFD simulation with a small cycloidal propeller with diameter of 0.11m\(^{(1,2)}\). Their numerical results showed that the stream line formed a distorted doublet and the shape of the doublet is time dependent which results in total force fluctuation. With the help of FFT on aerodynamic forces, they concluded that there are strong interactions between the blades and the wakes of neighboring blades. In Seong Hwang and Seung Yong Min \textit{et al} developed a quad-rotor cyclogyro and proved that the cycloidal propeller can provide enough thrust for hovering and forward flight\(^{(3-6)}\). Benedict and Chopra \textit{et al.} conducted extensive experimental and numerical simulation on the cycloidal propellers for MAVs\(^{(7-16)}\). Under hovering status, they made experiments with different aerofoil, blade number, rotor solidity, blade pitch angle and aspect ratio\(^{(11,13)}\). The aero-elastic analysis was performed\(^{(9)}\) and the effect of flow curvature at forward flight status was also studied\(^{(14)}\). According to their experiments and analysis, the cycloidal propeller can be more efficient than the conventional screw propeller under hovering status\(^{(11)}\). The torsion of the blade will cause lower thrust of the cycloidal propeller\(^{(9)}\) and the effect of flow curvature significantly influences the performance of the cycloidal propeller under either hovering status or forward flight status\(^{(9,13,14)}\). Based on these research work, they finally found the most efficient cycloidal rotor design with NACA0015 aerofoil and successfully developed a tri-rotor cyclogyro which can fly in any direction\(^{(15)}\). Kan Yang made CFD analysis incorporated with the aero-elastic model developed by Moble Benedict. The CFD analysis signified that both 2D and 3D analysis could produce results comparable to experiment results\(^{(16)}\).

The experimental studies and the numerical simulations were also carried out by us and several successful cycogyroes had been developed by us\(^{(17,18,19)}\), as shown in Fig. 1.

![Figure 1. The cycogyro developed by us.](image-url)
From the numerical simulations, it was found that the motion of the cycloidal propeller blade is comprised of the rotation about rotor shaft and the pitching oscillation about the pitching axis on the blade. If viewed in the moving reference frame attached to the cycloidal propeller, each blade is actually performing pitching oscillation in the curved flow. Therefore, the aerodynamic forces of the cycloidal propeller are primarily influenced by the effect of the blade dynamic stall, the interaction between the blades, the downwash in the rotor cage and the effects of the curved relative inflow (i.e. the inverse camber effect).

The previous works are primarily concentrated on studying the effects of design parameters by experimental approach. Despite these experiments and numerical simulations, the principle of the cycloidal rotor is still not fully understood.

In this paper, the effect of the aerofoil thickness on the performance of the MAV scale cycloidal propeller is discussed based on 2D numerical simulation. The numerical simulation is based on URANS and sliding mesh. The CFD simulation results are compared with the experimental results to validate the numerical model. Then the analysis is performed in both the inertial frame and the moving frame. The streamlines, pressure and vorticity contour are drawn in both inertial frame and moving frame. This helps us to better understand the details of the flow around and within the cycloidal propeller and how the effects of the aerofoil thickness influence the performance of the cycloidal propeller.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>The parameters of the experimental cycloidal propellers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (mm)</td>
<td>360</td>
</tr>
<tr>
<td>Number of blades</td>
<td>4</td>
</tr>
<tr>
<td>Chord length (mm)</td>
<td>70</td>
</tr>
<tr>
<td>Blade span (mm)</td>
<td>270</td>
</tr>
<tr>
<td>Aerofoil</td>
<td>NACA0015</td>
</tr>
<tr>
<td>Maximum $\alpha_p$ (deg)</td>
<td>45</td>
</tr>
<tr>
<td>Minimum $\alpha_p$ (deg)</td>
<td>$-45$</td>
</tr>
<tr>
<td>Blade pitching axis location</td>
<td>0.5C</td>
</tr>
</tbody>
</table>

2.0 THE EXPERIMENT APPARATUS

The experiments were performed on a cycloidal rotor so that the CFD results can be validated with experimental data. The experiment apparatus consists of a six-component force balance, the data acquisition and conditioning system, a cycloidal propeller driven by a brushless motor and its gear system. The blade pitching mechanism is based on the eccentric mechanism and sinusoidal pitching motion is assumed.

The data acquisition and conditioning system is composed of a NI SCXI-1520, a NI PCI-6133 card and a NI SCXI-1314 terminal block. The parameters of the experimental cycloidal propellers are shown in Table 1. The cycloidal propellers with blade chord length of 70mm were tested in hovering status.
3.0 THE NUMERICAL SIMULATION MODEL

3.1 The numerical technique

There are three main types of turbulent modeling methods, i.e. Direct Numerical Simulation (DNS), Large Eddy Simulation (LES) and Reynolds-Averaged Navier-Stokes (RANS). DNS is the most advanced approach but it demands huge computation resources, therefore it is too prohibitive to be used for the cases in this paper. LES is more suitable for 3D simulations and also too computationally expensive to be used for the problems in this paper. The simulation based on RANS can provide good prediction on time averaged flow field parameters and aerodynamics force for blade dynamic stall with flow separation\(^{(20,21,22)}\). Therefore RANS would be the best choice that incorporates both acceptable computation cost and accuracy.

Since the aim of this paper is to study the effect of aerofoil thickness, 2D numerical simulation is employed in this paper. The numerical simulation results are then compared with experimental data where the blade is flexible and blade span is finite. The discrepancy between the experimental data and the 2D CFD results is expected since effects of the blade torsional deformation and the blade span are excluded by 2D simulation. The elastic torsional deformation of the blade will decrease the level of the aerodynamics force produced by cycloidal rotor\(^{(9)}\). The aerodynamic forces would be over predicted by 2D numerical simulations since rigid blade is assumed. The effects of the blade tip vortex also could not be captured by 2D numerical simulations. However, from the numerical simulation based on OVERTURNS, both 2D and 3D analysis could produce results comparable to experiment results and 2D CFD simulation can predict the velocity field at blade mid-span well\(^{(16)}\). Therefore despite these limitations, it is appropriate to study the time averaged aerodynamic forces and flow field of the cycloidal propeller based on 2D CFD simulation as far as only the effect of aerofoil thickness is concerned.

Two co-ordinate systems were defined in this paper. The first one is an inertial frame whose origin is located at the axis of the cycloidal propeller. Its \(X\) and \(Y\) axis points to the horizontal and
vertical direction respectively (Fig. 3(a)). The vertical force and side force were defined in this frame. The positive vertical force points upwards along Y axis and the positive side force points rightwards along X axis. The resultant force of the vertical force and the horizontal force is defined as thrust. The second reference frame is a moving frame which is attached to cycloidal propeller (Fig. 3 (b)). Its origin is located at the axis of the cycloidal rotor. Since the moving frame rotates with the cycloidal propeller, only pitch oscillation of each blade can be observed if the moving frame is selected as the frame of reference. This helps us to figure out the actual AOA of each blade, the effect of dynamic stall and blade vortex interaction more clearly than in the inertial frame.

In Fig. 3, the blades are numbered in counter clock direction and the azimuth angle of the blade 1 equals to the cycloidal propeller azimuth angle $\theta$. $\theta = 0$ when the blade 1 is located at the highest point of its trajectory and the Y axis of moving frame passes through the pitching axis of blade 1. The radial force generated by a blade is positive when it points outwards. The tangential force generated by a blade is positive when it points to the direction of the linear velocity of the blade. Since all blades work at the same condition, each blade will experience the same aerodynamics forces with phase shift, only the forces on blade 1 are studied in this paper.

The kinetics of the blade can be divided into two levels of rotation, namely the rotation around cycloidal rotor shaft and pitching oscillation around blade pitching axis. In order to deal with the complexity of the blade motion, appropriate moving mesh techniques have to be employed. The moving mesh techniques available include overset mesh, dynamic mesh and sliding mesh. For the overset mesh, the holes will be cut in the background mesh and the blade meshes will be overset on to the back ground mesh. The mesh blocks communicate with each other though mesh connectivity\(^ {16}\). For the dynamic mesh, the mesh elements near the moving walls will be deformed and will be re-meshed if their quality is too low. For the sliding mesh, the holes are also cut in the background mesh and the blade meshes are fitted into the holes. The mesh boundaries will not overlap but there are sliding mesh interfaces. Two adjacent mesh blocks communicate with each other with mesh interfaces. The largest error occurs at mesh interfaces. The sliding mesh is limited to the cases where the element next to mesh interface must move along the direction tangent to the mesh interface. But compared to the other two candidates, the mesh elements need not to be updated for each time step. Especially in comparison with dynamic mesh, the low quality elements due to mesh deformation can be avoided. Therefore among these techniques, the sliding mesh possesses the best efficiency and accuracy. For the cycloidal rotors, since both of two levels of the blade kinetics are rotation, which match the requirements of the sliding mesh, the sliding mesh technique is selected in this paper.

![Figure 3. The definition of the co-ordinate system and blades.](image)
For the sliding mesh technique, the most straightforward approach is to use three levels of the rotating mesh domains and the simulation will be performed in the inertial frame. In this scheme, a circular hole is cut in the fixed mesh domain that will not move. The rotating mesh domain around cycloidal rotor is fitted into that hole\textsuperscript{(6,18)}. The circular hole for each blade is then cut in the rotating mesh domain around cycloidal rotor and each moving mesh domain around blade is fitted into the hole for it. However, for this technique, there are still two levels of sliding mesh interfaces, which will introduce interpolation error. And sometimes, there are gaps or overlapped mesh elements between two adjacent mesh blocks caused by truncation error from mesh block kinetics calculation. This will cause the failure of simulation. To solve the problem, the numerical simulation performed in the moving frame is proposed in this paper.

### 3.1.1 The governing equations defined in moving frame

The incompressible NS function defined in inertial frame is:

\[ \nabla \cdot \mathbf{V} = 0 \]  \text{(1)}

\[ \rho \frac{d\mathbf{V}}{dt} = \rho \mathbf{g} - \nabla p + \nabla \cdot \tau_{ij} \]  \text{(2)}

\[ \frac{d\mathbf{V}}{dt} = \frac{\delta \mathbf{V}}{\delta t} + u \frac{\delta \mathbf{V}}{\delta x} + v \frac{\delta \mathbf{V}}{\delta y} + w \frac{\delta \mathbf{V}}{\delta z} \]  \text{(3)}

The first term in RHS of Equation (2) denotes the gravitational force of the fluid. Since the pressure does not change with reference frame, the NS function defined in moving frame can be defined as:

\[ \nabla \cdot \mathbf{V}_r = 0 \]  \text{(4)}

\[ \rho \frac{d\mathbf{V}_r}{dt} = \rho \mathbf{a}_r - \nabla p + \nabla \cdot \tau_{ij} \]  \text{(5)}

According to the kinetics of the particle, the absolute velocity and acceleration is defined as:

\[ \mathbf{V} = \mathbf{V}_r + \mathbf{V}_e = \mathbf{V}_r + (\mathbf{V}_0 + \mathbf{\omega}_e \times \mathbf{r}') \]  \text{(6)}

\[ \mathbf{a}_a = \mathbf{a}_r + \left[ \mathbf{a}_e + \mathbf{\varepsilon}_e \times \mathbf{r}' + \mathbf{\omega}_e \times (\mathbf{\omega}_e \times \mathbf{r}') \right] + 2\mathbf{\omega}_e \times \mathbf{r}' \]  \text{(7)}

In this paper, the cycloidal rotor is supposed to be operated under hovering status. The moving frame only rotates in inertial frame and gravity of the air can be neglected. Hence \( V_0 = 0, a_x = 0, a_y = 0 \). It is assumed that the rotation speed of the cycloidal rotor is constant, so \( \varepsilon_e = 0 \). Then we have the expressions for relative velocity and relative acceleration:

\[ \mathbf{V}_r = \mathbf{V} - \mathbf{\omega}_e \times \mathbf{r}' \]  \text{(8)}

\[ a_r = -\mathbf{\omega}_e \times (\mathbf{\omega}_e \times \mathbf{r}') - 2\mathbf{\omega}_e \times \mathbf{V}_r \]  \text{(9)}

The first term in RHS of Equation (9) is transportation acceleration and the second term is Coriolis acceleration.
3.1.2 Boundary conditions

The velocity of the initial flow field is:

\[ V_r = V_{\infty} - \omega_c \times r' \quad \ldots (10) \]

The far field condition is:

\[ V_r \big|_{(x,y,z) \to \infty} = V_{\infty} - \omega_c \times r' \big|_{(x,y,z) \to \infty} \quad \ldots (11) \]

3.1.3 The sliding mesh technique for numerical simulation in moving frame

The simulation is performed in the moving reference frame that is attached to the cycloidal rotor shaft and only the pitching oscillation of each blade can be observed. Hence the moving mesh can be significantly simplified. Only two levels of mesh domains will be used, namely the fixed mesh domains with circular holes and moving domain around each blade, as shown in Fig. 4. Now the problem can be turned into dynamic stall of the blades in the moving frame with curved incoming flow and blade vortex interaction.

Figure 4. The grid system numerical simulation in moving frame.
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Table 2

<table>
<thead>
<tr>
<th>Cases for mesh dependency test</th>
<th>Case A1</th>
<th>Case A2</th>
<th>Case A3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesh count on each blade</td>
<td>466</td>
<td>933</td>
<td>1166</td>
</tr>
<tr>
<td>Total mesh count</td>
<td>92,597</td>
<td>131,911</td>
<td>192,996</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cases for time step dependency test</th>
<th>Case B1</th>
<th>Case B2</th>
<th>Case B3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time steps per cycle</td>
<td>720</td>
<td>1,200</td>
<td>1,600</td>
</tr>
</tbody>
</table>

The moving domain around each blade will pitch along with the blade. Moving sub-domains communicate with fixed domain with grid interfaces. The far field is defined with the local relative velocity with diameter of 30D. The dimension of the far field is determined by gradually increasing the diameter of the far field such that the results can match that from experiments well.

Unstructured mesh is deployed in whole computation domain. The prism elements are attached to the blade surface to capture the boundary-layer effects more efficiently. In order to simulate the boundary-layer effects more accurately, no wall functions are used. Hence the height of the first row prism near the blade surface is set such that $y^+$ is equal to or less than 1·0 and 10 rows of prisms are deployed. The Reynolds number ranges from 20,000 to 80,000, hence the SST $k$-$\omega$ model with low Reynolds correction is used. This model can predict the aerofoil dynamic stall with better accuracy than those assumes full turbulent flow, such as $k$-$\varepsilon$ model and standard $k$-$\omega$ model.

(a) The effect of mesh size

(b) The effect of time step

Figure 5. The convergence study (Blade chord length: 70mm, Aerofoil: NACA0015).
3.2 Mesh dependency and time step dependency study

Convergence study with different mesh size and time step were carried out. The details of the test cases are listed below.

The results of the mesh dependency study are shown in Fig. 5. It can be seen that the results from current numerical simulation model match the experiment data well. The number of mesh elements on the blade can significantly influence the results and the case with 933 meshes on each blade is selected to ensure both accuracy and efficiency. The test case with 1,200 steps per cycle is fine enough to guarantee both the accuracy and the efficiency. Therefore the test case with 933 cells on each blade and 1,200 steps per cycle is selected.

The iteration history indicates that usually after 4 cycles, the periodic solution appears and after 10 cycles, the solution converged. As shown in Fig. 6, the slip stream of the cycloidal propeller could be observed from the velocity magnitude contour. The flow pattern obtained by numerical simulation model presented in this paper is shown in Fig. 7(b). It is quite similar to the simulation result from Ref. 2, in which a distorted doublet can be observed.

Figure 6. The numerical simulation results (C = 70mm, Ω = 900RPM, NACA0015).

Figure 7. The comparison of the flow pattern of the cycloidal rotor.
3.3 Validation of the numerical model with flow pattern

In order to validate the flow pattern obtained by the numerical model presented in this paper, the CFD simulation based on a 2-bladed cycloidal rotor from Ref. 10 is performed. The velocity vectors are interpolated into a Cartesian mesh and compared with the DPIV data\(^{(10)}\), as shown in Fig. 8. The results from 2D CFD simulations matched the results from DPIV very well except near the region around the right part of the blade trace. The leading edge vortex and shed vortices visualised by DPIV are also captured by the 2D CFD model presented in this paper. The stream line of the 2D numerical simulation result also formed a distorted doublet similar to that in Ref. 2, although there were only two blades for the cycloidal rotor, as shown in Fig. 8(c). The differences between the DPIV and 2D numerical simulation may due to the fact that the span of the blade is finite and there are trailing vortices near the blade tip. The 2D simulation cannot capture the effects of the trailing vortex at blade tip.

Figure 8. The velocity vectors of the 2-bladed cycloidal rotor (θ = 0°).
4.0 RESULTS AND DISCUSSION

4.1 The comparison of the hovering efficiency of all test cases

The hovering efficiency of the propeller is measured by the Figure of Merit (FM). It is defined as the ratio of ideal power with respect to the actual power required to hover. Since the FM will increase with the thrust coefficient, usually the efficiency of two rotors will be compared with the same disc loading\(^\text{(16)}\).

The FM of the cycloidal propeller with different aerofoil is shown in Fig. 9(b). All these data correspond to rotation speed from 300rpm to 900rpm. It can be seen that the cycloidal rotor with NACA0015 aerofoil has the best FM and the one with NACA0006 aerofoil is the most inefficient. From Fig. 9(b) and Fig. 10, it can be seen that for all test cases, the FM and the thrust coefficients do not vary too much with disk loading and the rotation speed as the collective pitch of the cycloidal propeller is fixed. This also implies that the thrust of the cycloidal propeller is proportional to the square of the rotation speed and the averaged profile drag coefficients of the blades do not change too much as well.
4.2 The forces generated by the cycloidal propeller and blades

The magnitude of the thrust deflection is denoted by the thrust offset angle, as shown in Fig. 3(a).

\[
\varphi = -\sin^{-1}\left(\frac{F_h}{T}\right)
\]  

(12)

From Fig. 11(a), it can be seen that the rotors with NACA0006 and plate aerofoil have much larger thrust offset angle than others. For all test cases, very large instantaneous offset angle variation can be observed (Fig. 11 (b)). This will deteriorate the performance of the cycloidal propeller.

The forces generated by blade 1 of all test cases are shown in Fig. 12. The radial and tangential force coefficients measured in moving frame are shown in Fig. 13. It can be seen that there are force peaks when azimuth angle lies in the interval of 0° to 45° and 150° to 240°. It means that most of the vertical force is generated when the blade is located at up most and lowest position. There is a large side force peak when azimuth angle is about 225°. This is caused by intense blade vortex interaction and higher speed of incoming flow. Corresponding to the vertical force and side force peaks, there are two torque peaks. This is because that the leading edge vortices lead to very large radial force, but at the same time, very large tangential force. From Figs 12 and 13, it also can be seen that the case with NACA0018 generates smaller aerodynamics forces with much smaller force fluctuation and thrust deflection. This may provide much smoother operation and in turn result in higher mechanical efficiency and lighter structure. These benefits may compensate lower aerodynamics efficiency of NACA0018 aerofoil.

4.3 The forces generated by one blade in one cycle

The force generation history of blade 1 with NACA0015 is shown in Fig. 14. The force peaks due to pitching motion of the blade can be observed. The actual reduced frequency of the blade is changed due to the up wash and down wash induced by vortices. Hence the undulation of the force curve caused by blade vortex interaction also can be observed.

The stream line of all test cases when θ = 0° in moving frame are shown in Fig. 15. The velocity magnitude contour in moving frame is shown in Fig. 16. The trajectory of the blade pitching axis is marked by the dashed blue circle. It can be seen that all test cases share similar flow pattern. Therefore it is convenient to perform the qualitative analysis based on one of the test cases.
Fig. 16 shows that for all test cases, there is a low velocity region located in the upper-left part of the rotor cage and a high velocity region in the lower-right part of rotor cage. The low speed region and high speed region will rotate with the same speed as cycloidal rotor, but in reverse direction if observed in moving frame, as shown in Table. 2. It means that if observed in inertial frame, blade 1 is experiencing lower inflow velocity due to the downwash in the cycloidal propeller cage when the azimuth angle of the blade lies between about 0°–90°, and when the azimuth angle of blade 1...
lies between about 180°~270°, the blade is experiencing higher inflow velocity, as shown in Fig. 16. The stream line in moving frame also shows that when the blade is located at the lowest part of its trajectory, the actual AOA is very small. This is because that there is large downwash in the cycloidal propeller cage and the magnitude of the downwash velocity at the lowest position of the cycloidal rotor is of the same order of the tangential velocity of the blade, if viewed in the inertial frame (Fig. 17).

If viewed in the moving frame, the stream line is highly curved. Therefore, the effect of the inverse camber is significant. After the blade traveled through the lowest position of the trajectory (θ ∈ [180°, 270°]), there are increasing inflow velocity, decreasing αp due to pitching down motion and the down wash in the rotor cage. The combined effects of these factors will reduce both the
effective AOA of the blade and the curvature of the streamline, as shown in Fig. 15. Relatively straight streamline means that the effect of inverse camber is weakened. Combined with the effect of higher inflow velocity and blade-vortex interaction, the highest force peak can be seen in this region.

The stream line, vorticity and pressure contour of all test cases at some selected time steps are shown in Table 2. It can be seen that in most of time steps, the blade with NACA0006 aerofoil stalled. Therefore the test case with NACA0006 possesses the worst efficiency. For the rest of test cases, there are LEVs shed from leading edge of the blade when $\theta = 0^\circ$. The LEV caused a $C_n$ peak. The LEV shed from upstream blade induced downwash then up wash. The AOA
of the blade 1 varied quickly and this results in a drop in $C_n$ then another peak of $C_n$. Then the vortices moved into downstream and the blades stalled when $\theta$ is greater than about 30°. As the blade go on pitching down, negative $C_n$ can be observed. When $\theta$ is about 130°, highly curved flow results in large angle-of-attack and a small leading edge vortex can be seen above the blade surface, although blade already pitched downwards. This results in small positive $C_n$ peak. But if viewed in inertial frame, this causes negative vertical force. When $\theta = 180°$, the pitch angle of blade reached minimum. However, there is downwash in the cycloidal rotor cage and the downwash induced by the LEV of the upstream blade. Combined with the two effects, the AOA of the blade is small and blade is not stalled, although the pitch angle is as high as 45°. When $\theta = 207·17°$, the blade is pitching up. The TEV shed from upstream blade induced higher AOA at the leading edge of blade 1. The LESB can be observed on the lower surface of blades with plate, NACA0006, NACA0012 aerofoil. For the blade with NACA0015 and NACA0018, the time when the LESB appears is delayed. For the blade with NACA0015 and NACA0018, the trailing-edge separation appears before LESB can be observed and the blade with NACA0018 had larger trailing-edge separation area. When $\theta = 228·19°$, it can be seen that the LESB developed into LEV for all test cases. For the blades with plate, NACA0012 and NACA0015 aerofoil, the LEV and TEV shed from upstream blade first decrease then increase the AOA of the blade. Combined with the effect of larger velocity due to downwash in rotor cage, the force magnitude variation and very large force peaks can be observed. But for the case with NACA0018, the LEV and the TEV from upstream blade is aligned in radial direction since the creation of LEV is delayed. The effect of LEV and TEV cancels each other. For the case with NACA0006 aerofoil, there is no concen- trated LEV and TEV from upstream. Hence for NACA0006 and NACA0018, the effect of blade vortex interaction is weak. When $\theta = 243·50°$, the LEV began to move downstream for all test cases. And TEV can be seen for the test cases with plate, NACA0012, and NACA0015 aerofoil. Here again, the generation and convection of vortices on the blade with NACA0018 is delayed. After this, the vortices convected downstream and blade 1 stalled. After $\theta$ is greater than about 282·84°, the blade 1 moved toward the upper right portion of the trajectory where the downwash is weaker and the streamline is highly curved. The inverse camber effect becomes significant. The inverse camber effect will increase the AOA at leading edge and cause the flow separation from leading edge, then re-attach at the trailing-edge. The separated flow reduced the magnitude of $C_n$ and $L/D$, hence deteriorated the performance of the cycloidal propeller. When $\theta = 311·96°$, LESB appeared on the upper surface of the blade with plate aerofoil. When $\theta = 332·98°$, as the AOA is increasing, and combined with the effect of inverse camber, the LESB turned into LEV for cases with plate aerofoil and NACA0012. For the blade with NACA0006, the flow is fully separated, and the smallest $C_n$ is created. The size of LEV on NACA0012 is smaller since LESB appears later than plate aerofoil. For the blade with NACA0018, only LESB can be observed. And for the case with NACA0018, flow on the aerofoil is still attached. But there is a low pressure zone near the leading edge.

The leading edge radius of the blade with NACA0012 aerofoil is 1·11mm and the leading edge radius of the 2mm plate aerofoil is 1mm. From the force curve, stream traces and contours, it can be seen that the blade with 2mm plate aerofoil and NACA0012 aerofoil share quite similar flow pattern and performance, although their thickness are quite different. It can be seen that except NACA0006, if the leading edge radius and thickness is larger, the time when the LESB and LEV appears will be delayed, hence the time when the force peaks appears is delayed.
The flow pattern in moving frame
(For each azimuth angle, the first row is coloured by pressure contour and the second row is coloured by Z-vorticity contour)

<table>
<thead>
<tr>
<th>Plate</th>
<th>NACA0006</th>
<th>NACA0012</th>
<th>NACA0015</th>
<th>NACA0018</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta = 0^\circ, \alpha_p = -45^\circ )</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
</tr>
<tr>
<td>( \theta = 27.32^\circ, \alpha_p = -40^\circ ), Pitching down</td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
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<td>( \theta = 48.34^\circ, \alpha_p = -30^\circ ), Pitching down</td>
<td><img src="image9" alt="Image" /></td>
<td><img src="image10" alt="Image" /></td>
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The effect of the airfoil thickness on the performance of the MAV scale...
V. Conclusions

The CFD simulation is conducted to evaluate the effect of airfoil thickness. The comparison between the data from CFD simulation and experiments showed that the results from CFD simulation and experiments match each other well. The forces generated by test cases with plate, NACA0006, NACA0012, NACA0015 and NACA0018 are presented and compared. In order to investigate the flow field inside and around the cycloidal rotor, the streamline, pressure contour, velocity contour and vorticity contour are presented and analyzed. The analysis and comparison can lead to the following conclusions:

1). The FM and thrust coefficient do not vary with rotation speed if the blade pitch amplitude is fixed. Therefore the force coefficients are proportional to the square of the rotation speed;

2). There is rapid variation of the side force, which will induce vibration and hence deteriorates the mechanical efficiency of the cycloidal rotor. The blade with thin airfoil introduces much larger averaged thrust offset angle;

3). The cycloidal propeller with NACA0015 airfoil has the highest FM. However, the cycloidal rotor with NACA0018 generates smaller aerodynamics forces with much smaller force fluctuation and smaller total force deflection. This is because of delayed creation of LEV and the effect of blade vortex interaction is weaker. Hence for the cycloidal rotor with NACA0018, much smoother operation can be obtained. This results in higher mechanical efficiency and lighter mechanical structure weight. Thicker airfoil is also beneficial to the structure weight. All these factors may compensate lower aerodynamics efficiency caused by NACA0018.
5.0 CONCLUSIONS

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4. The analysis showed that the blade is located at low speed region when azimuth angle of blade is between 0° and 90° and the aerodynamic forces are smaller in this region. When the azimuth angle of blade No.1 lies between 180° and 270°, the streamline is less curved, and also the inflow speed is higher due to the downwash in the cycloidal propeller cage. Combined with the effect of the TEV shed from upstream blade, the blade generates largest force peak. In this region, the inverse camber effect is less significant due to relatively straight streamline in moving frame.

5. The flow curvature will change the effective AOA of the blade and causes negative vertical force of the blade. This will deteriorate the performance of the rotor.

6. For NACA aerofoils, thicker aerofoil tends to results in trailing-edge separation. For the NACA0015 and NACA0018, the trailing-edge separation occurred before the LESB and LEV appeared.

7. The leading edge radius will significantly affect the performance of the cycloidal propeller. The leading edge radius and thickness of NACA0006 is too small and during most of the time intervals, the blade stalled. The blades with plate aerofoil and NACA0012 aerofoil share quite similar leading edge radius and quite similar flow pattern and performance, although their thickness is quite different. It also can be seen that except NACA0006, if the leading edge radius is larger, the time when the LESB, LEV and TEV appeared will be delayed, therefore the time when the force peaks appears is delayed.
ACKNOWLEDGEMENT

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