

Influence of blade negative twist on aerodynamic performance of cycloidal propeller

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Abstract: In order to improve the analysis accuracy of the influence of shape parameters on the aerodynamic performance of cycloidal propeller, a set of CFD methods suitable for the simulation of the cycloidal propeller flow field based on the dynamic overset mesh and Unsteady Reynolds time average method equation were established. The characteristics of the spanwise lift distribution and surface pressure distribution in case of different negative twist were provided. The influence of the negative twist on the aerodynamic performance of cycloidal propeller was emphasized. The results showed that, the change of negative twist caused the change of azimuth for cycloidal propeller lift. The larger the absolute value of negative twist, the lower the figure of merit of the cycloidal propeller; the smaller the negative twist, the more gentle the instantaneous aerodynamic fluctuation; the influence mechanism of negative twist on the aerodynamic performance of cycloidal propeller was generated from changing the non-uniform distribution of the cycloidal propeller's effective angle of attack.

Key words: cycloidal propeller; figure of merit; negative twist; dynamic overset mesh; dynamic stall

CLC number: V211.3

Document code: A

The cycloidal propeller is a new concept propulsion device with a blade span parallel to the axis of rotation and perpendicular to the direction of flight. The pitch angle of the blade undergoes periodic changes in each rotation, causing a very strong unsteady flow phenomenon. During the hovering process, the trajectory of the blade is a circle, and in the forward flight state is a cycloid^[1]. By varying the blade pitch and pitch phase angles, the magnitude and direction of the thrust can be changed instantaneously^[2-3]. The cycloidal propeller has the advantages of two-dimensional omnidirectional vector propulsion characteristics and low low-speed noise^[3], and has strong application potential. According to the test and numerical simulation,

the aerodynamic efficiency of the cycloidal propeller is higher than that of the conventional rotor in the case of proper design^[4], which makes the cycloidal propeller become a research hotspot in the field of aviation at home and abroad. In recent years, the influence of geometric design parameters on the aerodynamic performance of the cycloidal propeller has been studied by means of experimental means at home and abroad, and some conclusions have been drawn. For example, Kellen and Benedict, et al.^[5-7] studied the influence of the dynamic parameters (pitch angle, phase angle) of the cycloidal propeller on the aerodynamic performance of the cycloidal propeller based on the test, and further prototyped the prototype. It was found that the cy-

Received: 2019-06-30

Foundation: Priority Academic Program Development of Jiangsu Higher Education Institutions

Author: ZENG Jianan(1996—), male, M. S., the main research interest is overall design of rotorcraft.

Citation: ZENG Jianan, ZHU Qinghua, WANG Kun, et al. Influence of blade negative twist on aerodynamic performance of cycloidal propeller[J]. Journal of Aerospace Power, 2020, 35(3): 620-632.

cycloidal propeller has a high stability in the hovering state. Iosilevskii, et al.^[8] conducted a numerical study on a cycloidal rotor with a diameter of 0.11 m and found that there was severe vortex interference between the blades in the hovering state. Tang, et al.^[9-12] studied the aerodynamic performance of the pitching paddle with key design parameters such as the number of blades, the thickness of the airfoil, the position of the pitch axis of the blade, the maximum pitch angle of the blade and the maximum pitch angle of the upper and lower half. Influence, The analysis shows that the increase of airfoil thickness can improve the figure of merit of the cycloidal propeller, and the figure of merit is the highest when the pitch axis position is in the middle of the airfoil. Walther^[13] studied the unsteady aerodynamic mechanism of the cycloidal propeller with ultra-low Reynolds number (below 18000) by measuring the instantaneous aerodynamic force of the blade and the PIV flow field measurement. They concluded that the figure of merit of the micro-small cycloidal propeller is higher than that of the traditional rotor, and large dynamic virtual camber induced by the inherent flow curvature and blade pitch rate caused asymmetry in lift and drag coefficients between positive and negative pitch for both the static and dynamic pitching cases^[14].

Previous research work provides basis for revealing the variation law and flow mechanism of the aerodynamic characteristics for cycloidal propeller. Because of inadequate understanding about the unsteady aerodynamics of a cycloidal propeller, one of the most challenging tasks in the cycloidal propeller general design remains to optimize the aerodynamic performance by properly selecting the geometric design parameters. Prior to this paper, there were few papers on the influence of the blade shape on the performance of the cycloidal propeller. Only Hu and Jarugumilli carried out the analysis of the blade parameters such as the aspect ratio and the tip ratio^[1,15].

In view of this, based on the relevant research at home and abroad, a high-precision dy-

namic overset mesh method for cycloidal propeller is developed in this paper. The effectiveness of the proposed method is verified by comparison with experimental results. Based on this, the influence of blade negative twist on aerodynamic performance and flow field characteristics of cycloidal propeller in hover are studied. Then, the influence of blade negative twist on spanwise induced velocity and lift distribution is analyzed. This paper provides a reference for the further aerodynamic performance research and aerodynamic optimization of cycloidal propeller.

1 Numerical calculation method

1.1 Calculation model

The finite volume method is used to discretize the incompressible Navier-Stokes equation^[16]. The motion control equation for the unsteady incompressible problem is

$$\begin{aligned} \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} &= 0 \\ \rho \frac{du}{dt} &= S_{mx} - \frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \\ \rho \frac{dv}{dt} &= S_{my} - \frac{\partial p}{\partial y} + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \\ \rho \frac{dw}{dt} &= S_{mz} - \frac{\partial p}{\partial z} + \mu \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \end{aligned} \quad (1)$$

Where ρ is density, p is pressure, t is time, (u, v, w) is velocity, μ is viscosity coefficient and (S_{mx}, S_{my}, S_{mz}) is source term.

The control equation is spatially discretized on the mesh elements based on the finite volume method. The solver adopts the diagonal form of the implicit approximation factorization method proposed by Pulliam and Chaussee. The non-viscous term is calculated using the third-order MUSCL (monotonic upwind scheme for conservation law) format and the Roe's flux difference splitting and Koren limiter, while the viscous term is calculated using a second-order central difference. The two-form shear stress transport (SST) $k-\omega$ model is selected as the turbulence model. For the transient simulation, the second-order implicit dual-time propulsion format is a-

adopted^[17]. The boundary of the blade surface is taken not containing the slip boundary condition, and the far field is adopted based on the far field boundary condition of the Riemann invariant.

1.2 Dynamic overset mesh

According to the flow field characteristics, the mesh is divided into two parts by three-dimensional structured overset mesh: (1) the CO-shaped mesh around the airfoil, the number of nodes per blade mesh is $141 \times 35 \times 31$, corresponding to the circumferential direction, normal direction and spanwise direction of the blade, respectively; (2) Cartesian background mesh, the number of nodes is $190 \times 130 \times 126$, corresponding to the x, y, z direction; The amount of mesh is about 3.7 million. In order to capture the internal flow characteristics of the cycloidal propeller accurately, the blade rotation area of the background mesh is refined, and the mesh size of the refining zone is about $0.05c$. Hole-map method is used to determine the mesh oversetting relationship, and Inverse-map method is also applied to improve the computation efficiency. Taking the 2-blade cycloidal propeller as an example, Fig. 1 shows the three-dimensional overset mesh system used in this paper. It can be seen from the figure that the partial areas of the two blade-fitted mesh overlap, but there

is no mesh passing through the solid part of the blade, which satisfies the condition for passing of flow field.

2 Coordinate system

The coordinate system for cycloidal propeller used in this paper is shown in Fig. 2. The blade rotates anticlockwise at angular velocity ω , and the tangential speed is $\omega \cdot R$. It is defined that the forward flow direction is positive when the forward blade is above the rear blade. The azimuth Φ for each blade starts from the clockwise direction from the positive x -axis. The angle between the blade tangential velocity and the blade airfoil chord is the pitch angle θ , and the negative twist angle is φ , and the blade pitch motion is expressed as a sinusoidal function:

$$\theta(\Phi) = \left(\frac{\theta_{\text{top}} + \theta_{\text{bot}}}{2} \right) \cdot \sin \Phi + \frac{\theta_{\text{top}} - \theta_{\text{bot}}}{2} \quad (2)$$

The lift for cycloidal propeller is defined as

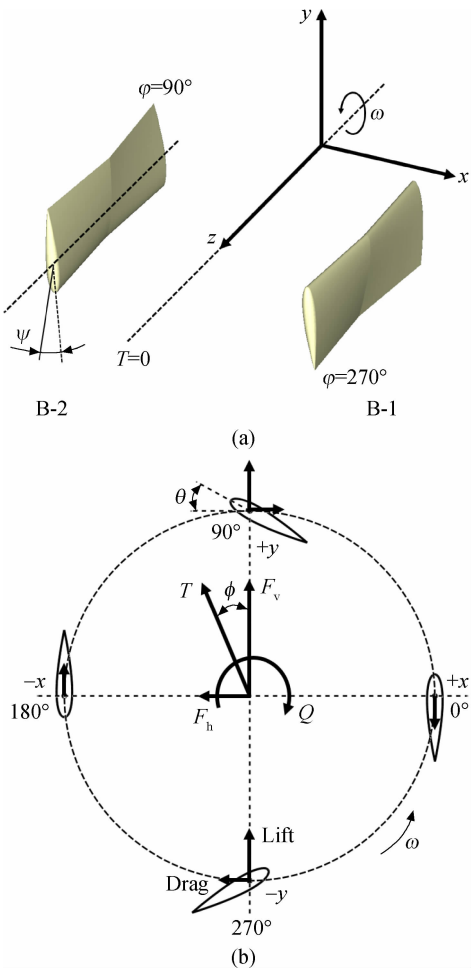


Fig. 2 Coordinate system for cycloidal propeller

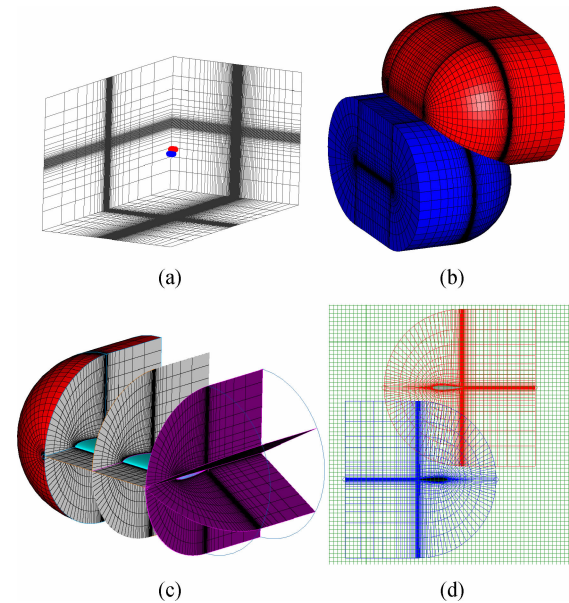


Fig. 1 Three-dimensional overset mesh system

the net aerodynamic force generated in the $+y$ direction (perpendicular to the free flow), and the thrust is expressed as the net aerodynamic force in the $-x$ direction. Where T is the instantaneous thrust for cycloidal propeller, F_h the horizontal component of T , F_v the vertical component of T , Q is the instantaneous moment for cycloidal propeller.

The main parameters of the cycloidal propeller used in this paper are shown in the table below.

Table 1 Configuration parameters of cycloidal propeller model

Parameter	Magnitude
Number of blades N_b	2
Blade span b/mm	160
Blade chord length c/mm	50
Rotor radius R/mm	76.2
Max pitching angle $\theta/(\circ)$	35
Negative torsion angle $\phi/(\circ)$	0
Local axis	40% chord
Airfoil section	NACA 0015

3 Results and discussion

This paper takes the small-scaled cycloidal propeller test from University of Maryland as an example^[2] to verify the reliability of the calculation method. Fig. 3 shows the verification results in the case of forward flight. It can be seen from the figure that the three-dimensional numerical simulation results agree well with the experimental results, particularly the lateral force calculation results, which is also reflected in the study of Hu^[18] and Kan^[19]. The above example verification shows that the three-dimensional calculation model used in this paper can be used for flow analysis in hover.

Figure 4(a) shows the corresponding relationship between disk loading and power loading at different negative twists based on the same RPM (revolutions per minute). The disk loading increases monotonously with the increase of negative twist, while the power loading increa-

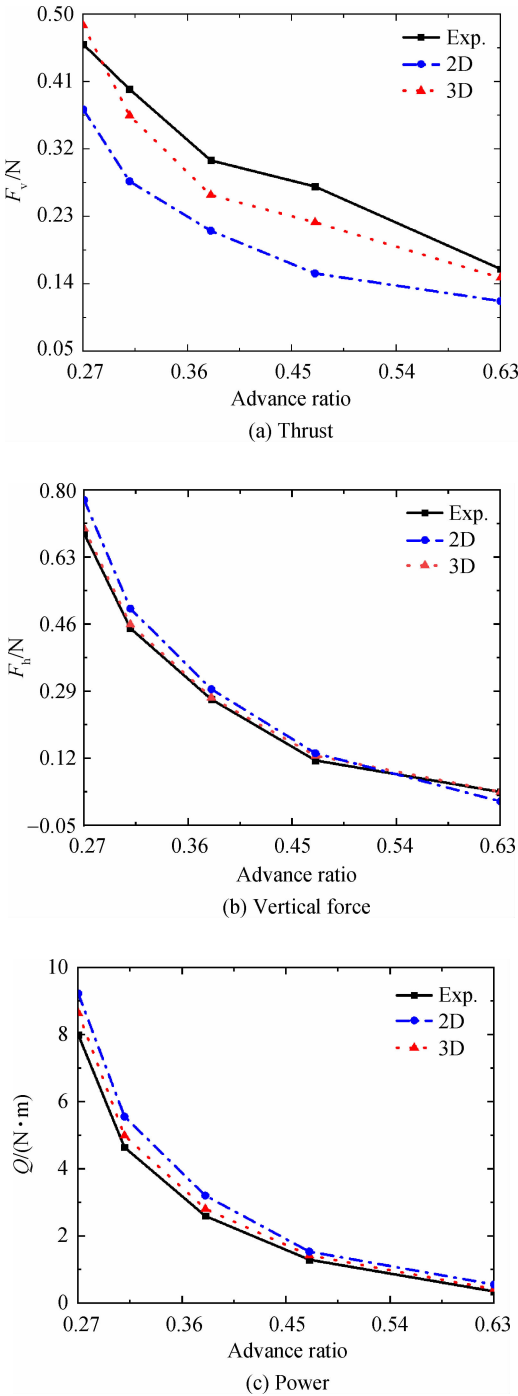


Fig. 3 Comparison of aerodynamic characteristics between computational results and experimental data

ses first and then decreases with the increase of negative twist. Both disk loading and power loading reaches the maximum when the negative twist is -5° ; the figure of merit with different negative twists is shown in Fig. 4(b). It can be seen that the figure of merit remains a relatively great value with the negative twist changing from -5° to 5° , the larger the absolute value of

the negative twist, the lower the FM (figure of merit), and the power loading and disk loading share the same trend.

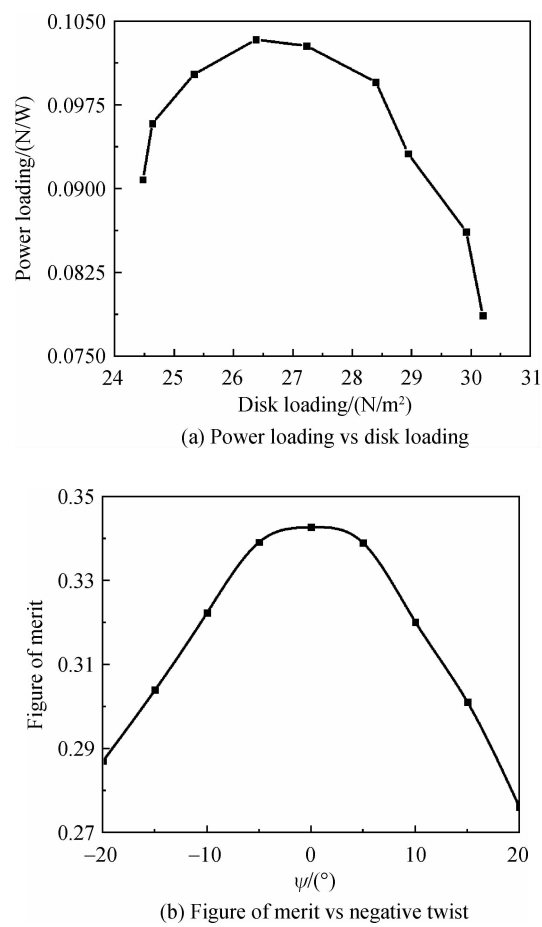


Fig. 4 Aerodynamic characteristics of cycloidal propeller

The time-average aerodynamic characteristics of the cycloidal propeller with different negative twists are shown in Fig. 5. It can be seen from Fig. 5(a) that the vertical force amplitude increases first and then decreases as the negative twist increases, which shows slightly different trend from the disk loading change, and the vertical force peaks at a negative twist of about 15° ; the lateral force monotonously decreasing within $\pm 20^\circ$, whose direction changes at a negative twist of 13° , causing the thrust direction to change from left to right. The power change curve approximates a saddle curve, which is because the absolute value of the vertical force increases monotonously with the increase of the negative twist in the range of negative twist of $-20^\circ \sim 15^\circ$, and the absolute value

of the lateral force increases first and then decreases, while the torque and resultant force generated by the cycloidal propeller share the same tendency, so the required power reaches the minimum at the negative twist of -10° .

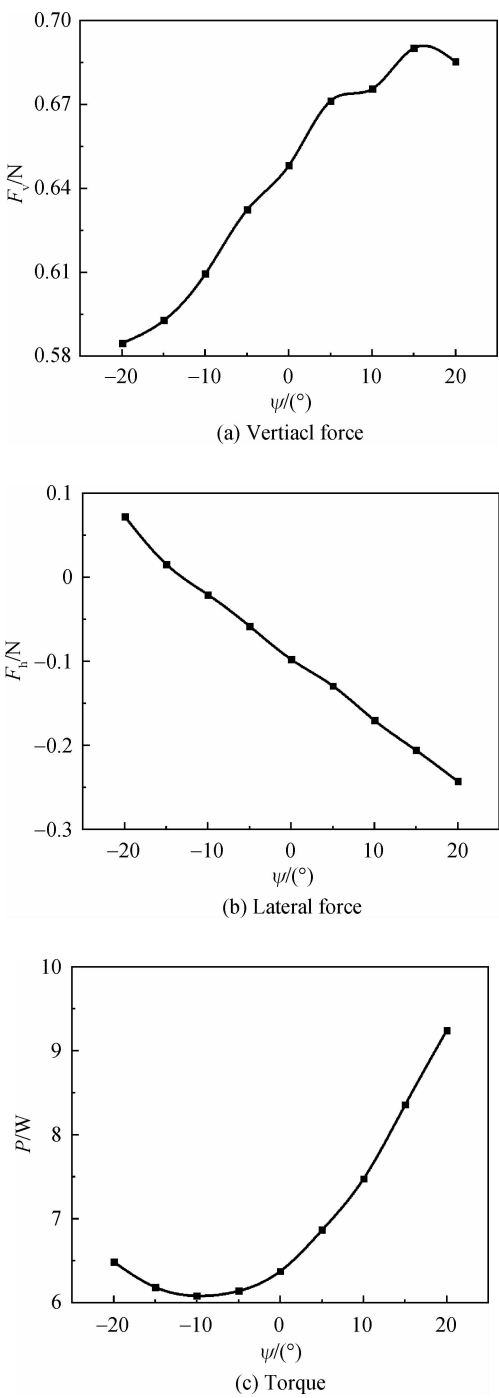


Fig. 5 Time averaged aerodynamic comparison of different negative twist angles

Figure 6 shows the instantaneous aerodynamic characteristics of cycloidal propeller with different negative twists. The vertical, lateral

force and power consumption fluctuations in the case of different negative twists are similar to the sine wave^[20-22]. Fig. 6(a) is a comparison of the instantaneous thrust during one revolution. The difference in negative twist makes the fluctuation amplitude of the vertical force show a large change. The negative force fluctuation amplitude of the cycloidal propeller reaches the minimum in the case of negative twist of -20° , and reaches the maximum in the case of negative twist of 20° . This is because in the first half cycle, the outer surface of the blade is the upper surface, and the large negative twist is equivalent to reducing the effective angle of attack of the blade. Then the blade lift in the first half cycle is reduced. In the second half cycle, the inner surface of the blade becomes the upper surface, and the negative twist greater than 0° is equivalent to increasing the effective angle of attack of the blade, and the blade lift in the second half cycle is increased. Therefore, the fluctuation amplitude of the blade aerodynamics increases as the negative twist increases. During the second half of the motion, the phase angle of the lateral force lags by 21° in the case of negative twist of 20° compared with that in the case of negative twist of -20° . The lagged phase angle for lateral force is 37° . From the instantaneous torque and thrust curve in Fig. 6(c), the instantaneous torque fluctuation range reaches the minimum in the case of negative twist of -20° , which is beneficial to reduce the mechanical loss during the rotation^[12], indicating that appropri-

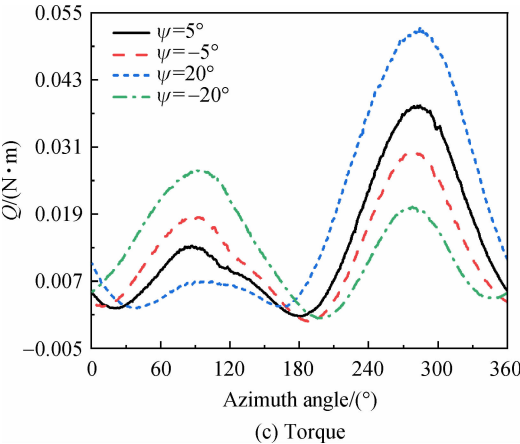
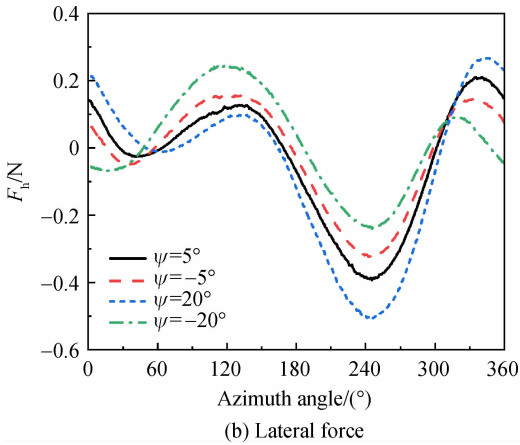


Fig. 6 Instantaneous aerodynamic comparison of different negative twist angle

ate negative twist is conducive to improving the thrust stability of the cycloidal propeller.

Since the relative flow velocity experienced by the cycloidal propeller during rotation is constantly changing in both amplitude and direction, the unsteady aerodynamic analysis of the cycloidal propeller is much more complicated. Another method is to plot the blade normal force coefficient C_n and tangential force coefficient C_t as a function of the blade pitch angle^[12]. C_n and C_t are defined as:

$$C_n(\varphi) = \frac{F_n(\varphi)}{(1/2)\rho V_r^2 bc} \tag{3}$$

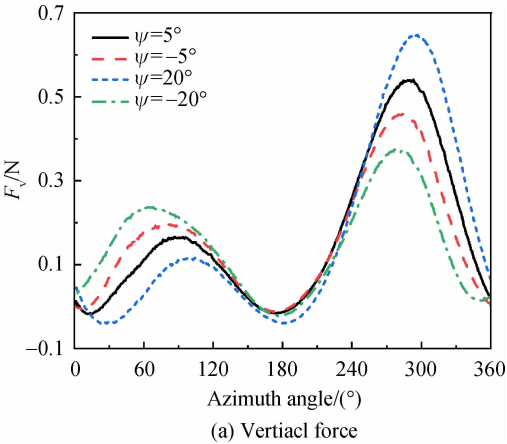
$$C_t(\varphi) = \frac{F_t(\varphi)}{(1/2)\rho V_r^2 bc} \tag{4}$$

where φ is the blade phase angle, and the blade tangential force and normal force are defined as:

$$F_n(\varphi) = F_v(\varphi) \cdot \sin \varphi - F_l(\varphi) \cos \varphi \tag{5}$$

$$F_t(\varphi) = F_v(\varphi) \cdot \cos \varphi - F_l(\varphi) \sin \varphi \tag{6}$$

From Fig. 7, it can be seen that the blade



aerodynamic curves under different negative twists share similar trends, and the normal/tangential force shows obvious hysteresis loop, reflecting strong unsteady effect^[11]. For the normal/tangential force coefficient, the larger the negative twist, the larger the change amplitude in the first half cycle, the smaller the change amplitude in the second half cycle, and the smaller the amplitude range at the current azimuth. The reason for the phenomenon above can be explained here: the effective angle of attack of the blade during the rotation is changed because of the negative twist, and the negative twist increasing the actual angle of attack during the first half cycle, the normal force increases linearly; while during the second half cycle, the blade flow has experienced a reversal. And the upper surface of the blade in the first half cycle becomes the lower surface of the blade in the

second half cycle, causing the normal force to increase monotonically with the increase of the negative twist. Therefore, the variation range of the right half of the blade hysteresis loop caused by the stall also increases monotonically.

Figure. 8(a) shows the resultant force direction vs the negative twist. The resultant force deflects 10.8° in the case of negative twist of 5° , which means that although the eccentric azimuth can be adjusted to change the resultant force direction^[18], the blade negative twist can also effectively change the resultant force direction. As can be seen from Fig. 5, the absolute value of the lateral force slope is greater than the vertical force slope, resulting in the increase of deflected direction angle of the resultant force as the negative twist increases. Fig. 8(b) shows the instantaneous resultant force vector distribution during the rotation. It can be seen that the instantaneous resultant force amplitude and direction are constantly changing during the rotation, and the change law is similar to the “pendulum” motion. Compared with the calculation results from Tang^[12], the swinging change region of the micro-small two-blade cycloidal propeller is larger, and the swing range increases as the negative twist increases, which is consistent with the conclusion from Fig. 6(c). Therefore, the larger the negative twist in a certain range, the more favorable it is for the cycloidal propeller to produce stable lift during the rotation period, which is also beneficial to the flight control for cycloidal propeller.

Figure. 9(a) shows the velocity contour at

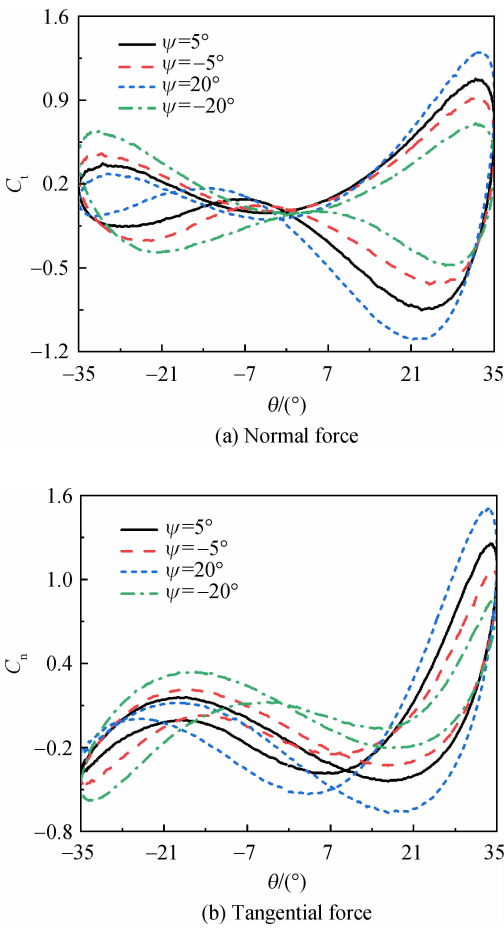
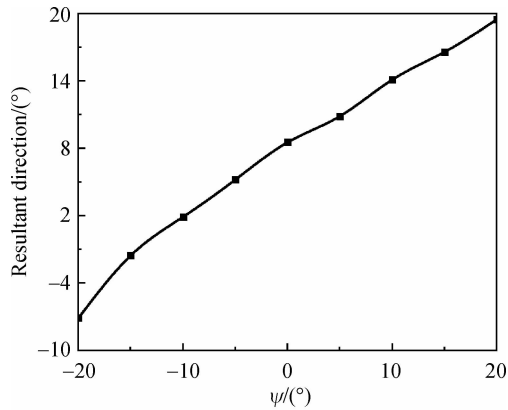


Fig. 7 Blade aerodynamic comparison of different pitch angle



(a) Resultant force direction vs negative twist

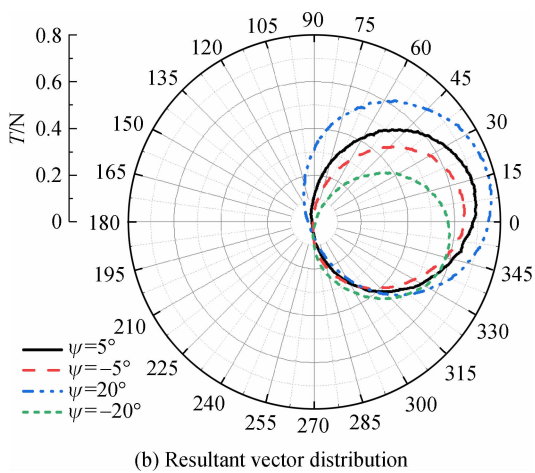


Fig. 8 Lift direction distribution

the symmetrical section. It can be seen that as the negative twist increases, the range and intensity of the downwash-affected area gradually increase, which is the cause of the gradual increase of the resultant force and aerodynamic power consumption; The downwash-affected area is caused by the blade motion and the blade-vortex disturbance. In the case of negative twist of 20°, there are two obvious wakes; when the blade is in the second half cycle, the vertical velocity is larger compared with the first half cy-

cle, so the vertical force of the cycloidal propeller in the second half cycle is greater than that in the first half cycle. And in the second half cycle, the vertical induced velocity in the downwash-affected area increases because of large negative twist, which is consistent with the conclusion from Fig. 6(a). As shown in Fig. 9(b), it can be seen that the slipstream of the cycloidal propeller with different negative twists shrinks above and below the blade, which converges in the wake flow downstream because of convolution vortex pair from the generation and falling off of the blade tip vertex at the trailing edge and leading edge; there is a certain phase lag in the dynamic stall process under different negative twists, which affects the strength and position of the vortex pair converged in the downstream of the cycloidal propeller, further affecting the instantaneous blade aerodynamics. The downwash intensity at the middle end of the blade is greater than that in the blade tip end. As the negative twist increases, the vertical induced velocity increases, and the greater the downwash shrinkage rate, the greater the vertical force generated.

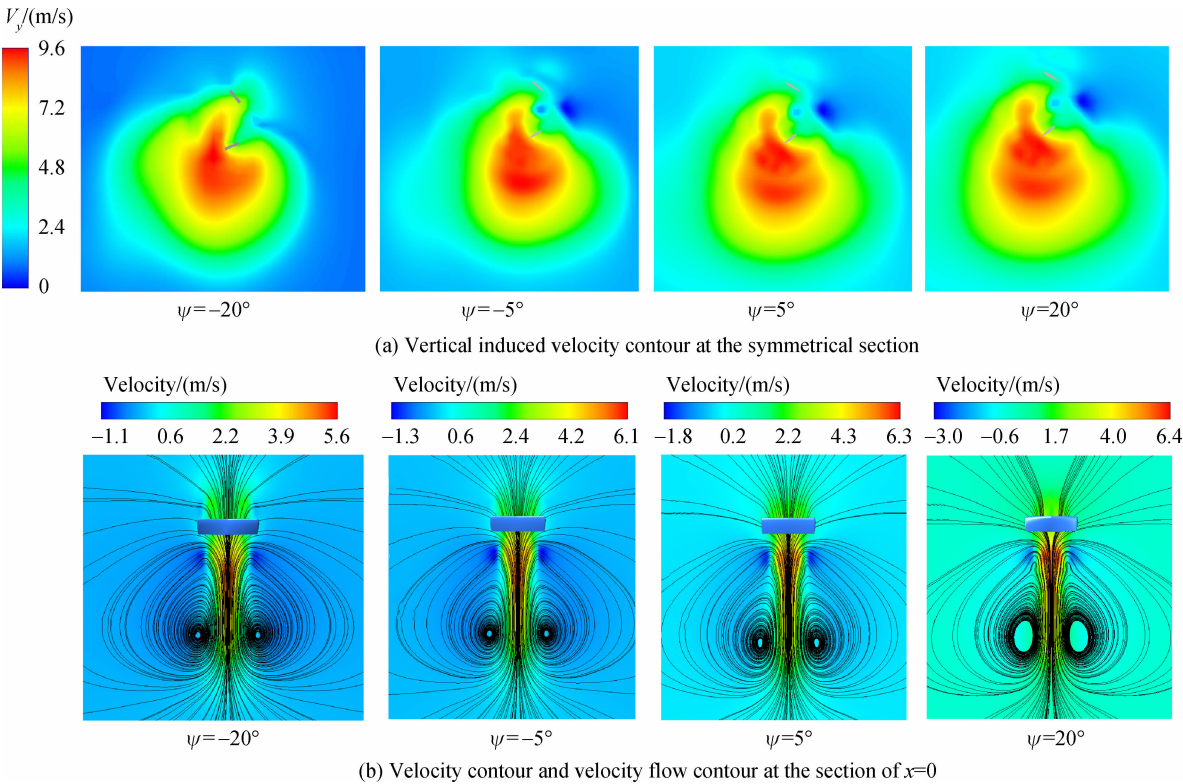


Fig. 9 Flow field of the cycloidal propeller with different negative twist

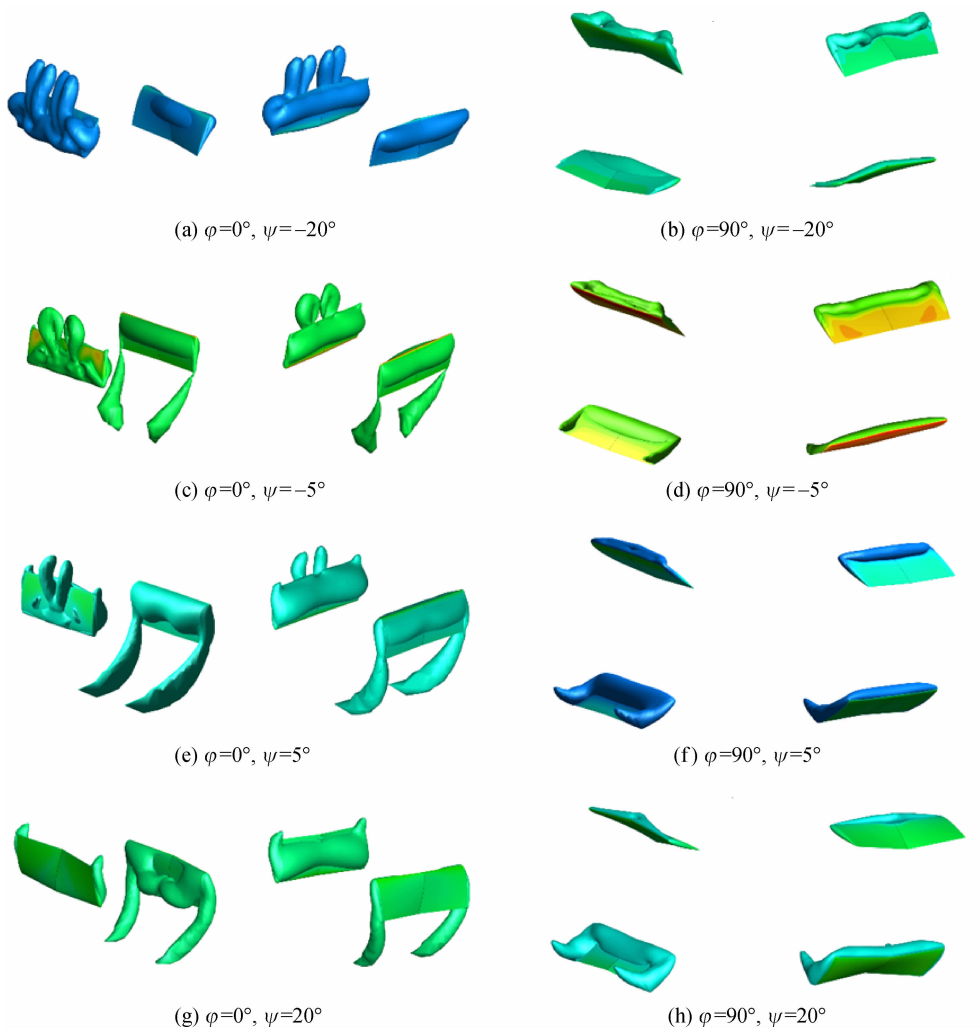


Fig. 10 Vortex contour vs negative twist

The vortex structure in the rotating area for cycloidal propeller with different negative twists is shown in Fig. 10. It can be seen that under different negative twist conditions, the pitch motion of the blades induces three-dimensional dynamic stall. The leading edge vortex and the trailing edge paddle vortex are continuously detached and reattached as the blades rotate. It can be seen that the leading edge vortex is highly distorted, and the vortex intensity at 0° azimuth angle gradually decreases with the increase of the negative twist. In the case of negative twist of 20° , the tip vortex at azimuth angle of 270° does not start to detach due to the dynamic stall effect, while there is no blade tip shedding vortex on the outer surface at azimuth angle of 180° . The leading edge vortex intensity at the current azimuth increases gradually with the in-

crease of the negative twist, which is also the reason why the cycloidal propeller with large negative twist has a larger lift in the latter half of the cycle as shown in Fig. 6(b).

Figure 11 shows the spanwise lift/lateral force distribution at azimuth angle of 270° in case of different negative twists. The abscissa is non-dimensionalized with chord length. It can be seen that compared with the case of large negative twist, the aerodynamic distribution in the case of small negative twist is more balanced, and with the increase of the negative twist, the spanwise lift is gradually increased; in all negative twist situations, the spanwise lift distribution of the blade is nonlinear, which share the same property with the vorticity distribution in Fig. 10 for the following reasons: the trailing edge tip vortex near the trailing edge of the blade

causes a local peak of the thrust, and the unstable detachment of the leading edge vortex changes the lift distribution in the middle of the blade. The most obvious case arises in the case of negative twist angle of -20° . It is worth mentioning that, the blade tip is passivated in the meshing process, so the blade chord length is slightly increased. The aerodynamic results of the passivated tip are not output during the post-processing, which explains why the aerodynamic force at the blade tip is not zero as shown in Fig. 11.

In order to capture the instantaneous vertical induced velocity V_y at the disk, a monitoring section is set at the vertical position of $-1.8R$, wherein the tip velocity V_{tip} is nondimensionalized. As shown in Fig. 12, the vertical induced velocity of the cycloidal propeller changes sharply with the position of the spanwise direction in the case of different negative twists, and the closer to the middle section, the greater the induced velocity, which is consistent with the conclusion from Fig. 9; There is a backflow zone at the outer section of the blade at the azimuth an-

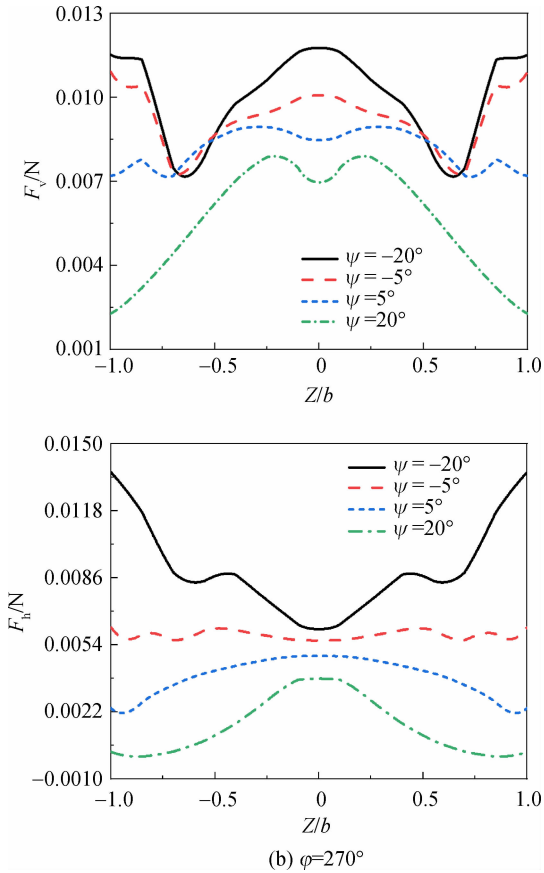
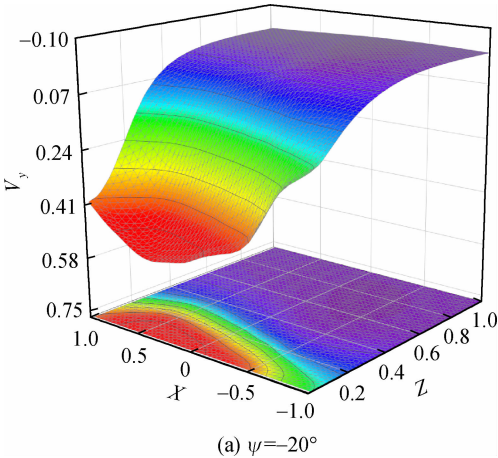
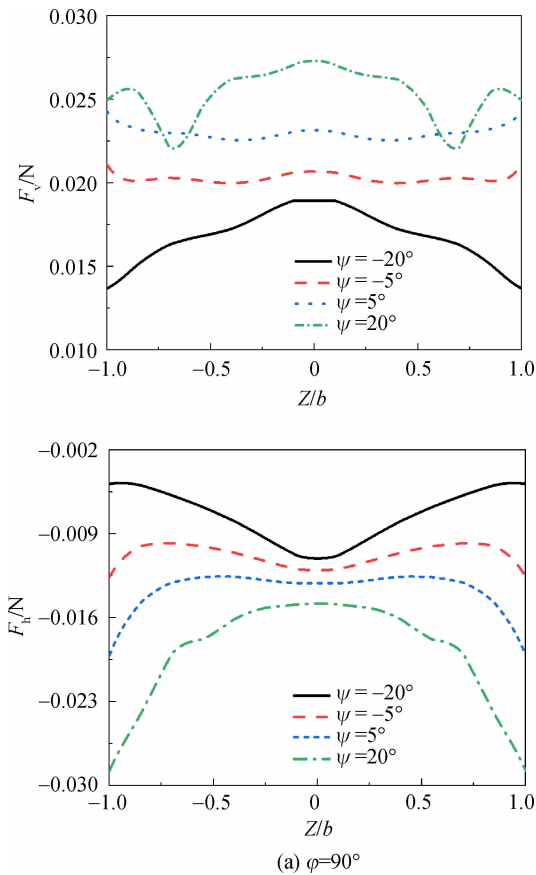


Fig. 11 Spanwise vertical/lateral force distribution of the blade

gle of 210° because of blade-vortex interference, causing the effective angle of attack of the blade increases as the induced velocity decreases, which results in the increase of blade lift. With the increase of the negative twist, the induced velocity at the middle section is obviously increased, and the area and intensity of backflow zone for blade tip induced velocity gradually increases, leading to the imbalance of the spanwise



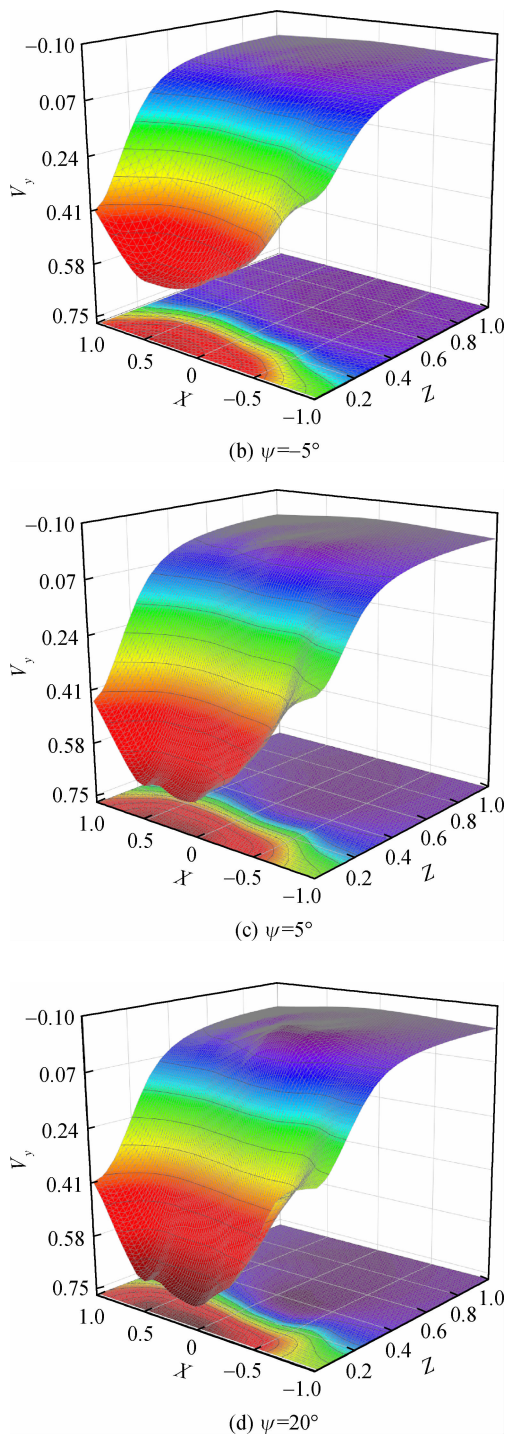


Fig. 12 Vertical induced velocity vs negative twist

lift distribution of the blade, which is the cause of the sudden drop in spanwise lift at 25% and 75% as shown in Fig. 11(b).

In order to further study the influence of negative twist on the aerodynamic interference of the cycloidal propeller, Fig. 13 shows the pressure distribution at the azimuth angle of 0° and 180°. The comparison shows that as the negative twist increases, the negative pressure region and

strength of the upper surface are significantly reduced, and the negative pressure center gradually moves toward the leading edge, which is consistent with the conclusion that the peak hysteresis in the instantaneous aerodynamic characteristics of the blade of Fig. 6; obvious negative pressure zone is present at the blade tip of the lower surface, and the negative pressure center gradually moves toward the front edge. It can be seen that the reverse pressure gradient at the blade tip is reduced because of large negative twist, which effectively delays the airflow separation phenomenon, consistent with the conclusion shown in Fig. 10, indicating that large negative twist of the blade causes the lag in the detachment cycle for the blade tip vortex at trailing edge.

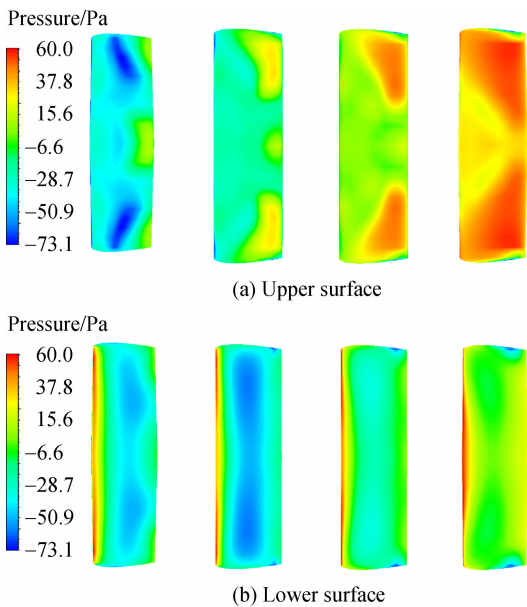


Fig. 13 Pressure contour of the blade upper and lower surface

4 Conclusions

Based on CFD method and dynamic overset mesh, the aerodynamic performance and flow field characteristics of cycloidal propeller in hover are investigated. The influence of negative twist on the aerodynamic characteristics is then analyzed. Based on this, the effect of the negative twist on the three-dimensional dynamic stall effect of the cycloidal propeller is studied, leading to the following conclusions:

1) With the increase of the negative twist, the vertical force gradually increases, which peaks at a negative twist of about 15° . The lateral force continuously reduces as the negative twist increases, which reaches 0 at the negative twist of -13° , causing the resultant thrust to point vertically. The change trend of power is similar to the saddle curve, which reaches the minimum at the negative twist of -5° . The negative twist has a significant influence on the time-average thrust direction of the cycloidal propeller. The deflected direction angle of resultant force increases monotonically with the increase of the negative twist.

2) The vertical, lateral force and power consumption fluctuation of the cycloidal propeller is similar to the sine wave. As the negative twist increases, the fluctuation amplitude for blade aerodynamics gradually increases, and the phase angle of the amplitude gradually lags behind. In the case of negative twist of 20° , the azimuth lags by 21° , and the instantaneous torque fluctuation range is the smallest, which is beneficial to reduce the mechanical loss during the rotation process. This indicates that the proper negative value of the negative twist is conducive to improving cycloidal propeller's thrust stability.

3) Due to the three-dimensional dynamic stall effect, the spanwise distribution of the lift of the cycloidal propeller is not uniform. The lift in the middle of the blade with the azimuth angle of 270° is large, and the lift at both ends is small. The existence of the tip edge vortex causes the local lift to peak at the blade tip. The negative twist has a significant influence on the spanwise aerodynamic distribution. For the calculated state in this paper, the spanwise aerodynamic distribution of the cycloidal propeller is more balanced in the case of small negative twist.

4) The influence of the negative twist on the cycloidal propeller in hovering is mainly reflected in the change of the resultant force direction and the falling re-attachment frequency of the leading edge vortex, and the FM of the cycloidal

propeller is higher in the case of small negative twist. Further study in the condition of forward flight will be carried out.

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(编辑:张 雪)