

Aerodynamic optimization design of general parameters for cycloidal propeller in hover based on surrogate model

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Abstract: A surrogate-model-based aerodynamic optimization design method for cycloidal propeller in hover was proposed, in order to improve its aerodynamic efficiency, and analyze the basic criteria for its aerodynamic optimization design. The reliability and applicability of overset mesh method were verified. An optimization method based on Kriging surrogate model was proposed to optimize the geometric parameters for cycloidal propeller in hover with the use of genetic algorithm. The optimization results showed that the thrust coefficient was increased by 3.56%, the torque coefficient reduced by 12.05%, and the figure of merit (FM) increased by 19.93%. The optimization results verified the feasibility of this design idea. Although the optimization was only carried out at a single rotation speed, the aerodynamic efficiency was also significantly improved over a wide range of rotation speeds. The optimal configuration characteristics for micro and small-sized cycloidal propeller were: solidity of 0.2—0.22, maximum pitch angle of 25°—35°, pitch axis locating at 35%—45% of the blade chord length.

Key words: cycloidal propeller; aerodynamic shape optimization; key design parameters; surrogate-based optimization; dynamic overset mesh

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The cycloidal propeller is a new concept of propulsion device with blade span running parallel to the rotation axis and perpendicular to the flight direction. The blade pitch angle experiences a periodic variation over each revolution, causing a very strong unsteady flow phenomenon. The orbit of a blade is a circle in hover vs a cycloid in forward flight^[1]. By varying the amplitude and azimuth of the eccentric ring relative to the rotation axis, the magnitude and direction of thrust can be changed instantaneously. Fig. 1 shows a two-dimensional sketch of a four-blade cycloidal propeller, ω represent the angular velocity. The cycloidal propeller holds promising

application potentials because of some special advantages, such as two-dimensional omnidirectional vector propulsion and low rotation noise. According to the test and numerical simulation, the aerodynamic efficiency for a properly-designed cycloidal propeller is higher than that of the conventional rotor^[2], which makes the cycloidal propeller a research hotspot in the aviation field. In recent years, the influence of geometric design parameters on the aerodynamic performance for cycloidal propeller has been studied by means of test means at home and abroad^[3-7]. Leger, et al^[8] investigated the influence of the dynamic parameters for cycloidal pro-

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propeller, such as pitch angle, azimuth, on the aerodynamic performance through tests. Tang, Hu, et al^[9-11] discussed the influence of key design parameters on the aerodynamic performance for cycloidal propeller, such as the number of blades, airfoil thickness, position of blade pitch axis, maximum pitch angle of the blade and the symmetry setting for the upper and lower half of the cycloidal propeller, and they also carried out the cycloidal propeller airfoil optimization based on the class/shape transformation-computational fluid dynamics (CST-CFD) method^[12]. Walther^[3] studied the unsteady aerodynamic mechanism for cycloidal propeller with ultra-low Reynolds number (below 18000) through measuring the instantaneous aerodynamic force of the blade and particle image velocity (PIV) flow field. Kan^[13] studied the spanwise distribution of blade thrust for cycloidal propeller vs the azimuth by developing a high-precision dynamic overset mesh method, and the PIV flow test on the three-dimensional flow for cycloidal propeller was carried out. Shen, et al^[14] carried out unsteady aerodynamic analysis and simulation for cycloidal propeller in hover and forward flight, and calculated the aerodynamic interferences among multiple blades by studying airfoil dynamic stall to optimize the number of blades. Kellen, et al^[15] investigated the influence of several parameters, such as airfoil, blade pitch angle, disk loading, chord length, and span length, on hover performance in the case of Reynolds number below 200 000 through lots of tests, and they suggested that the peak thrust coefficient for cycloidal propeller can reach 0.6.

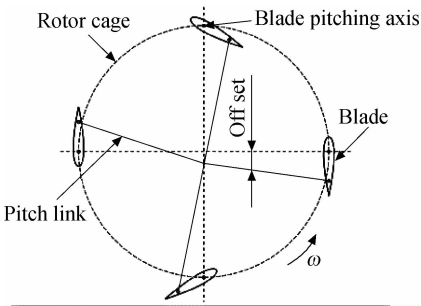


Fig. 1 Construction of a four-blade cycloidal propeller

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. The current way to select the parameters is carrying out studies on key geometric parameters, and obtain feasible solutions for several specific design values^[16-18]. However, such method always leads to repeated research work because of some subjective factors, so it is of great importance to consider the figure of merit (FM, denoted as F_m) in the general design stage. In this way, not only the design requirements for high FM can be met, but also the credibility of general design can be strengthened. What's more, this method reduces the FM analysis and design work during the detailed design, thereby shortens the design cycle and decreases the design costs. Few papers about the aerodynamic optimization design of general parameters for cycloidal propeller in hover are available in the literature by far. This paper aims to propose an aerodynamic design optimization method for cycloidal propeller in hover based on surrogate model. In this method, the optimal latin hypercube design (OLHD) is used to design the sample space with the maximum FM as the objective function, and CFD method and two-dimensional overset mesh are used to obtain the aerodynamic solutions for the sample points. The surrogate model is established based on Kriging model, and genetic algorithm (GA) as well as gradient optimization algorithm are used as the hybrid optimization strategy for further optimization.

In this paper, the surrogate model optimization algorithm is applied to the aerodynamic optimization design for cycloidal propeller in hover. By studying the key parameters, the ideas and principles of aerodynamic design for cycloidal propeller are provided, and an aerodynamic optimization design method for engineering application is proposed. Some guidance and reference are provided in this paper for aerodynamic

performance study on cycloidal propeller and its optimization design.

1 Surrogate-based aerodynamic optimization design method

1.1 Surrogate-based optimization (SBO) framework

The flow chart of optimization design method for cycloidal propeller based on Kriging surrogate model is shown in Fig. 2. The process can be described as follows: ① determine the initial geometric parameters and design space; ② carry out the test design sampling through OLHD in the design space; ③ calculate the aerodynamic performance of the sample points using CFD; ④ construct the Kriging surrogate model to capture the surrogate relationship between the design parameters and the aerodynamic characteristics (system response) in the purpose of replacing the CFD calculations; ⑤ use the hybrid optimization strategy to optimize the Kriging model to obtain the optimal design parameters in a given sample space; ⑥ check the optimal design model obtained to verify it meets the accuracy requirement, if yes, proceed to step ⑦, if no, return to step 4 while adding the result as new sample data to the existing data set; ⑦ output the optimal design model.

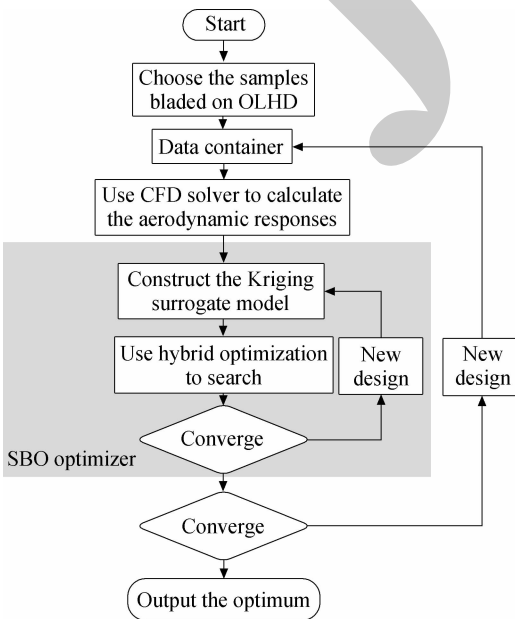


Fig. 2 Surrogate-based optimization (SBO) framework

1.2 Numerical calculation method

Two-dimensional numerical simulation for cycloidal propeller is performed using dynamic-overset mesh method. The governing equation for the unsteady incompressible turbulence problem is expressed as

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[(\nu + \eta_t) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] \quad (2)$$

The definitions of the parameters in the formula can be found in the Ref. [19]. The incompressible Navier-Stokes equation is discretized by the finite volume method. The overset structured mesh solver adopts the diagonal form of the implicit approximation factorization method proposed by Pulliam and Chaussee, and shear stress transport $k-\omega$ model is chosen as the turbulence model. The preprocessed dual time format is used to solve the compressible Reynolds-averaged Navier-Stokes (RANS) equation. The non-viscous term is calculated using the third-order monotonic upstream-centered scheme for conservation laws (MUSCL) format and the Roe's flux difference splitting and Koren limiter^[18], while the viscous term is calculated using a second-order central difference.

According to the flow field characteristics, the mesh is divided into two parts by two-dimensional structured overset mesh^[20]: ① O-shaped mesh around the airfoil (145×64), ② structured background mesh (201×201). In order to capture the internal flow characteristics for cycloidal propeller accurately, the blade revolution area of the background mesh is refined with mesh spacing of $0.02R$, and the length and width for background mesh boundary are $500R$ (R is the radius of cycloidal propeller). Hole-map method is used to determine the mesh oversetting relationship, and Inverse-map method is also applied to improve the computation efficiency^[21]. Take the four-blade cycloidal propeller as an example, Fig. 3 shows the overset mesh system used in this paper.

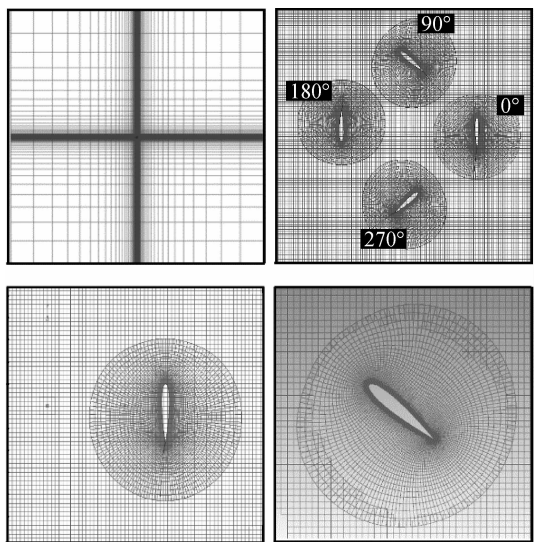


Fig. 3 Overset mesh system

1.3 Verification of surrogate model

The main body of the surrogate model is to establish a predictive model for data fitting^[22]. Based on the theory of variogram and structural analysis, the Kriging model used in this paper is a method for unbiased estimation of regionalized variables in a finite region. The error square R^2 is chosen as the criterion for judging the accuracy of the surrogate model. The closer R^2 is to 1, the better the global approximation of the surrogate model will be. R^2 is expressed as

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \bar{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (3)$$

Where y_i is the true value for checking the accuracy of the surrogate model, $\bar{y}_i$ the prediction value from the surrogate model, $\bar{y}$ the mean value of test sample points.

150 sample points are selected to establish the sample point rangeusing OLHD. The response calculated based on the objective function is used to fit the sample space. Fig. 4 illustrates the comparison between the test function and fitting function, where x, y is the function variable, $F(x, y)$ the function value, showing that the extreme points agree well with the fitting range, and the maximum error value is 2.25%, indicating that the surrogate model method used in this paper holds good fitting effect.

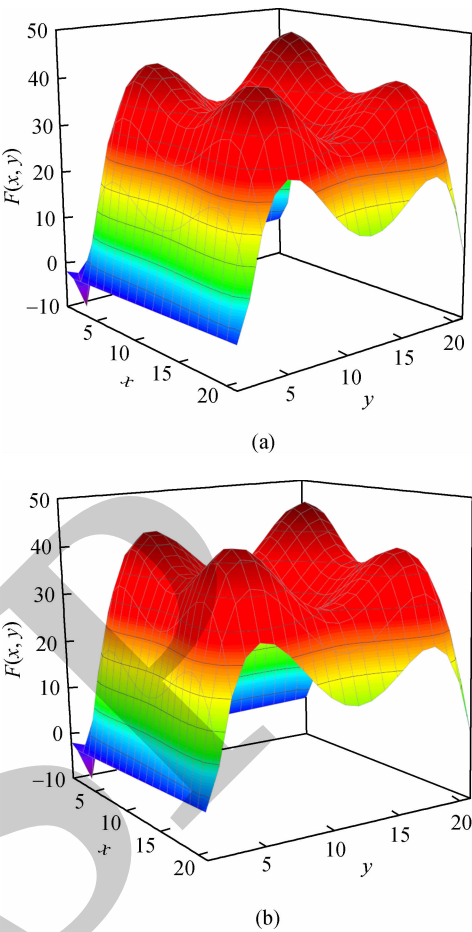


Fig. 4 Comparisons of analytic solution between the test and fitting function

2 Aerodynamic optimization design for cycloidal propeller

2.1 Coordinate system

The coordinate system for cycloidal propeller used in this paper is shown in Fig. 5. The blade rotates anticlockwise at angular velocity ω , and the tangential speed is ωr . 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 α , and the blade pitch motion is expressed as a sinusoidal function

$$\theta(\Phi) = \left(\frac{\theta_{top} + \theta_{bot}}{2} \right) \sin \Phi + \frac{\theta_{top} - \theta_{bot}}{2} \quad (4)$$

The lift for cycloidal propeller is defined as 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.

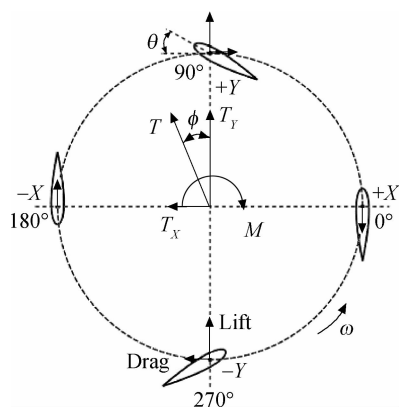


Fig. 5 Coordinate system for cycloidal propeller

Referring to Fig. 5, the aerodynamic efficiency for cycloidal propeller over acircle is defined as follows

$$C_t = \frac{T}{(1/2)\rho V_r^2 S} \tag{5}$$

$$C_m = \frac{P}{(1/2)\rho V_r^2 R \omega S} = \frac{P}{(1/2)\rho V_r^3 S} \tag{6}$$

$$F_m = \frac{C_t}{C_m C_r} \cdot \frac{\sqrt{0.5\rho V_r^2 C_t}}{\sqrt{2}p} = \frac{1}{2} \cdot \frac{C_t^{1.5}}{C_m} \tag{7}$$

Where T is the instantaneous thrust for cycloidal propeller, T_x is the horizontal component of T , T_y is the vertical component of T , M is the instantaneous moment for cycloidal propeller, P is the instantaneous aerodynamic power consumption, V_r is the tip speed and $V_r=R \cdot \omega$, R is the radius of the cycloidal propeller, ω is the rotation speed, S is the projected area of cycloidal propeller, $S=D \cdot B_l$, D is the diameter of the cycloidal propeller, B_l is the chord length.

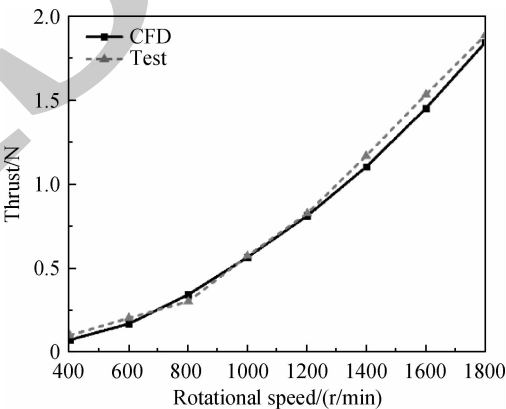
2.2 Test case

This paper uses the small-scaled cycloidal propeller test^[17]from the University of Maryland as an example to verify the reliability of the calculation method. Table 1 shows the main parameters of the cycloidal propeller in this example. The comparison about thrust and power between the calculation value and the test data is shown in Fig. 6. It can be seen that, although the spanning effect and tip loss for three-dimensional flow are not taken into account in the two-

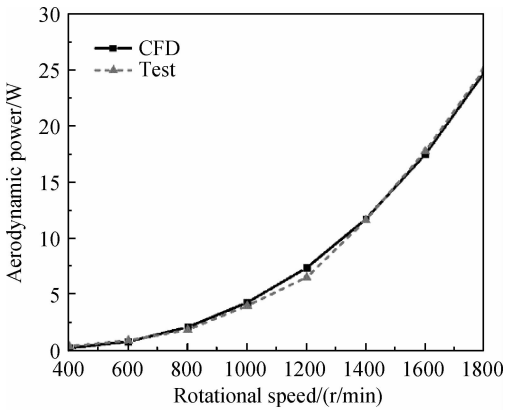
dimensional numerical simulation in this paper, the calculated results agree well with the test results and the results from Jarugumilli, et al^[6] and HU, et al^[16], indicating that the two-dimensional calculation model used in this paper can be used to optimize the aerodynamic performance for cycloidal propeller in hover.

Table 1 Configuration parameters of cycloidal propeller model

Parameter	Magnitude
Number of blades N_b	4
Blade span b/mm	158.8
Blade chord c/mm	49.5
Rotor radius R/mm	33.8
Pitching angle $\theta/(\text{^\circ})$	40
Local axis	25% chord
Airfoil section	NACA 0015



(a) Thrust



(b) Aerodynamic power

Fig. 6 Comparison of computational results and test data in Ref. [17]

2.3 General parameters optimization design for cycloidal propeller

Through studying the aerodynamic performance of the cycloidal propeller with different parameters in hover, it has shown that the thrust coefficient C_t , power coefficient C_m and F_m for cycloidal propeller can be changed to a large extent. The design variables in this paper include chord length c , pitch axis position x , pitch angle θ . The range of these design variable is shown in Table 2.

Table 2 Design variable and variation range

Design variable	Variation range
c/mm	$45 \leq c \leq 55$
$x/\%$	$15 \leq x \leq 45$
$\theta/(\text{^\circ})$	$20 \leq \theta \leq 40$

Subject to: $C_t \geq C_{t0}, C_m \leq C_{m0}$

Optimization objective, max: F_m .

Where C_{t0} is the datum thrust coefficient thrust for cycloidal propeller, the Datum moment coefficient of C_{m0} , For the optimization design based on Kriging model, the optimized CFD calibration results of the geometric parameters are shown in Table 3. It can be seen from the table that the optimized thrust coefficient is increased by 3.56% (from 0.336 8 to 0.348 8) compared with the baseline model, and the aerodynamic power consumption is reduced by 12.05%. (from 0.232 3 to 0.204 3), the F_m increased by 19.93% (from 0.420 5 to 0.504 3).

Table 3 Optimization results at the design point (rotational speed of 1 400 r/min)

Parameter	Baseline model	Optimized model	$\Delta/\%$
C_t	0.336 8	0.348 8	+3.56
C_m	0.232 3	0.204 3	-12.05
F_m	0.420 5	0.504 3	+19.93
c/mm	45.2	50.1	+10.84
Local axis/ $\%$	59.32	41.94	-29.29
$\theta/(\text{^\circ})$	29	29	0

characteristics (C_t, C_m) between the optimized model and the baseline model over the rotation range of 400—1 400 r/min. As shown in Fig. 7, both the C_t and C_m are significantly improved over a wide range of rotation speeds.

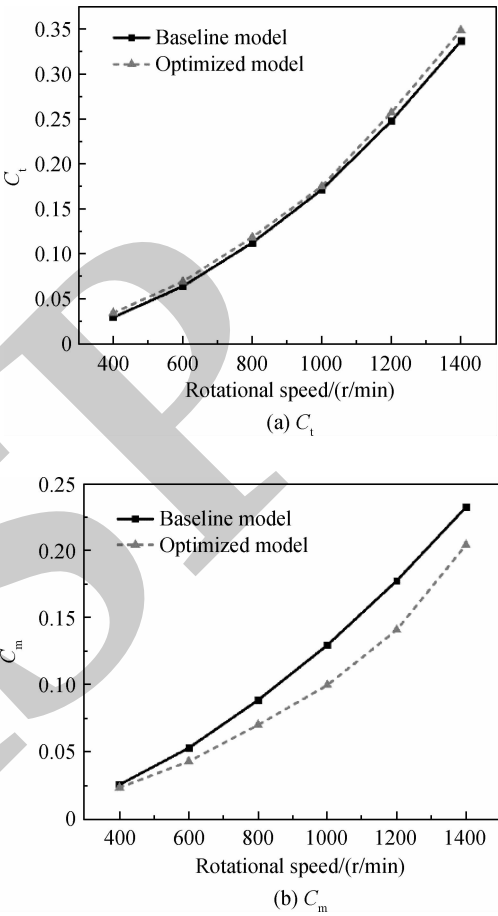


Fig. 7 Comparison of optimized model and baseline model

Fig. 8 shows the aerodynamic efficiency of a two-blade cycloidal propeller vs. azimuth. As shown in Fig. 8, for the variation of the vertical force coefficient for the blade vs. azimuth, the main difference between the optimized model and baseline model is that the vertical force coefficient at azimuth of $25^\circ - 160^\circ$ and $240^\circ - 360^\circ$, $25^\circ - 160^\circ$ for the baseline model is higher than that of the optimized model, but only a small part of the fluctuation range of the optimized model stays in the negative region, resulting in that the time-averaged vertical force $C_{v,b}$ of the optimized model is greater than that of the baseline model. As shown in Fig. 8(c), the aerody-

Fig. 7 shows the comparison of aerodynamic

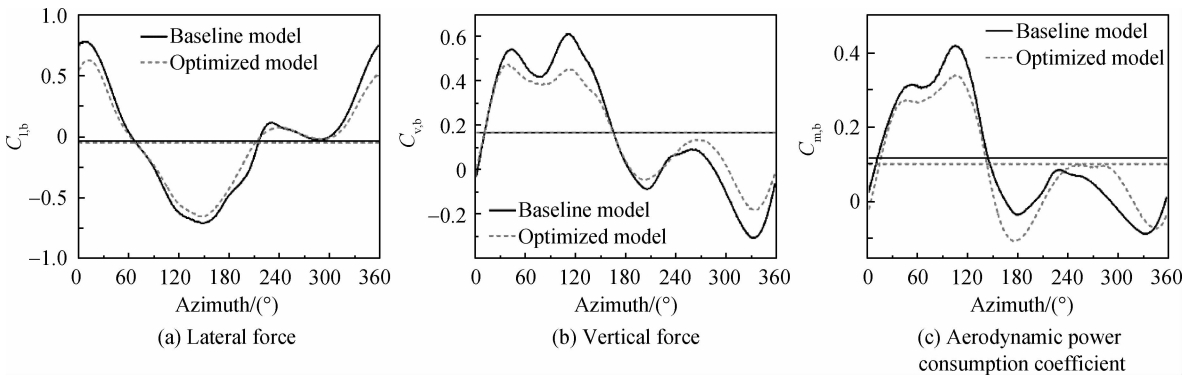


Fig. 8 Comparison of a blade for the baseline model and optimized model

dynamic power consumption coefficient $C_{m,b}$ for the blade in the optimized model is less than that of baseline model at azimuth of $0^\circ-140^\circ$. Although $C_{m,b}$ of the optimized model is greater than that of baseline model at azimuth of $235^\circ-320^\circ$, the time-averaged power consumption of the optimized model is still less than that of baseline model. As shown in Fig. 9, the fluctuation peak for vertical force coefficient $C_{v,t}$ and the lateral force coefficient $C_{l,t}$ of the optimized model are smaller than that of baseline model, making the average thrust of the optimized model greater than that of baseline model. For the change of the aerodynamic power consumption coefficient C_m over one period, the main difference between these two models is the region at azimuth of $0^\circ-80^\circ$, $150^\circ-280^\circ$ and $330^\circ-360^\circ$. The difference about the aerodynamic power consumption coefficient is mainly from the negative region. Therefore, the aerodynamic performance of the optimized model is better than that of the baseline model.

For oscillating airfoil, unsteady aerodynamic forces can be represented by plotting instantaneous lift and drag relative to the pitch angle.

However, the analysis about unsteady aerodynamics for cycloidal propeller is much more complicated because the relative flow rates experienced by the blade during rotation vary in magnitude and direction. Another method is to plot the normal force coefficient C_n and the tangential force coefficient C_t for the blade as a function of the pitch angle^[10]. C_n and C_t are defined as

$$C_n(\psi) = \frac{F_n(\psi)}{(1/2)\rho V_r^2 B_l c} \tag{8}$$

$$C_t(\psi) = \frac{F_t(\psi)}{(1/2)\rho V_r^2 B_l c} \tag{9}$$

Where ψ is the blade azimuth, and the tangential force and normal force of the blade are defined as

$$F_n(\psi) = F_v(\psi)\sin(\psi) - F_l(\psi)\cos(\psi) \tag{10}$$

$$F_t(\psi) = F_v(\psi)\cos(\psi) - F_l(\psi)\sin(\psi) \tag{11}$$

As shown in Fig. 10, the blade aerodynamics for the optimized model and the baseline model show similar trends, and the blade normal force and tangential force show obvious hysteresis loops, indicating strong unsteady effects. For the blade normal aerodynamic force, the difference between the optimized and baseline

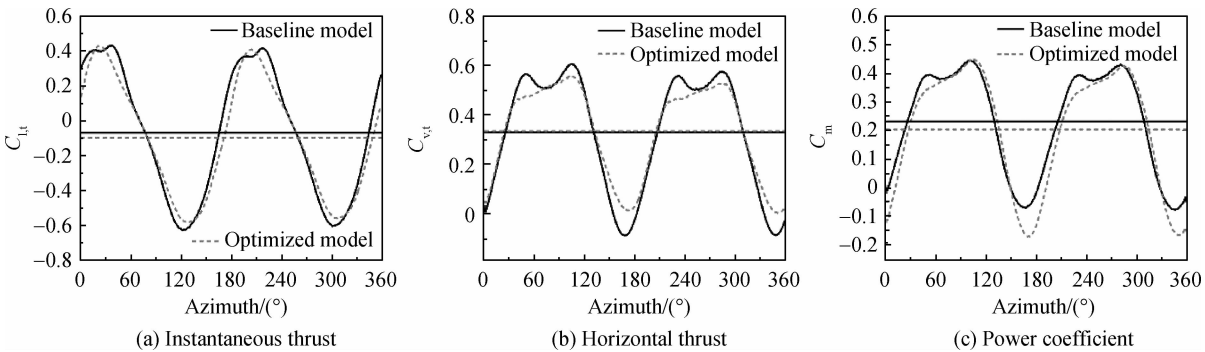


Fig. 9 Comparison of baseline model and optimized model

model is mainly reflected in the region at azimuth of $270^{\circ}\sim 360^{\circ}$, because the lower right area is the strong blade vortex interaction (BVI) zone for cycloidal propeller in hover.

Fig. 11 shows the thrust and power change vs. azimuth. In Fig. 11(a), the dark part represents positive thrust, the light part represents the negative thrust, and the dark part in Fig. 11 (b) is the anti-rotation zone, while the light part is the rotation-driving zone. The torque in the anti-rotation zone is greater than zero, while the torque in the rotation-driving zone is less than zero. It is worth mentioning that, in the case of pitch amplitude, chord length and pitch axis position change, the force and torque fluctuates because of the BVI, and the relative position and shape of anti-rotation and rotation-driving zone will also change.

Fig. 12 shows the average flow field of

the optimized model Fig. 12(a) — Fig. 12(e) and baseline model Fig. 12(f) — Fig. 12(j) at different azimuths. Since the upper and lower parts are symmetric, only the flow field of the upper part is displayed. In the velocity isoline contour, only 1/2 of the maximum velocity vector diagram is shown for the sake of clarity, and the evolution of the blade/wake interaction is clearly shown in the flow field diagram. The blade/wake shape are indicated in the figure (marked as wake A and wake B, respectively). In one rotation period, Fig. 12 shows that the blades interact with the wake once at azimuth of 150° and 300° , respectively. In the baseline model, the two wakes meet at azimuth of about 300° , but in the optimized model, there is no obvious intersection of these two wakes. In addition, the strength and position of the wake vortex varies with the rotation speed of the cycloidal propeller.

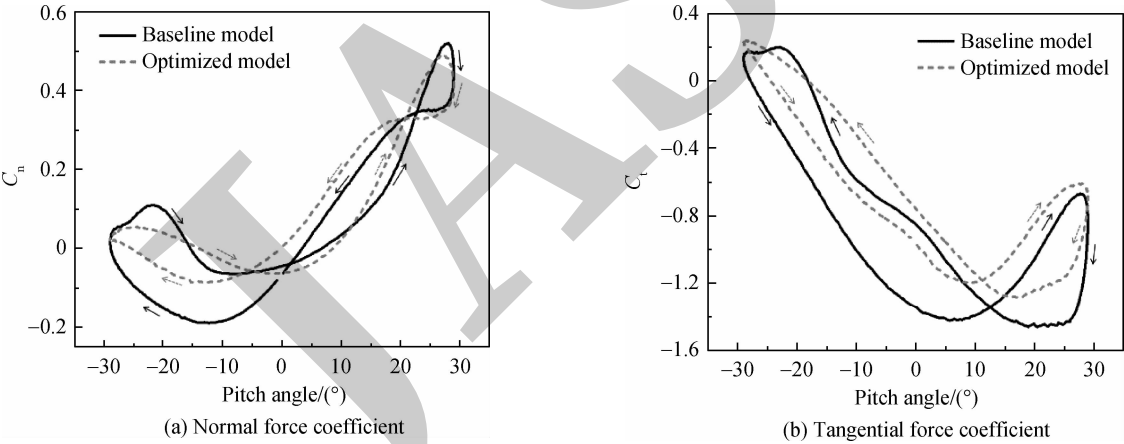


Fig. 10 Normal force coefficient and tangential force coefficient vs. pitch angle

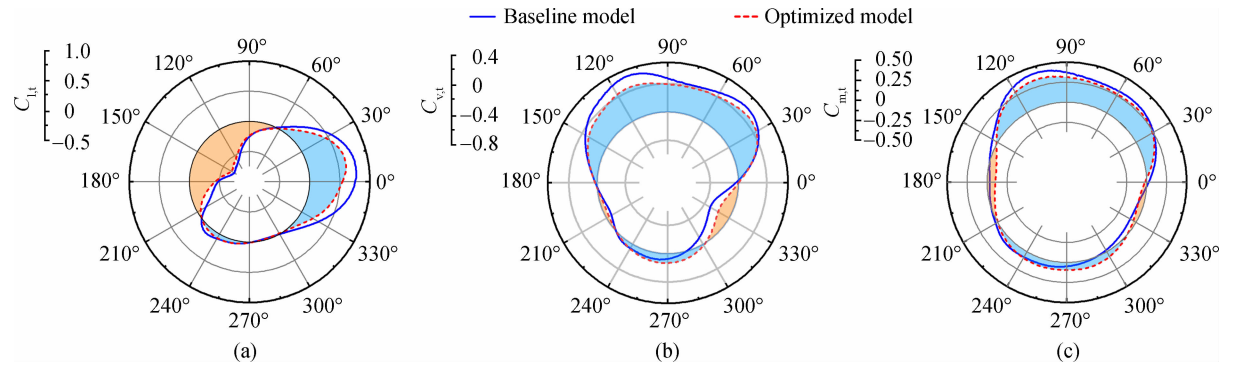


Fig. 11 Comparison of aerodynamic performance for baseline model and optimized model

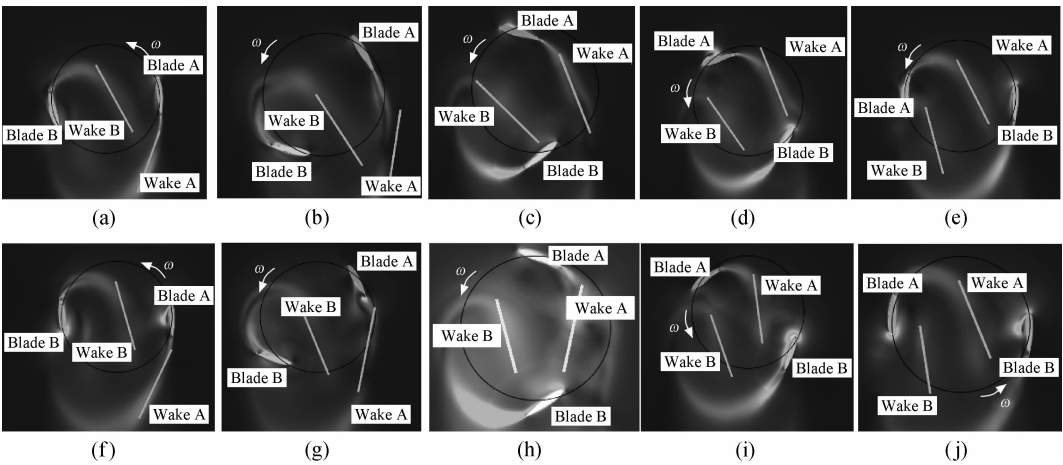


Fig. 12 Comparison of flow field for optimized model and baseline model

3 Conclusions

The basic criteria of aerodynamic optimization design for cycloidal propeller in hover are introduced in this paper. For the key design parameters of cycloidal propeller, the Kriging model-based optimization design method is proposed, and the aerodynamic characteristics for the models in hover before and after optimization are evaluated, indicating that the aerodynamic characteristics have been significantly improved.

1) The two-blade cycloidal propeller produces two wakes that interfere with the blade, which will change the airflow velocity on the blade surface. In addition, the strength and position of the wake vortex will affect the aerodynamic efficiency for cycloidal propeller.

2) The thrust of the optimized cycloidal propeller has a small range of fluctuations, which is extremely important for cyclogyro flight control.

3) During the combination change of key parameters, BVI will cause fluctuations in force and torque, resulting in various changes in the relative position and shape of the rotation-driving and anti-rotation zone.

4) Relying on the Kriging model-based aerodynamic optimization design method for the general parameters of cycloidal propeller, the thrust coefficient is increased by 3.56%, torque coefficient reduced by 12.05%, FM increased by 19.93%.

5) Due to the limitations of two-dimensional

calculations, the influence of the spanwise flow on the aerodynamic performance for cycloidal propeller is not considered in this paper. It is necessary to use three-dimensional numerical simulation method for further discussion in the subsequent research.

From the perspective of verifying and demonstrating the optimization design method, the optimization design for baseline cycloidal propeller in hover is mainly considered in this paper. In the actual design process, it is also necessary to consider the advance ratio in forward flight as well as the comprehensive performance such as cruise efficiency and flight envelope. The main problem at present is that, the number of design variables used cannot meet the multi-objective optimization of cycloidal propeller, and the optimization method needs to be further improved.

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