Research on the Influence of Key Parameters on the Aerodynamic Characteristics of Shaftless Ducted Rotors

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The shaftless ducted rotor (SDR) is a new type of ducted rotor system built using a ducted-rotor-motor integration design. Based on unstructured sliding grid technology, the effects of four key parameters, such as rotor disk height, number of blades, the center hole radius and the blade root mounting angle, on the aerodynamic characteristics of the SDR were investigated. The calculation results show that the thrust performance gradually improves as the rotational speed increases. It is different from traditional ducted rotors where the rotor is installed near the lip of the duct to obtain the optimal aerodynamic performance, the rotor of the SDR is installed away from the duct entrance to obtain the best aerodynamic performance. Additionally, the number of blades is increased to improve peak thrust and ducted thrust performance; however, this results in decreasing the power load. The central hole radius of the SDR should not be too small, as this can result in an excessive blocking effect when the central airflow passes through the paddle. Finally, when the rotational speed is constant, increasing the blade root mounting angle results in a large increase in thrust, but this decreases the power load as well.

Key Words: Shaftless Ducted Rotor, Sliding Mesh, Ducted-Rotor-Motor Integration, Key Parameters, Aerodynamic Characteristics

Nomenclature

\[
\begin{align*}
\vec{S} & : \text{velocity vector} \\
u, v, w & : \text{axial velocity, radial velocity and circumferential, respectively, the three-dimensional cylindrical coordinates} \\
\theta & : \text{general variable} \\
\Gamma & : \text{generalized diffusion coefficient} \\
\mathcal{Q} & : \text{gas phase source term} \\
\Omega & : \text{rotor angular velocity} \\
\rho & : \text{determined by the complete gas state equation} \\
C_T & : \text{thrust coefficient} \\
T & : \text{total thrust} \\
T_D & : \text{ducted thrust} \\
R & : \text{rotor radius} \\
Ne & : \text{power} \\
q & : \text{power load} \\
G_k & : \text{turbulent kinetic energy term generated by the laminar velocity gradient} \\
G_s & : \text{turbulent kinetic energy term generated by buoyancy} \\
Y_H & : \text{contribution term of the dissipation rate} \\
\alpha_k & : \text{turbulent Prandtl number of the } k \text{ equation} \\
\alpha_s & : \text{turbulent Prandtl number of the } s \text{ equation} \\
S_k & : \text{user-defined turbulent kinetic energy terms} \\
S_s & : \text{turbulent dissipation terms}
\end{align*}
\]

1. Introduction

The ducted rotor (DR) is a power unit where the rotor is installed inside the duct. The duct can improve the slipstream condition downstream of the rotor and weaken the vortex strength drawn by the tip, thereby reducing the energy loss of the wake flow. Compared to an isolated rotor, the aerodynamic performance of the ducted rotor is better.

Many studies have been conducted and a large number of applications introduced for ducted rotors. In researching the aerodynamic characteristics of DRs, various researchers have used experimental methods to analyze the thrust distribution relationship between duct and rotor. Other researchers have studied the influence of tip clearance on the aerodynamic performance of DRs. It was found that the tip clearance results in the formation of a tip vortex; a larger tip clearance decreases rotor thrust and power load, and a small tip present challenges when processing the duct and the overall safety of the system. Regarding the application of DRs, in the 1960s, the French company Nord applied DRs as the main power source of a vertical take-off and landing aircraft. Cai et al. applied DRs as the aircraft body and the main power source to new configurations of aircraft and micro-air vehicles.

In order to expand the application range of ducted aircraft and solve the aerodynamic interference problem of the tip clearance to DRs, this paper proposes a shaftless ducted rotor (SDR) based on the structural characteristics of the shaftless rim-driven propulsion system in the ship-building industry. The SDR removes the rotor support shafting and center body. The motor is installed inside the duct. The rotor and duct are free of gaps. They rotate together with the rotor.
of the motor to replace the axial connection of the DR with a radial connection. The SDR adopts the motor-ducted-rotor integration design, so there is no tip clearance, which effectively eliminates the disturbance of the tip leakage vortex. At the same time, the SDR removes the supporting rotor shafting and center body, thereby increasing the duct flow area and reducing small flow resistance.

At present, there are few studies on the aerodynamic characteristics of the SDR, and it is structurally different from DRs. Therefore, the SDR does not necessarily have some universal aerodynamic characteristics of DRs, especially, the influence of key parameters on the overall aerodynamic performance. With the development of computer technology, numerical calculation methods have been widely used in the field of rotating machinery, and can obtain more accurate calculation results. Therefore, in this paper, the aerodynamic characteristics of the SDR are numerically simulated using a sliding grid technology based on an unstructured grid. The influence of the four key parameters of rotor disk height, number of blades, center hole radius and blade root mounting angle on the aerodynamic characteristics of the SDR are analyzed. The research results in this paper can provide a reference for the overall design and aerodynamic optimization of SDRs.

2. Structure of the SDR

Figure 1 is a structural diagram of the SDR, which is mainly composed of the motor rotor, multi-pole stator, fixed bearing, rotating ring, duct, rotor, etc. The fixed bearings are mounted on either side of the rotating ring to ensure the axial position of the rotating ring and to transmit the thrust generated by the rotor. The motor is located between two fixed bearings. The rotating ring connects the rotor to the motor rotor, so that the rotor and motor are integrated, and the radial connection is used instead of the axial connection of the DR. During operation of the device, the motor rotor drives the rotor to rotate relative to the multi-pole stator.

3. Numerical Calculation Method

3.1. Control equation

This paper uses the $k-\varepsilon$ RNG model for the turbulence model. The three-dimensional compressible flow N–S equation is solved numerically based on the finite volume method. The steady-state governing equation\(^{(10)}\) is:

$$\frac{\partial(\rho \tilde{\theta})}{\partial t} + \text{div}(\rho \tilde{S} \tilde{\theta}) = \text{div}(\Gamma \text{grad} \tilde{\theta}) + Q$$

(1)

where

$$\tilde{S} = \tilde{u} \tilde{m} + \tilde{v} \tilde{n} + \tilde{w} \tilde{I}$$

(2)

$$\text{div} \tilde{S} = \nabla \cdot \tilde{S} = \frac{\partial u}{\partial x} + \frac{\partial (ru)}{\partial r} + \frac{\partial w}{\partial z}$$

(3)

Therefore, Eq. (1) can be expanded to:

$$\frac{\partial(\rho \tilde{\theta})}{\partial t} + \frac{\partial}{\partial x} (\rho u \tilde{\theta}) + \frac{\partial}{\partial y} (\rho v \tilde{\theta}) + \frac{\partial}{\partial z} (\rho w \tilde{\theta}) = \frac{\partial}{\partial x} \left( \tilde{k} \frac{\partial \tilde{\theta}}{\partial x} \right) + \frac{1}{\rho} \frac{\partial}{\partial y} \left( \tilde{r} \frac{\partial \tilde{\theta}}{\partial y} \right) + \frac{\partial}{\partial z} \left( \tilde{r} \frac{\partial \tilde{\theta}}{\partial z} \right) + Q$$

(4)

3.2. Turbulence model and solver settings

The turbulence model in this paper uses the “Renormalization Group” (RNG) $k-\varepsilon$ turbulence model. This turbulence model uses the RNG mathematical method to improve the standard $k-\varepsilon$ turbulence model, thereby obtaining some other functions. The RNG $k-\varepsilon$ turbulence model improves the calculation accuracy of turbulent eddies and provides an analytical formula for low viscosity Reynolds flow. Therefore, the RNG $k-\varepsilon$ turbulence model has higher accuracy and credibility than the standard $k-\varepsilon$ turbulence model. The turbulent kinetic energy of the RNG $k-\varepsilon$ turbulence model and the transport equation of turbulent dissipation are shown below:

$$\frac{\partial}{\partial t} (\rho ku_i) + \frac{\partial}{\partial x_j} (\rho \mu_e \frac{\partial k}{\partial x_j}) + \frac{\partial}{\partial x_j} (\rho \varepsilon) = \frac{\partial}{\partial x_j} \left[ \alpha_k \mu_e \frac{\partial k}{\partial x_j} \right] + \frac{\partial}{\partial x_j} \left[ \Gamma \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{\partial}{\partial x_j} \left( \tilde{r} \frac{\partial \tilde{\theta}}{\partial y} \right) + Q$$

(5)

$$\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_j} (\rho \mu_e \varepsilon) = \frac{\partial}{\partial x_j} \left[ \alpha_\varepsilon \mu_e \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{\partial}{\partial x_j} \left[ \Gamma \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1e} \frac{\varepsilon}{k} (G_k + C_{3e} G_\varepsilon)$$

(6)

$$- C_{2e} \rho \frac{\varepsilon^2}{k} - R_e + S_e$$

In this paper, the semi-implicit method for pressure linked equations (SIMPLE) algorithm is used to solve the pressure-velocity coupling equation. Additionally the second-order, upwind-style discrete flow control equation in time and space is used. Local time step, implicit residual smoothing technology, and parallel computing technology are used to accelerate the calculation convergence.

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3.3. Model and meshing

The specific parameters of the SDR benchmark model are shown in Table 1, and the duct cross-section is shown in Fig. 2. The section is rotated 360° around the central axis to form a duct. The model is divided into two parts: static domain and rotating domain. The duct and outer field are static domains, and the rotor and rotating ring are rotating domains. The flux transfer between the two interfaces is performed using a slip mesh technology. The unstructured mesh of the duct and rotor, in which the duct is simplified, is shown in Fig. 3. Ignoring the structure of the motor stator and rotor in the DR slot, the rotor and rotating ring are integrated.

4. Calculation Method Verification

The TsAGI ducted tail rotor discussed in previous literature is used to verify the example. The TsAGI ducted tail rotor model is shown in Fig. 4. Figures 5 and 6 show the calculated and experimental values of the axial induction velocity and circumferential induction velocity of the rotor. It can be seen that the axial and circumferential induced velocity calculations are substantially the same as the experimental values. In this paper, the numerical calculation result of the rotor thrust is 86.5 N, and the test result reported in the previous literature is 90 N, which is close to the experimental value. Based on the above calculation results and analysis, the validity of the numerical calculation method can be verified and applied to the numerical calculation of SDR in this paper.

5. Calculation Results and Analysis

Figure 7 shows several main characteristic parameters of the duct. Among them, \( h \) is the height of the rotor disk, which represents the distance between the plane of the paddle and the inlet of the duct; \( H \) is the height of the duct; \( K \) is the diameter of the ducted outlet; \( k \) is the diameter of the ducted inlet; \( R \) is the radius of the lip of the duct; \( e \) is the thickness of the duct; \( U \) is the central hole radius, which represents the distance between the tips of the two blades; and \( \beta \) is the ducted taper angle, and represents the angle between the chord line of the duct section and the central axis.

The thrust coefficient \( C_t \) is expressed as:

\[
C_t = \frac{2T}{\rho \omega^2 R^2 \cdot \pi R^2}
\]

The power load \( q \) is expressed as:

\[
q = \frac{1}{2} \rho \omega^2 R^2 \cdot \pi R^2
\]
5.1. Effect of the rotor disk height

For the influence of the rotor disk height on the aerodynamic characteristics of the SDR, the reference model of Table 1 is used as the calculation model to calculate the aerodynamic characteristics of the five different rotor disk heights.

Figure 8 shows the SDR thrust performance as a function of rotor disk height. The abscissa indicates the rotational speed. It can be seen that when the rotational speed is low, the thrust coefficient of each component of the SDR is small, which rapidly rises and stabilizes as the rotational speed increases. At the same time, the farther the rotor is away from the entrance of the duct, the greater the peak value of the thrust coefficient of each component, and the greater the total thrust generated in the rotor at high speed.

Figure 9 is a plot of the ratio of the duct thrust to the total thrust ratio as a function of the rotor disk height (i.e., $T_D$ is the ducted thrust, $T$ is the total thrust). It can be seen that the farther the distance of the rotor from the entrance of the duct, the larger the peak value of the duct thrust. The lower the speed of the rotor, the duct thrust becomes relatively small. When $h/H = 2/3$, the ratio of the peak value to the minimum value of the ducted thrust reaches 1.50.

Figure 10 shows the relationship between the power load and the rotor disk height of the SDR at a rotational speed of 8,000 rpm. It can be seen that as the rotor moves away from the duct entrance, its power load gradually increases, the power load at $h/H = 4/5$ is 1.04 times that of $h/H = 5/18$. 

\[ q = \frac{T}{Ne} \] (8)
The above calculations show that as the rotor moves away from the duct entrance, its overall aerodynamic performance increases. In general, the rotor of the DR is placed around the lip of the duct to obtain the best aerodynamic performance. However, for the SDR, the rotor should be placed away from the duct lip.

Figure 11 shows the pressure distribution contour in the section for different rotor disk heights. It can be seen that a large low-pressure zone is formed at the lip of the duct, and the low-pressure zone gradually expands as the rotor moves downward. The pressure difference between the rear part of the duct and the lip of the duct increases, so the additional thrust produced by the duct increases.

Figure 12 shows the velocity streamline of a duct cross-section at different rotational speeds. It can be seen that there is no gap between the rotor and the duct of the SDR. Therefore, there is no leakage vortex at the tip of the blade, but when the rotor rotates at a low speed, there is an interference vortex near the wall of the duct at the top of the rotor. As the rotational speed of the rotor increases, the vortex strength gradually weakens and eventually disappears. This confirms that the aerodynamic performance of the rotor at low rotational speeds is poor for the SDR.

5.2. The influence of the number of blades

Focusing on the influence of the number of blades on the aerodynamic characteristics of SDR, the reference model of Table 1 is used as the calculation model to keep the rotor solidity unchanged. The aerodynamic performance of three, four and six blades at different rotational speeds was calculated, respectively. The number of blades indicates the number of individual blades included in the rotor.

Figure 13 shows the SDR thrust performance as a function of the number of blades. It can be seen that as the number of blades increase, the peak value of the rotor thrust coefficient...
first increases and then decreases, and the duct thrust coefficient increases. The larger the number of blades, the larger the peak value of the total thrust coefficient of the SDR. It can be seen from the curve that the ratio of duct thrust to total thrust changes together with the number of blades in Fig. 14. As the number of blades increases, the proportion of duct thrust gradually increases. This indicates that as the number of blades increases, the thrust performance of the duct increases more than that of the rotor.

Table 2 shows the SDR power load data for the different number of blades when the rotational speed is 8,000 rpm. It can be seen that the power load is the maximum when the number of blades is four. When the number of blades is six, the peak value of the total thrust coefficient is the largest, but the power load is the smallest. Although it can generate a large thrust, it has higher power requirements for the motor.

Figure 15 shows the pressure distribution for the blade section of the three blade numbers. It can be seen that the smaller angle-of-attack at the root of the blade results in a smaller relative pressure difference between the upper and
lower surfaces of the leading-edge of the blade. Additionally, as the number of blades increases, the relative pressure difference decreases from the root to the blade tip. This leads to a reduction in the thrust performance of the rotor.

5.3. Influence of the central hole radius

The SDR has no central body components, so its central hole radius can be reduced to increase the effective diameter of the rotor. The reference model of Table 1 is used as the calculation model. The negative torsion value of the rotor is zero and the installation angle of the blade root is 14°/C14.

Keeping the rotor solidity unchanged, the aerodynamic performance is calculated for when the central hole radius is 10 mm, 20 mm, and 25 mm.

Figure 16 shows the SDR thrust performance as a function of the central hole radius. It can be seen that the thrust coefficient of each component of the SDR is smaller when the central hole radius is 20 mm and 25 mm. However, the peak value of the thrust coefficient of each component of the SDR appears for the rotor at low rotation speed when the central hole radius is 10 mm. When the rotational speed exceeds 4,000 rpm, the larger the center hole radius, the greater the thrust coefficient of each component.

Figure 17 is a plot of the ratio of the duct thrust to the total thrust force as a function of the central hole radius. It can be seen that under different central hole radius, the ratio of the ducted thrust of the SDR (TD/T) when the rotational speed is similar. That is, the ratio is larger when the rotational speed is lower, and decreases as the rotational speed increases and finally stabilizes.

Table 3 shows the power load data of SDRs with different central hole radii. It can be seen that the power load is minimum when the central hole radius is 10 mm. Looking to Fig. 15 it can also be seen that the smaller the central hole radius, the worse the thrust performance. This indicating that reducing the central hole radius will reduce the aerodynamic performance of the SDR.

Figure 18 is a cross-sectional velocity streamline diagram of three central hole radii. It can be seen that increasing the central hole radius reduces the turbulence intensity below the rotor to reduce the blocking effect of the rotor.

5.4. Effect of the blade root mounting angle

The pitch of the SDR is defined as the part connected to the rotating ring of the motor. The speed at the blade root is large, so the blade root mounting angle has a significant influence on the aerodynamic performance of the SDR. In the calculation, the data model of Table 1 is used to keep the rotor solidity constant, and the blade root mounting angle is 4°, 14° and 20°.

Figure 19 shows the SDR thrust performance as a function of the blade root mounting angle. It can be seen that the SDR thrust characteristic changes significantly as the blade root mounting angle increases. When the blade root mounting angle is increased from 4° to 20°, the peak value of the rotor thrust coefficient increases 1.7398 times and the peak value of the duct thrust coefficient increases 0.3396 times. From Fig. 20, the relationship between the ratio of the total thrust and radius of the ducted lip is shown. As the blade root mounting angle increases, the ratio of the thrust of the duct
rapidly decreases. This shows that the thrust gain of the rotor is obviously higher than that of the duct.

The SDR power load data of the different blade root mounting angles in Table 4 show that although increasing the blade root mounting angle can improve thrust performance, the power load decreases to a large extent. This indicates that the required power increases sharply as the blade root mounting angle increases.

6. Conclusion

Based on the unstructured slip grid technology, the effects of four key parameters (i.e., rotor disk height, number of blades, central hole radius and blade root mounting angle) on the aerodynamic characteristics of SDRs were investigated. The following conclusions were obtained:

1) The thrust performance of the SDR is greatly affected by the rotational speed, becoming poor at low speed and rapidly decreases. This shows that the thrust gain of the rotor is obviously higher than that of the duct.

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gradually improving and stabilizing as the speed increases.

(2) The farther the rotor position is from the duct entrance, the better the aerodynamic performance.

(3) The larger the number of blades, the larger the peak value of the SDR total thrust coefficient. Furthermore, the improvement range of the aerodynamic performance of the duct is higher than that of rotor.

(4) Reducing the central hole radius of the SDR will result in enhancing the airflow blocking effect of the central airflow, thereby reducing overall aerodynamic performance.

(5) When the rotational speed is constant, increasing the blade root mounting angle can result in a large increase in thrust, but lead to a reduction in power load.

The next step is to carry out a combined optimization design of key parameters of the SDR in order to obtain the key parameter combination with the best aerodynamic performance.

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