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# THE INVESTIGATION OF TIP CLEARANCE EFFECTS IN DUCTED ROTOR AERODYNAMIC CHARACTERISTICS USED IN UNMANNED AERIAL VEHICLES

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**Keywords**: *ducted fan; tip clearance; aerodynamics; UAV*

## Abstract

*The paper investigated the influence of tip clearance on ducted fan aerodynamic characteristics based on theoretical analysis and numerical simulation. From the theoretical analysis, it proved that the rotor was being off-loaded which could avoid flow separation. From the numerical simulation, with the increase of tip clearance, thrust coefficient was dropped greatly, especially when tip clearance was over 2%D which was less than the open rotor's. As to power coefficient, it was totally different, $C_P$ of open rotor was higher than ducted rotor's. Although the power needed by tip clearance 3%D and 5%D was a little lower than the other two, $C_T / C_P$ value was also lower. For the tip clearance 5%D, $C_T / C_P$ was almost the same as open rotor.*

## 1 Introduction

Ducted fan has been a popular choice in vertical taking-off and landing (VTOL) unmanned aerial vehicles (UAV) which produces a higher thrust and needs lower power for a given diameter and rotation speed compared with open rotors. At the same time, the duct serves as a safety feature, protecting both the rotating blades from damage by other objects as well as personnel from injury by the blades. In fact, in most cases, it is the latter reason (improved safety) that the ducted fan is chosen for an aircraft design[1].

This configuration has been extensively investigated for more than half a century. Robin B. Gray[2] researched the determination of the design parameters for optimum heavily loaded ducted fans. He developed a consistent mathematical model of the constant-diameter vortex wake, however, he neglected the compressibility, viscosity, and tip clearance which had great influence on the aerodynamics of ducted fan. Michael and Selden[3] investigated ducted fan performance by theoretical method. The capabilities had been added for modeling the center-body, and calculating nonlinear blade lift characteristics and evaluating performance at very low advance ratios Rajagopalan and Zhang[4] analyzed the performance and flow flied of a ducted propeller, comparing with open propeller by solving the Navier-Stokes equations. The research showed that the pressure distribution on the duct was unaffected by the presence of the propeller and propeller performance improved as advance ratio increased. Ghanem et al.[5, 6] investigated the tip-leakage flow on the ducted propeller using particle imaging velocimetry (PIV). The core size of the tip-leakage vortex was on the order of the tip clearance. Pereira[1] investigated the influence of ducted fan parameters systematically by experiments. The tests were performed on seventeen models with various values of diffuser expansion angle, diffuser length, inlet lip radius and blade tip clearance. The uniformity of the wake was improved by decreasing the tip clearance, resulting in lower induced power losses. There are still other papers about aerodynamics and tip clearance influence in ducted fan[7-12].

Although it has the high performance in UAV applications and such researches, some problems are still unresolved. This paper investigated the influence of tip clearance on ducted fan aerodynamics characteristics based on theoretical analysis and numerical simulation.

## 2 Theoretical Analysis

Figure 1 and 2 display the three-dimensional diagram of ducted rotor which was researched in this paper and the two-dimensional profile diagram of ducted rotor. The diameter of rotor is 0.346m. The height of duct is 0.2m. The tip clearance means the distance between rotor tip and the inner wall of duct which is varied from 1%*D*, 2%*D*, 3%*D* to 5%*D* (*D* represents the diameter of rotor).

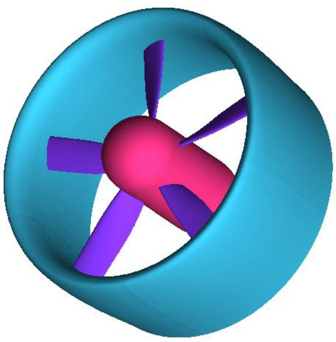

Fig. 1. The Three dimensional diagram of ducted rotor

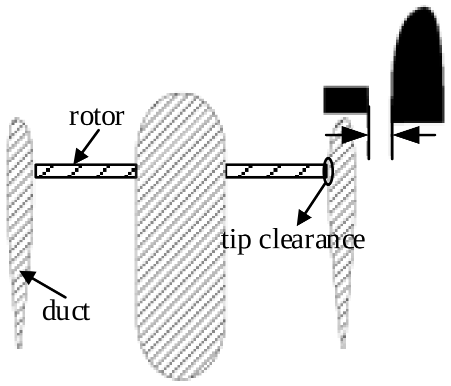


Fig. 2. Two dimensional profile diagram of ducted rotor

Instead of using the actuator-disk model of the rotor, based on the momentum theory and Bernoulli equation, we can deduce the distribution of pressure coefficient upstream and downstream the rotor, which assumption is made that the slipstream has fully expanded back to ambient atmospheric pressure at the exit plane of the diffuser. The detailed derivations can be seen in [1, 13]. $\sigma$ is the ratio of the diffuser exit plane area to the area of the rotor disk. $C_T$ is the thrust coefficient of duct fan. $v$ is the flow velocity at any given axial station in the flow. $v_i$ is the induced velocity.

Pressure coefficient upstream the rotor:

$$C_p = -(\sigma C_T)\bullet\left(\frac{v}{v_i}\right)^2 \tag{1}$$

Pressure coefficient downstream the rotor:

$$C_p = (\sigma C_T)\bullet\left[\frac{1}{\sigma^2}-\left(\frac{v}{v_i}\right)^2\right] \tag{2}$$

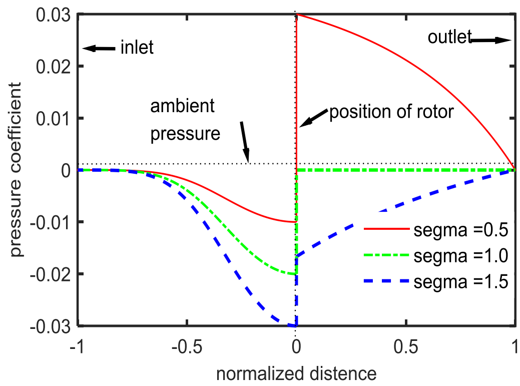


Fig. 3. Variations in pressure of open and ducted rotors in the hover condition, at the same thrust coefficient

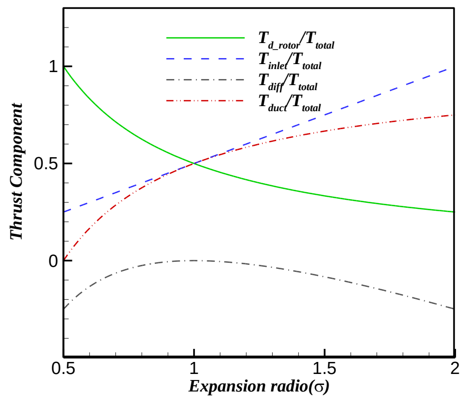


Fig. 4. The thrust produced by each part of duct fan

From Figure 3, we can see that with the increase of $\sigma$, the pressure difference value becomes small. At the same time, as displayed in Figure 4, the ratio of $T_{rotor}/T_{total}$ decreases greatly when expansion radio is 2, compared with expansion radio (0.5). The rotor is off-loaded (the rotor produces less thrust). The rotor section airfoils are operating at lower angles of attack, and therefore it is expected that the profile power losses would decrease as well when duct is added.

## 3 Calculation Methods and Meshes

### 3.1 Calculation Methods

Unsteady computational fluid dynamics calculation based on the Reynolds-averaged Navier-Stokes equations were performed in this paper. The control equations are shown in Eq.(3). The turbulence model is *SST* $k-\omega$. The meaning of each team in Eq.(3) and Eq.(4) can be seen in [14].

$$\frac{\partial}{\partial t}\iiint_{\Omega} U dV + \iint_{\partial\Omega} F(U)\bullet \boldsymbol{n} dS = \iint_{\partial\Omega} G(U)\bullet \boldsymbol{n} dS \quad (3)$$

Turbulence Model:

$$\frac{D\rho\omega}{Dt} = \frac{\gamma}{v_t}\tau_{ij}\frac{\partial u_i}{\partial x_j} - \beta\rho\omega^2 + \frac{\partial}{\partial x_j}\left[\left(\mu + \sigma_\omega \mu_t\right)\frac{\partial \omega}{\partial x_j}\right] + 2\rho\left(1-F_1\right)\sigma_\omega \frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \quad (4)$$

$$\frac{D\rho k}{Dt} = \tau_{ij}\frac{\partial u_i}{\partial x_j} + \beta^* \rho\omega k + \frac{\partial}{\partial x_j}\left[\left(\mu + \sigma_k \mu_t\right)\frac{\partial k}{\partial x_j}\right]$$

### 3.2 Meshes

The computational simulation analysis for ducted fan aerodynamic characteristics is performed on two separate computational domains, which are connected by two interfaces. The data information between two regions is changed by the two interfaces. The stationary region and rotating region are shown in Figure 5. Stationary region includes duct surface that is considered as a solid wall with no-slip condition with its inlet located at 6 propeller diameters upstream of propeller plane, and its outlet located at 10 propeller diameters downstream of propeller plane, and cylinder radius being equal to 4 propeller diameters. The rotating region includes rotor blades, rotor hub region where rotating fluid motion is simulated by sliding mesh method (SSM). The other boundary conditions are pressure inlet, pressure outlet and far field. Structured meshes are built in the two regions. The topological structure and boundary mesh of the rotor are shown in Figure 6. All simulations done in this work with rotors have been performed with wall treatment providing wall $Y^+$=1.

All the calculation method and meshes have been verified and validated in [7] which proved that the method could be used to calculate such problems and calculation results approximately agree with experimental data.

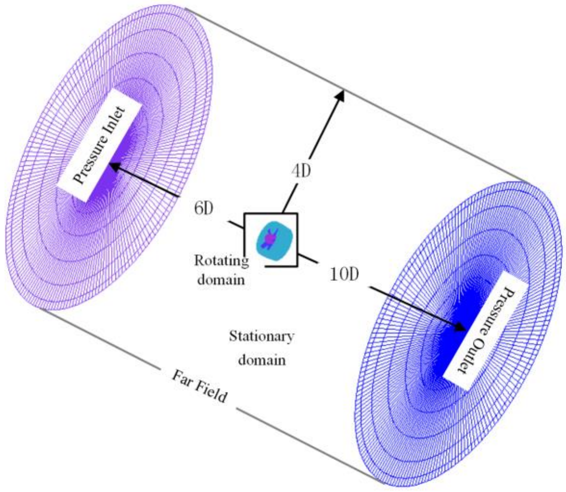


Fig. 5. The diagram of the computational domain and boundary conditions

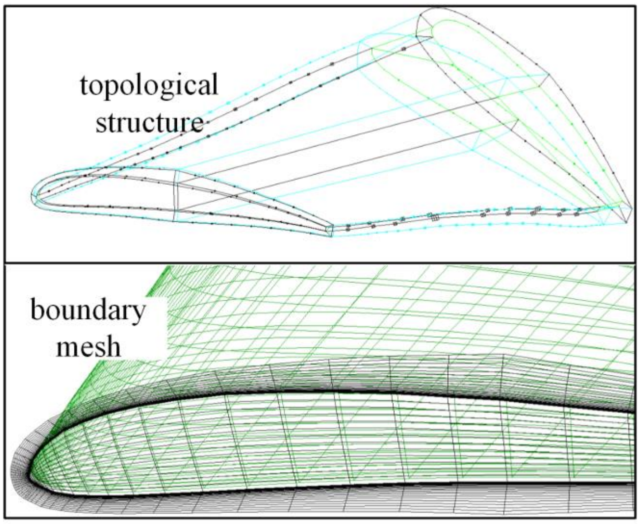


Fig. 6. The topological structure and boundary mesh of the rotor

## 4 Numerical Simulation of Ducted Fan

### 4.1 Analysis of Tip Clearance Influence

From Figure 7 to Figure 9, they display the numerical simulation results of different tip clearance in ducted fan aerodynamic characteristics. All of them have compared with the results of open rotor. The rotating speed is varied from 3000r/min to 8500r/min.

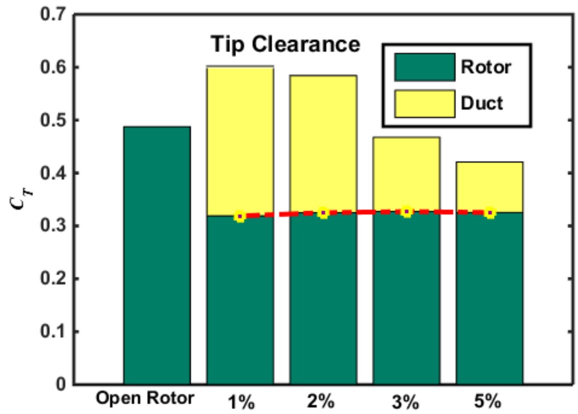


Fig. 7. The tip clearance influence of Ducted Fan in $C_T$

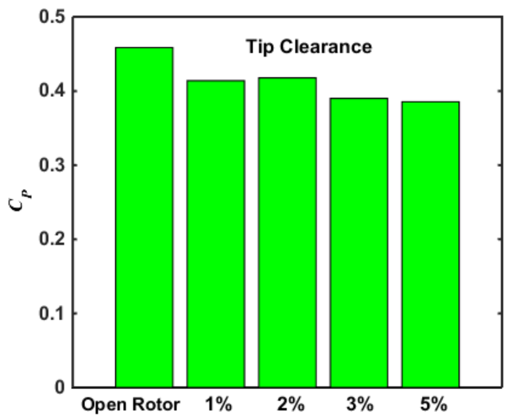


Fig. 8. The tip clearance influence of Ducted Fan in $C_P$

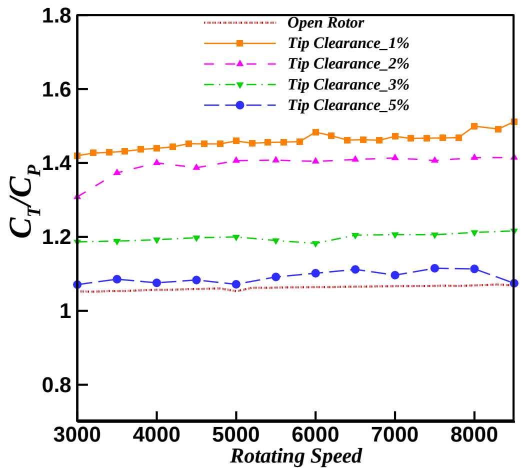


Fig. 9. The tip clearance influence of Ducted Fan in $C_T$ / $C_P$

The tip clearance influence of ducted fan is shown in Figure 7. The blue part represents $C_T$ produced by rotor, the yellow part represents $C_T$ produced by duct. It can be found that the blue part has little change with the increase of tip clearance which is approximately 0.32. However, the total thrust coefficient drops deeply. The main reason is that the thrust coefficient (duct) goes down greatly. The highest value is 0.6, and lowest is 0.41, when tip clearance is 5%D, which is lower than the value of open rotor (0.49). When tip clearance is 3%D, it is almost the same as open rotor. The tip clearance influence of Ducted Fan in $C_P$ is displayed in Figure 8. The power coefficient of open rotor is the highest among the five situations, which is about 0.46. As to the tip clearance 1%*D* and 2%*D*, they are almost the same. It is close to 0.41. The other two are a little lower than 0.39. From Figure 9, it is clear that all of the ratio $C_T$ / $C_P$ of ducted fan is higher than open rotor. The value is nearly not changed with rotating speed. For open rotor, the ratio $C_T$ / $C_P$ is about 1.06, which is a little lower than tip clearance 5%D. The lower tip clearance is, the higher ratio $C_T$ / $C_P$ is. The ratio of tip clearance 1%*D* is higher than others, which is close to 1.43. When designing a ducted fan UAV, taking into consideration of weight, structure and oscillation, it is better to make tip clearance lower than 2%D.

## 4.2 Analysis of Flow Field

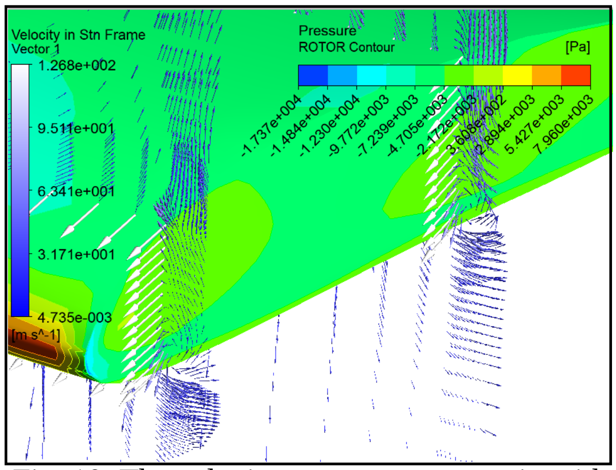


Fig. 10. The velocity vector near rotor tip with 1%*D* tip clearance

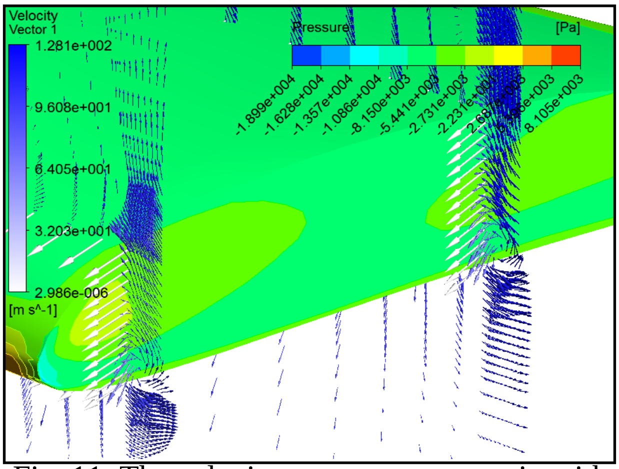


Fig. 11. The velocity vector near rotor tip with 2%*D* tip clearance

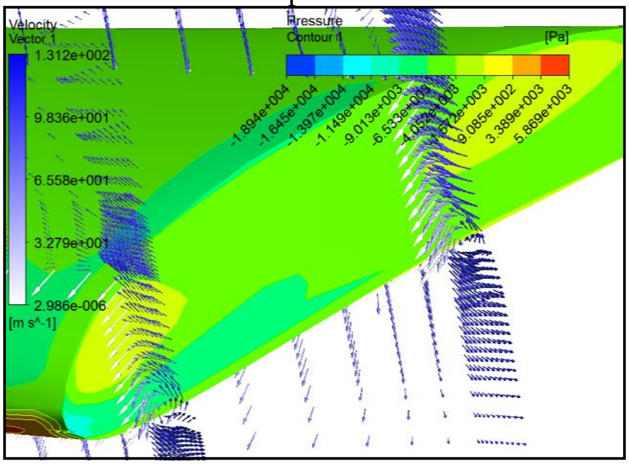


Fig. 12. The velocity vector near rotor tip with 2%*D* tip clearance

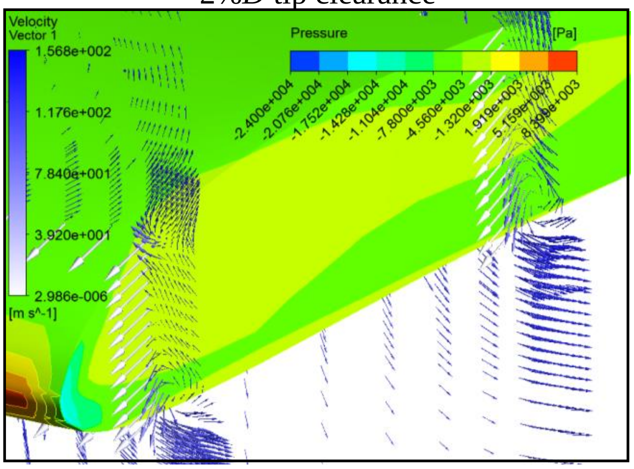


Fig. 13. The velocity vector near rotor tip with 5%*D* tip clearance

From figure 10 to figure 14, the velocity vector and pressure counter near rotor tip with different tip clearance are displayed. The velocity vector around open rotor tip is shown is figure 15. With the increase of tip clearance, the reverse flow velocity grows gradually which results in loss of energy. Near the open rotor tip, the reverse flow is obvious that is the reason why duct is introduced.

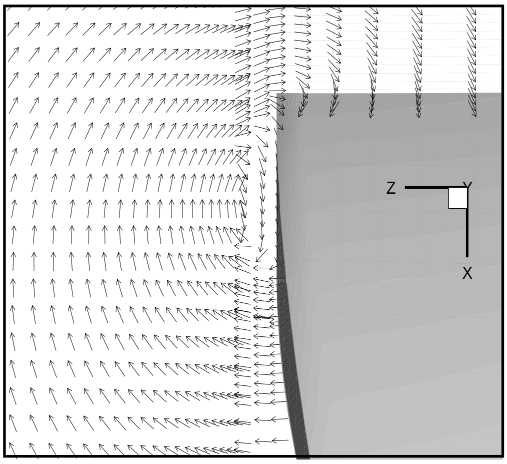


Fig. 14. The velocity vector around open rotor tip

## 5 Conclusion

The influence of tip clearance in ducted fan aerodynamic characteristics based on theoretical analysis and numerical simulation was researched in this paper. Through theoretical analysis, it proved the rotor was being off-loaded because ducted rotor section airfoils was operating at lower angles of attack. From the numerical simulation, with the increase of tip clearance, thrust coefficient was dropped greatly, which is mainly the change of duct thrust coefficient. As to power coefficient, it was totally different, $C_P$ of open rotor was higher than ducted rotor. Although the power needed by tip clearance 3%D and 5%D was a little lower than the other two, $C_T / C_P$ value was also lower. For the tip clearance 5%D, $C_T / C_P$ was almost the same as open rotor. The lower tip clearance was, the higher $C_T / C_P$ value was.

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