The Effect of Tip Clearance on Performance of a Counter-Rotating Ducted Fan in a VTOL UAV*

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This research analyzed the effect of tip clearance on counter-rotating ducted fans for vertical take-off and landing in unmanned aerial vehicles using commercial computational fluid dynamics tools. The computational results were verified using the subsonic wind tunnel at Hanyang University. In this study, the tip leakage flow of the counter-rotating ducted fan was analyzed in order to enhance the fan performance. The thrust coefficient decreases with increasingly larger front rotor tip clearance due to the increase in tip leakage flow. The power coefficient is influenced by viscous and tip leakage losses from the large tip clearances for the rear rotor. Smaller figures of merit are captured at larger tip clearances for the front and rear rotors because the direction of vortex core changes quickly. In conclusion, to improve the aerodynamic performance of counter-rotating ducted fans, it is necessary to reduce the mass flow rate across the tip clearance and tip vortex loss.

Key Words: Counter-Rotating Ducted Fan, Tip Clearance, CFD, Wind Tunnel Test

Nomenclature

- $A_P$: cross-sectional area of the propeller
- $A_W$: cross-sectional area of the wind tunnel
- $C_P$: power coefficient
- $C_T$: thrust coefficient
- $D$: inner diameter of the duct
- $E$: input voltage
- $FOM$: figure of merit
- $H_e$: normalized helicity
- $I$: current
- $J$: advance ratio
- $L$: input shaft power
- $N$: rotational speed
- $P_{total}$: total pressure
- $P$: static pressure
- $R$: rotor tip radius
- $S_E$: energy source
- $S_M$: momentum source
- $t$: tip clearance
- $U$: mean velocity vector
- $V$: wind tunnel datum velocity
- $V_{in}$: free stream velocity
- $h_{tot}$: specific total enthalpy
- $x$, $y$, $z$: coordinate
- $x_b$, $y_b$, $z_b$: ducted fan body fixed coordinate
- $y^+$: dimensionless wall distance
- $\eta$: efficiency of ducted fan
- $\eta_m$: efficiency of the motor
- $\lambda$: thermal viscosity
- $\mu$: molecular(dynamic) viscosity
- $\xi$: absolute vorticity
- $\rho$: air density
- $\tau$: mean viscous stress tensor
- $w_i$: relative vorticity

1. Introduction

Ducted fans are widely used in propulsion systems for vertical take-off and landing (VTOL) in unmanned aerial vehicles (UAVs). The flow fields around a ducted fan in a VTOL UAV are complicated due to the effects of the finite hub, annulus wall and leakage flows. Tip leakage flow is one of the most complex phenomena in turbo-powered machinery. Because of the pressure difference between the pressure and suction sides of the blade, leakage flow is produced. Leakage flows in the tip clearance region of the rotor adversely affect the aerodynamic performance and noise. The strength of the tip vortex depends on the tip clearance leakage. Therefore, reducing the tip leakage mass flow improves the efficiency of ducted fan systems.

In this research, a new concept diagram for a multi-ducted fan VTOL UAV was designed at Hanyang University as shown in Fig. 1. The vehicle has three ducted fans. Two of the ducted fans are part of the propulsion. The other sub-ducted fan can be tilted by a stepper motor, which is located on the axis of the rotation ($x$-axis), giving the vehicle yaw motion.

The sub-ducted fan is a counter-rotating fan, consisting of two counter-rotating rotors, namely, the front rotor and rear rotor. The rear rotor is rotated in the opposite direction to remove the torque generated by the front rotor. The counter-rotating fan has higher performance characteristics, as well as a
higher noise level compared to the other fan. The pitch of the vehicle can be controlled by adjusting the rotor rotational speed.

Tip leakage loss is a source of aerodynamic noise generation. Understanding the effect of tip clearance is important in reducing tip leakage loss. There is an abundance of research on tip leakage loss in turbo-powered machinery.\textsuperscript{1–5} Jang et al.\textsuperscript{6,7} analyzed the vertical flow field in a propeller fan using laser Doppler velocimetry (LDV) measurements and large eddy simulation (LES). They studied the structure and behavior of the vertical flow near the tip region in propeller fans, confirming that three vortex structures are formed near the tip: tip vortex, leading-edge separation vortex and tip leakage vortex.

Lee et al.\textsuperscript{8} investigated the structure of tip leakage flow in axial flow fans using LDV measurements and computational fluid dynamics (CFD). These results show the generation mechanism of tip leakage vortex-induced noise, as high momentum flux was observed below the tip leakage vortex. The ducted fan commonly consists of a rotor located in the duct. Therefore, the clearance between the blade and the shroud wall produces leakage flow. Reducing tip leakage loss is critical for improving the performance of a ducted fan.

Martin and Tung\textsuperscript{9} developed a wind tunnel test as a design tool and validated the CFD analysis for ducted fans. They found that the hover stability a crosswind improved when the radius of the leading-edge in the duct was decreased. The smaller leading-edge radius of the duct shape improves the pitching moment under stall conditions. Furthermore, the tip clearance changed from 1% of radius to 4.5% of radius as the suction pressure near the leading-edge was suddenly disrupted due to the increase in tip clearance. This then caused a decrease in duct lift.

Cho et al.\textsuperscript{10} performed a computational analysis and wind tunnel test on ducted fans in an attempt to improve performance. These researchers confirmed that the thrust performance was only improved in terms of the rotor because of the ducted effect. Furthermore, this research highlighted an aerodynamic design step for the rotor and stator blades of the ducted fans.

Akturk and Camci\textsuperscript{11–13} studied the large tip clearance effect in ducted fans for VTOL UAV using a kiel total probe, six-component load cell, torque measurements, and 3D Reynolds-averaged Navier-Stokes (RANS) analysis. They suggested new tip treatments for the ducted fan in order to improve the overall performance. Decreasing the tip clearance increased the thrust and hover efficiency. This research confirmed the effectiveness of the new tip treatments, as they reduce tip clearance leakage mass flow rates.

Various studies have focused on the aerodynamic characteristics of the ducted fan. The ducted fan is more efficient and safer than open rotor blades because the rotor is located in the duct. A counter-rotating ducted fan is used in the ducted fan UAV.\textsuperscript{14,15}

Although tip clearance of the ducted fan has been studied, there is a lack of research concerning the effect of tip clearance on ducted fans. Understanding the tip leakage flow fields for ducted fans is required in order to improve the performance of a ducted-fan UAV. The effective radius of the ducted fan can be increased by reducing the tip vortex. The ducted fan typically has good aerodynamic characteristics.

In a previous study, the static performance of a counter-rotating ducted fan was analyzed.\textsuperscript{16} However, the relation of tip clearance and performance was not clarified.

In the present study, the tip leakage flow of a counter-rotating ducted fan was analyzed in order to enhance the performance of the ducted fan. The CFD analysis included applying various tip clearances of the counter-rotating ducted fan using commercial tools. The computational method solved the RANS equations using a finite volume method. The computational results were verified using the results of wind tunnel tests.

2. Analysis Model

2.1. Counter-rotating ducted-fan model

The counter-rotating ducted-fan model consists of a front rotor, rear rotor and duct. The rotor blades are designed according to the free vortex design method where the product of the blade radius and tangential component of absolute velocity is a constant. The axial velocity is constant along the radial direction of the rotor blades.\textsuperscript{10} The diameter of the ducted fan is 150 mm. The NACA 65 Series airfoil is used in this study. The rotational speed is 10,000 rpm. The rotational direction is contrary for each rotor. Therefore, the anti-torques from each rotor are reduced. Detailed specifications of the counter-rotating ducted fan are described in Table 1.

Figure 2 shows the counter-rotating ducted-fan model in the wind tunnel. The Reynolds number of this model is 9.49 × 10\textsuperscript{6}, which was based on mid-blade chord length.

The tip clearance \((t)\) is divided by the height \((h)\) of the rotor. The non-dimensional tip clearance ratio \((t/h)\) of the baseline model is 1.80% in the front and rear rotors.

3. Experimental Method

3.1. Experimental setup

The aerodynamic forces of the counter-rotating ducted fan were measured using the subsonic wind tunnel at Hanyang University. Figure 3 shows the schematic diagram of the ex-
Experimental apparatus for the counter-rotating ducted fan in the wind tunnel. Table 2 shows the operating parameters of the wind tunnel. The blockage ratio is 4.27%, which is less than acceptable ratio 7.5%.\cite{17} The forces were measured using an external balance system (CAS six-axis load cell). The measurements of force and moment are 5 kg and 0.5 kg \( \times \) m, respectively. The accuracy of the load cell was 0.5% FS for each of the components.

Figure 4 shows a schematic diagram of the counter-rotating ducted-fan system. The front rotor and rear rotor are rotated in opposite directions by two motors. The rear motor shaft, which rotates the front rotor, is wrapped by the front motor shaft.

![Fig. 2. Counter-rotating ducted fan unit.](image1)

![Fig. 3. Schematic diagram of the counter-rotating ducted fan in the wind tunnel.](image2)

Figure 5 shows the counter-rotating ducted-fan model tested in the wind tunnel. A 375W CR23L counter-rotating Brushless DC electric motor (HobbyKing) was used to operate the counter-rotating ducted-fan rotor. The BLDC motor was controlled by a brushless speed controller (HobbyKing 40A SBEC).

The input shaft power \( (L) \) of the BLDC motor, which turns the rotor of the ducted fan, is calculated from the motor input voltage \( (E) \), current \( (I) \) and motor efficiency \( (\eta_m) \), as described in Eq. (1). The electric motor efficiency was acquired from a calibration test performed by the motor manufacturing company.

\[
L = E \times I \times \eta_m \tag{1}
\]

The results of the wind tunnel tests for the ducted fan were corrected using the Glauert method and are shown in Eq. (2).\cite{18} The ducted fan was tested in a closed-throat wind tunnel.
$\frac{V'}{V} = 1 - \frac{\tau_4 \alpha_1}{2\sqrt{1 + 2\tau_4}}$  \hspace{1cm} (2)

where,

$\tau_4 = -\frac{F_z}{\rho A_P V^2}$, $\alpha_1 = A_P/A_W$.

4. Computational Method

4.1. Governing equations and turbulence model

The steady, incompressible, three-dimensional and turbulent flow in the counter-rotating ducted fan was calculated using the commercial solver ANSYS-CFX Academic Ver. 14.5. This numerical simulation solves the RANS equations using a finite volume method. The continuity, momentum and energy equations were simultaneously calculated and are represented in Eqs. (3)–(5), respectively:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0$$  \hspace{1cm} (3)

Momentum equation:

$$\frac{\partial (\rho U)}{\partial t} + \nabla \cdot (\rho U \times U) = -\nabla p + \nabla \cdot \tau + S_M$$  \hspace{1cm} (4)

Energy equation:

$$\frac{\partial (\rho h_{tot})}{\partial t} = -\frac{\partial p}{\partial t} + \nabla \cdot (\rho U h_{tot})$$

$$= \nabla \cdot (\lambda \nabla T) + \nabla \cdot (U \cdot \tau) + U \cdot S_M + S_E$$  \hspace{1cm} (5)

The $k$-$\omega$ based shear stress transport model was used for this computation. This turbulence model predicts the adverse pressure gradient near the wall and flow separation well.\(^{20-22}\)

In order to evaluate the aerodynamic performance of a counter-rotating ducted fan, the following conventional performance parameters were used. The aerodynamic characteristics of the ducted fan are represented in Eqs. (6)–(10)\(^{23}\):

Advance ratio: $J = \frac{V_\infty}{ND}$  \hspace{1cm} (6)

Thrust coefficient: $C_T = \frac{\text{Thrust}}{\rho N^2 D^4}$  \hspace{1cm} (7)

Power coefficient: $C_P = \frac{\text{Power}}{\rho N^3 D^5}$  \hspace{1cm} (8)

Efficiency: $\eta = \frac{C_T}{C_P}$  \hspace{1cm} (9)

Figure of merit: $\text{FOM} = \frac{C_{TL}^{1.5}}{\sqrt{2C_P}}$  \hspace{1cm} (10)

4.2. Computational domains and boundary conditions

The tip clearance ratio ($t/h$) of the front and rear rotors was 1.80–7.62%. All of the models were calculated for hovering conditions. Figure 6 shows the computational domain and boundary conditions for the CFD simulation of the analyzed model. The computational domain consists of the front rotor, rear rotor and an outer region. Multiple frames of reference (MFR) were used in this study. The frozen-rotor interface model (quasi-unsteady) was used to predict the interaction between the front and rear rotors. The frozen-rotor interface model has been documented as showing large circumferential flow variation.\(^{24,25}\) This technique is widely used in axial flow turbo-powered machinery. The rotational speed of the front and rear rotors was fixed at 10,000 rpm.

The boundary conditions of the inlet for the outer domain were set to the total pressure conditions for hovering and at the velocity inlet for forward flight conditions. The outlet boundary conditions were set at the pressure outlet ($P_{\text{gage}} = 0$). The boundary conditions of the front rotor, rear rotor, hub and duct were determined to be no-slip boundary conditions. The outer surface defines the opening boundary conditions for the hovering and free-slip wall for forward flight. In order to reduce the computing time, the outer domain and front and rear rotor regions were divided by 120° using periodic boundary conditions.

5. Results

5.1. Grid independent study

The outer domain has a hexahedral grid, which was generated using ICEM CFD, as shown in Fig. 7. The grid on the front and rear rotor domains were generated using TurboGrid. All of the grids were composed of hexahedral mesh.

In order to confirm that the computational results are independent for the number of meshes, grid convergence test was performed. Figure 8 shows the aerodynamic coefficients of the counter-rotating ducted-fan in the independent grid test. When the number of elements is $2.2 \times 10^6$, the variation of the FOM is less than 1%. Consequently, $2.2 \times 10^6$ elements are chosen in this study using the independent grid test. In order to take account of the viscous sublayer in the typical velocity profiles for the turbulent boundary layer based on the law of the wall,\(^{26}\) the dimensionless wall distance was set less than 1. The expansion ratio of the grid is 1.2 and a 30-prism layer is generated.

5.2. Computational results validation

The comparison results of the computational and experimental ducted-fan behaviors are shown in Fig. 9, where the difference in thrust coefficient is less than 7%. The discrepancy was caused by experimental effects such as blockage and the model support strut of the ducted fan. The computational and experimental results showed good agreement with respect to the advance ratio, except at a large advance...
When the free-stream velocity increased, the thrust coefficient of the ducted fan decreased, which is similar to previous research. Because the blade section angles of attack can be reduced by increasing the inflow velocity, the power coefficient is nearly constant with all advance ratio values. The dissidence of power coefficient in this research was less than 13%. However, a tendency toward efficiency was also seen in the experimental results. The efficiency of the ducted fan increases as the advance ratio increases until it reaches 0.4. The difference in efficiency is increased at a high advance ratio because of the prediction of lower thrust in the CFD.

### 5.3. Aerodynamic characteristics for tip clearance

Figure 10 shows the thrust coefficient of the counter-rotating ducted fan for various tip clearance ratios of the front and rear rotors. The tip clearance of the rear rotor changed from 1.80% to 7.62%, as did several tip clearance values of the front rotor. The thrust coefficient decreases as the tip clearance of the front rotor increases. The thrust coefficient decreases because the tip leakage flow increases. The tip leakage flow is determined by calculating the mass flow rate during tip leakage. When the tip clearance of the front rotor is less than 3.67%, the thrust coefficient increases as the tip clearance of the rear rotor increases.

Figure 11 shows the power coefficient of the counter-rotating ducted fan for various tip clearances of the front rotor. The increasing tip clearance of the rear rotor affects the power coefficient. Therefore, the large tip clearance of the rear rotor affects viscous loss and tip leakage loss. Conversely, the power coefficient decreases with the tip clearance of the front rotor.

In order to evaluate the efficiency of the ducted fan for hovering conditions, we used FOM. Figure 12 shows the FOM of the counter-rotating ducted fan for various front rotor tip clearances. As the tip clearance of the rear rotor decreases, the hover efficiency increases. Conversely, when the tip clearance of the front rotor increases, the efficiency decreases. In the baseline model \((t/h)_{\text{Front}} = 1.80\%\) to \((t/h)_{\text{Front}} = 1.80\%\), FOM was reduced to 4.21% when the tip clearance changed from \((t/h)_{\text{Rear}} = 7.62\%\) to \((t/h)_{\text{Rear}} = 7.62\%\). In addition, FOM was reduced to 7.38% when the tip clearance changed from \((t/h)_{\text{Front}} = 1.80\%\) to \((t/h)_{\text{Front}} = 7.62\%\). This phenomenon indicates that the tip clearance effect of the front rotor is larger than that of the rear.
rotor in the counter-rotating ducted fan.

Figure 13 shows the variations in thrust coefficient for the components of the ducted fan when the front rotor has a fixed tip clearance. The total thrust coefficient of the counter-rotating ducted fan increases as the tip clearance of the rear rotor increases. The part of the thrust coefficient for the rear rotor ranges from $(t/h)_{Rear} = 1.80\%$ to $(t/h)_{Rear} = 7.62\%$.

The mass flow rate was calculated for various tip clearances of the rear rotor.

Figure 15 shows the mass flow rate across the tip clearance of the rear rotor. The variation in mass flow rate increases significantly for a large front rotor tip clearance. This variation changed from 21.68% to 58.80% when the tip clearance of the rear rotor increased. When the mass flow rate of the tip leakage flow increases, the performance of the turbo-powered machinery decreases. The variation in mass flow rate is greatly affected by the rear rotor tip clearance.

5.4. Flow field analysis

The total pressure coefficient measurement plane is described in Fig. 16. Figure 17 shows the total pressure coefficient contour with the leakage flow patterns of various tip clearances for a counter-rotating ducted fan. The leakage flows from the left side (pressure side) to the right side (suction side) of each figure for the front rotor and in the opposite direction for the rear rotor.

The total pressure coefficient is defined as

$$C_{p\text{t}} = \frac{P_{\text{total}} - P_{\text{total inlet}}}{1/2 \times \rho \times V_{\text{inlet}}^2}$$

A small amount of tip leakage vortex was observed on the front and rear rotors at $(t/h)_{Front} = 1.80\%$ and $(t/h)_{Rear} = 1.80\%$, as shown in Fig. 17(a). The front rotor pressure difference was smaller than that of the baseline model, as shown
in Fig. 17(b). A wide region of tip leakage flow occurred on the suction side of the front rotor with small tip clearance, indicating wide leakage flow, as shown in Fig. 17(c). Furthermore, the pressure difference was greater than that for the other cases. A strong tip vortex was generated from a large tip clearance for each rotor, as shown in Fig. 17(d). The smallest thrust coefficient was confirmed, as shown in Fig. 9.

In order to analyze the vortex cores, the normalized helicity $H_n$ was used in the present study. The normalized helicity is necessary in order to identify the vortex structure$^{1,6}$ and is defined by:

$$H_n = \frac{\xi_i \cdot w_i}{||\xi_i|| ||w_i||}$$  \hspace{1cm} (12)

where $\xi_i$ and $w_i$ are the absolute vorticity and relative velocity vectors, respectively. The normalized helicity refers to the cosine absolute vorticity and relative velocity vectors and can be used to predict the magnitude of normalized helicity.

Figure 18 shows the measurement plane for the normalized helicity on the counter-rotating ducted fan.

Figure 19 shows the normalized helicity contour with the vortex cores of the counter-rotating ducted fan. The visualization planes were located at 0, 0.2, 0.4, 0.6, 0.8 and 1.0 blade chords from the leading edges of the front and rear rotors at the tip region. As the tip clearance of the rear rotor increased the thrust increased. The $H_n \approx 1$ region decreased at $(t/h)_{\text{Front}} = 7.62\%$ and $(t/h)_{\text{Rear}} = 1.80\%$ as shown in Fig. 19(b). This indicates that the tip leakage flow of the counter-rotating ducted fan is significantly affected by the tip clearance. An increase in tip clearance of the rear rotor caused an increase in the region of $H_n \approx 1$, which affected the rear rotor, as shown in Fig. 19(c). In this case, the thrust coefficient was larger than that of the baseline model. At $(t/h)_{\text{Front}} = 7.62\%$ and $(t/h)_{\text{Rear}} = 7.62\%$ in Fig. 19(d), the normalized helicity changed rapidly, causing FOM to decrease. In the case $(t/h)_{\text{Front}} = 1.80\%$ and $(t/h)_{\text{Rear}} = 7.62\%$, the vortex core direction did not change. If the vortex core direction is changed, the momentum loss increases as shown in Fig. 19(a), (b), (d).

### 6. Conclusions

We analyzed the aerodynamic performance of a counter-rotating ducted fan for VTOL UAV using computational fluid dynamics. The computational analyses were validated using wind tunnel tests. The tip clearances of the front and rear rotors were changed. The following conclusions were derived.

1. The thrust coefficient decreases as the tip clearance of the front rotor increases due to the increasing tip leakage flow.
2. The power coefficient is influenced by the increase in tip clearance of the rear rotor. This clearly shows that the
large tip clearance of the rear rotor incurs viscosity and tip leakage losses.

(3) A small tip clearance affects the amount of pressure difference between the pressure and suction sides of the rotor. The largest thrust coefficient was observed at the largest tip clearance, which was located behind the smallest tip clearance.

(4) The smallest FOM occurred with large clearance of the front and rear rotors. In this case, the normalized helicity quickly changed.

A small tip clearance for the front rotor and a large tip clearance for the rear rotor were selected in this study. This enables the thrust coefficient to be increased in correlation with the large tip clearance.

For the tip clearance of a rotor, the thrust increases at the counter-rotating ducted fan. The tip clearance of the rear rotor has a significant effect on the total thrust of the counter-rotating ducted fan.

To reduce the amount of tip leakage vortex for each rotor in the counter-rotating ducted fan, further studies on tip treatment are needed.

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