Aerodynamic Analysis of the Ducted Fan for a VTOL UAV in Crosswinds

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An aerodynamic analysis of a ducted fan for vertical take-off and landing unmanned aerial vehicles was performed using computational simulation. A commercial computational fluid dynamics tool was used to solve the Reynolds-averaged Navier-Stokes equations. The calculated results were validated in the subsonic wind tunnel at Hanyang University. The objective of this study is to investigate the aerodynamic performance of a ducted fan in crosswinds. The thrust, normal and side forces of the ducted fan are affected by the velocity magnitude and in-flow angle of the crosswind. The pitching moment of the ducted fan is significantly influenced by the crosswind due to asymmetric lift force created by the difference in suction velocity magnitude on the duct lip. Flow separation at the duct lip occurs under hovering and crosswind conditions. The inlet flow fields of the ducted fan are distorted by the duct lip separation. In conclusion, to improve the stability of the ducted fan, the pitching moment must be reduced.

Key Words: Ducted Fan, CFD Analysis, Wind Tunnel Test, Aerodynamic Characteristics, Crosswind

Nomenclature

- \( A_D \): ducted fan planform area
- \( A_p \): propeller area
- \( A_W \): wind tunnel cross-section area
- \( C_I \): rolling moment coefficient
- \( C_m \): pitching moment coefficient
- \( C_n \): yawing moment coefficient
- \( C_p \): pressure coefficient
- \( C_P \): power coefficient
- \( C_T \): thrust coefficient
- \( C_X \): normal force coefficient
- \( C_Y \): side force coefficient
- \( D \): inner diameter of the duct
- \( F_X \): force in the \( x \)-direction
- \( F_Y \): force in the \( y \)-direction
- \( F_Z \): force in the \( z \)-direction
- \( h_{tot} \): specific total enthalpy
- \( J \): advance ratio
- \( M_X \): rolling moment
- \( M_Y \): pitching moment
- \( M_Z \): yawing moment
- \( N \): rotational speed
- \( P \): static pressure
- \( R \): rotor tip radius
- \( r \): rotor local radius
- \( S_E \): energy source
- \( S_M \): momentum source
- \( t \): time
- \( U \): mean velocity vector
- \( V_{in} \): free stream velocity
- \( x, y, z \): coordinate
- \( x_b, y_b, z_b \): ducted fan body fixed coordinate
- \( y^+ \): dimensionless wall distance
- \( z_{cp} \): center of pressure location
- \( \alpha_{cross} \): angle of crosswind
- \( \eta \): efficiency
- \( \lambda \): thermal viscosity
- \( \mu \): molecular(dynamic) viscosity
- \( \rho \): air density
- \( \tau \): mean viscous stress tensor

1. Introduction

Various types of unmanned aerial vehicles (UAVs) have been developed worldwide.1) Conventional fixed-wing UAVs have certain disadvantages: they are difficult to operate in urban areas because they cannot take off and land vertically (VTOL). On the contrary, rotary-wing UAVs, which can take off and land vertically, have been introduced and developed for continuous monitoring. However, rotary-wing UAVs can be difficult to operate in urban areas because the rotor is exposed. Therefore, small UAVs using a ducted fan lifting/propulsion system have been developed to address these mobility issues. UAVs that use a ducted fan lifting/propulsion system are more efficient and safer than other conventional fixed- and rotary-wing UAVs because the rotor blades are located in the ducted fan.2,3)

A newly designed multi-ducted fan VTOL UAV is suggested in this paper, as shown in Fig. 1. The two side-by-side main ducted fans are designed to have counter-rotating rotors to eliminate the torque. The subducted fan consists of a counter-rotating system.

Martin and Tung4) performed a wind tunnel test for the ducted fan model to develop a design tool and validate the computational fluid dynamics (CFD). These researchers an-

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analyzed the aerodynamic characteristics of the ducted fan. Hover stability under crosswind conditions is improved because the leading-edge radius is decreased in the duct system. The small leading-edge radius of the duct shape improves the pitching moment under stall conditions. Graf\(^5\) studied the effects of duct lip shape and various control devices on the performance of the ducted fan. The flow separation of the duct lip reduces the static performance of the ducted fan by decreasing the lift force. The location of the center of pressure is influenced by the lip shape, and those effects enhance performance.

Pereira\(^6\) analyzed the effects of various shroud shapes for micro aerial vehicles using an open wind tunnel. This researcher studied the parameters of a shrouded rotor, such as the diffuser expansion angle, diffuser length, inlet lip radius, blade-tip clearance and rotor collective angles. A suitable pressure distribution over the shroud inlet surface is required to produce a high net shroud thrust.

Fleming et al.\(^7,8\) investigated the ducted fan using wind tunnel and CFD analysis under a crosswind. They confirmed that the auxiliary control device creates a more useful pitching moment in the gusts. The control device can increase the negative (nose-down) pitching moment.

Akturk and Camci\(^9\) measured the flow fields of a ducted fan using particle image velocimetry (PIV) and computational analysis for hovering and edgewise flight. A custom-developed rotor disk flow model was used to predict a pressure rise in the Reynolds-averaged Navier-Stokes (RANS) equations. Flow separation was observed at the leading side of the ducted fan in PIV measurements. This inlet distortion affects the performance of the ducted fan.

Ohanian and Karni\(^10\) investigated the synthetic jet actuator for flow control on ducted fans. These researchers demonstrated that the synthetic jet control could produce aerodynamic forces and moments on the ducted fan for various angles of crosswind using a wind tunnel. The synthetic jet can control the leading- and trailing-edge flows to reduce the pitching moment.

Cho et al.\(^11\) conducted design analysis, computational analysis and a wind tunnel test on ducted fans to research how to enhance performance. These researchers verified that the duct improved thrust performance compared to the rotor.

The aerodynamic design step for rotor and stator blades of the ducted fan was presented. Divitiis\(^12\) analyzed shrouded fans to predict performance and stability in mission flights and ground effects. The shroud and rotor models were developed and were consistent with existing data in literature.

Avanzini et al.\(^13\) performed a numerical analysis to determine the aerodynamic characteristics of a ducted fan. The aerodynamic database is appropriate for estimating the trim and performance.

Various researchers have studied the performance of ducted fans, which is more efficient and safer than systems that consist of open rotor blades. Ducted fans have numerous advantages, such as less tip loss and increased thrust for the same rotor size.

Figure 2 shows a mission profile for a multi-ducted fan VTOL UAV. The cruise speed is 10 m/s. The altitude is set to 10–20 m due to operation being in an urban area. Crosswind had unfavorable effects on the vehicle in all missions. Ducted fans also have drawbacks such as momentum drag, asymmetric lift and adverse pitching moment. Performance of the ducted fan unit can be adversely affected in transition or crosswind.\(^5,10\) Flow separation can also affect the inlet lip of a ducted fan. To overcome unstable flight, control devices for the ducted fan can be adopted in the vehicle and the duct lip shape can be modified. However, few researchers have attempted to increase the stability of ducted fans. The effect of crosswind on ducted fans stability remains particularly poorly understood. A detailed understanding of the aerodynamic characteristics of ducted fans under crosswind conditions is required to improve the performance of UAVs.

The objective of the present study was to investigate the aerodynamic characteristics of a ducted fan under crosswind conditions. Viscous and turbulent flow around the ducted fan were calculated using a commercial CFD tool. The computational results were verified by wind tunnel testing at Hanyang University.

The remainder of this paper is organized as follows: Section 2 describes the ducted fan model with governing equations, computational domains, boundary conditions, and the grid independence test. Section 3 introduces the wind tunnel test to validate the CFD results. Section 4 compares the computational and experimental results in terms of aerodynamic characteristics and flow fields. The conclusions are provided in Section 5.
2. Computational Method

2.1. Ducted fan model

The rotor and stator blades were designed using a reference method.11) The geometry of the main ducted fan unit is plotted in Fig. 3. The inflow angle is described as the angle of crosswind. The angle of crosswind is zero degrees during vertical climb. Horizontal crosswind means that the thrust and direction of the crosswind are perpendicular.

The specifications of the ducted fan model are shown in Table 1. The ducted fan inner diameter is 200 mm, the tip clearance is 1 mm, and a NACA 65 series airfoil is used in the blade section. The rotor of the ducted fan consists of three blades, whereas the stator has seven blades.

The momentum drag, called “ram drag,” is an important feature of the ducted fan in crosswinds.2,5,7,8) The ram drag acting at the center of pressure, the pitching moment acting at the center of gravity and the crosswind are described in Fig. 4.

2.2. Governing equations and turbulence model

The aerodynamic characteristics of the ducted fan were calculated using the commercial solver ANSYS-CFX Ver. 14.5. The computational simulation solves the RANS equations using a finite volume method. The continuity, momentum and energy equations are simultaneously calculated. The RANS equations are14):

\[
\frac{\partial (\rho U)}{\partial t} + \nabla \cdot (\rho U U) = -\nabla p + \nabla \cdot \tau + S_M
\]  

Momentum equation:

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

\[
= \nabla \cdot (\lambda \nabla T) + \nabla \cdot (U \cdot \tau) + U \cdot S_M + S_E
\]  

Energy equation:

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2.3. Computational domains and boundary conditions

Figure 5 shows the computational domains and boundary conditions of ducted fan analysis. There are rotating and stationary domains. To analyze the aerodynamic characteristics of the ducted fan, the following conventional performance parameters were used. The aerodynamic characteristics of the ducted fan are represented in Eqs. (4)–(12):15)

Advance ratio: \( J = \frac{V_\infty}{N D} \) (4)

Thrust coefficient: \( C_T = \frac{-F_z}{\rho N^2 D^4} \) (5)

Power coefficient: \( C_P = \frac{Power}{\rho N^3 D^5} \) (6)

Efficiency: \( \eta = \frac{C_T}{C_P} \) (7)

Normal force coefficient: \( C_X = \frac{F_X}{\rho N^2 D^5} \) (8)

Side force coefficient: \( C_Y = \frac{F_Y}{\rho N^2 D^5} \) (9)

Pitching moment coefficient: \( C_m = \frac{M_y}{\rho N^2 D^5} \) (10)

Yawing moment coefficient: \( C_n = \frac{M_z}{\rho N^2 D^5} \) (11)

Rolling moment coefficient: \( C_l = \frac{M_x}{\rho N^2 D^5} \) (12)

The \( k-\omega \) based shear stress transport model was used in this computation.16) This turbulence model is commonly used to predict the adverse pressure gradient near the wall and flow separation.17,18)

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of the ducted fan, multiple frames of reference (MFR) were used. Rotating reference frames (RRF) were used for the rotor blade in this study. The RRF for the ducted fan model were located at the center of the sphere. The computational domain was set to a spherical shape with a radius 20 times the rotor diameter. The outer surface was used as an opening boundary condition that lets the fluid cross the boundary surface in either direction. The angle of crosswind was set to the vector direction on the outer surface.

2.4. Grid independence test

A grid independence test was performed to confirm that the calculated results do not depend on the computational mesh. Three different mesh sizes were compared: a coarse mesh with $6.4 \times 10^6$ elements, a medium mesh with $9.8 \times 10^6$ elements and a fine mesh with $14.6 \times 10^6$ elements. Figure 6 shows the pressure coefficient distributions at $r/R = 0.75$ of the ducted fan rotor blade for three different grid resolutions under hovering conditions. The pressure coefficient is grid-independent when the number of $9.8 \times 10^6$ elements is exceeded. Thus, the medium mesh density was chosen.

A tetrahedral grid was used in this study, as shown in Fig. 7. The computational grids are $9.8 \times 10^6$. The number of elements in the rotating region is $1.2 \times 10^6$. The dimensionless wall distance is $y^+ \approx 1$ for consideration of a viscous sublayer for the turbulent boundary layer based on the law of the wall. The expansion ratio for prism layers up to 30 layers is 1.2. The Reynolds number based on the mid-blade chord is approximately $9.71 \times 10^4$.

3. Experimental Method

3.1. Experimental setup

The aerodynamic characteristics of the ducted fan were measured using the subsonic wind tunnel at Hanyang University. Figure 8 shows the schematic diagram of the ducted fan in the wind tunnel. The thrust was measured under vertical climb conditions, with a zero degree angle of crosswind. The angle of crosswind was changed from $-30$ degrees to 30 degrees under hovering conditions.

The specifications of the subsonic wind tunnel are shown in Table 2. The wind tunnel is an open circuit and closed-throat type. The test section of the wind tunnel is 0.8 m wide, 0.8 m high and 1.6 m long. The velocity can be changed from 2 to 70 m/s. The turbulence intensity is 0.2%, and the flow velocity rate varies within 1%. The blockage ratio, which is the ratio of the model frontal area to the test section area, is 1.23% in this wind tunnel test. This ratio is less than the allowable ratio of model frontal area to test-section cross-sectional area of 7.5%. The rotational speed of the ducted fan as measured by the proximity sensor is 10,000 rpm and is fixed for all experimental conditions.

The experimental model was set up in the wind tunnel as shown in Fig. 9. The six components of forces and moments were measured using a load cell-type external balance (six-axis CAS-Multi-axis load cell) located outside of the model and a wind tunnel test section. The measurement range of the thrust and moment were 5 kg and 0.5 kg-m, respectively. The accuracy of the load cell was 0.5% FS for each components.

A brushless DC (BLDC) electric motor was used to operate the ducted fan rotor. The input shaft power was calculated.
using Eq. (13). The efficiency of the electric motor was
determined using the calibration test results from the motor
manufacturing company.

\[ L = E \times I \times \eta_m \] (13)

The results of the wind tunnel tests for the ducted fan were
corrected using the Glauert method.\(^\text{21}\)

\[ \frac{V'}{V} = 1 - \frac{\tau_4 \alpha_1}{2\sqrt{1 + 2\tau_4}} \] (14)

where, \( \tau_4 = -F_c/\rho A_p V^2, \alpha_1 = A_p/A_W \).

4. Results

4.1. Computational model validation

The comparison results for the ducted fan are shown in
Fig. 10, where the difference in the thrust coefficient is less
than approximately 8.19%. This difference is caused by ex-
perimental effects, such as blockage and model support of
the ducted fan. When the free stream velocity increases,
the thrust coefficient of the ducted fan decreases, which is
similar to the references.\(^\text{5,22,23}\) Because the blade section
angles of crosswind are reduced with increasing inflow
velocity, the power coefficient is almost constant along the
advance ratio. The difference in the power coefficient is less
than 6.57%. However, the tendency for efficiency is in good
agreement with the experimental results. The efficiency of
the ducted fan increases as advance ratio increases up to
0.4. The difference in efficiency increases at a high advance
ratio because of the lower prediction of thrust in the CFD.

In order to validate the effect of the angle of crosswind
under hovering conditions, the angle of crosswind is changed
from 30 degrees to 120 degrees, as shown in Fig. 11. The
difference in the thrust coefficient is less than 3.44%, 2.16% and
4.21% for free stream velocities of 3, 6 and 9 m/s, respec-
tively. The tendency of the computational results shows good
agreement with the experimental results. The variation of the
thrust coefficient is 2.01, 5.28 and 10.24% for free stream ve-
locities of 3, 6 and 9 m/s, respectively. The thrust coefficient
decreases when the magnitude of the free stream velocity in-
creases.

4.2. Aerodynamic characteristics

In order to analyze the effect of crosswinds, the angle of
crosswind is changed from 30 degrees to 120 degrees,
which includes the range of hovering conditions (-30 to
30 degrees). Figure 12 shows that the thrust coefficient of the
ducted fan is the lowest at the zero-degree angle of crosswind
in all cases. As the velocity magnitude increases, the fluctu-
ation range of the thrust coefficient increases in all cases. The
thrust coefficient increases up to 90-degree angle of cross-
wind. After the angle of crosswind reaches 90 degrees, the
thrust decreases for \( V_\infty = 9 \text{ m/s} \). The thrust coefficient is
almost identical to this when the angle of crosswind is 90 de-
grees. The thrust of the ducted fan increases when the angle of
crosswind increases. The results have a similar tendency
to those of Ohanian and Karni.\(^\text{10}\)

Figure 13 shows the power coefficient of the ducted fan
versus the angle of crosswind. The range of the power coef-
ficient for the ducted fan is 1.80–1.88. The effect of the angle
of crosswind is small for \( V_\infty = 3 \text{ m/s} \). When the crosswind
becomes stronger, the variation in the power coefficient in-
creases with the angle of crosswind.
As shown in Fig. 14, the efficiency of the ducted fan is calculated for various angles of crosswind. The effect of the angle of crosswind is small at $V_1 = 3\text{ m/s}$, which implies that a weak crosswind does not affect the efficiency of the ducted fan because the variation in power coefficient is small. The efficiency increases with the crosswind because of the increase in thrust. Higher efficiency occurs at a large free stream velocity magnitude with an angle of crosswind $\approx 90$ degrees.

Figure 15 shows the range of normal force coefficient for the ducted fan. There is no normal force at the zero-degree angle of crosswind. The normal force magnitude decreases with strong free stream velocity until a 60-degree angle of crosswind. The maximum minus normal force is confirmed at an angle of crosswind $\approx 50$ degrees in all conditions.

As shown in Fig. 14, the efficiency of the ducted fan is calculated for various angles of crosswind. The effect of the angle of crosswind is small at $V_1 = 3\text{ m/s}$, which implies that a weak crosswind does not affect the efficiency of the ducted fan because the variation in power coefficient is small. The efficiency increases with the crosswind because of the increase in thrust. Higher efficiency occurs at a large free stream velocity magnitude with an angle of crosswind $\approx 90$ degrees.

As shown in Fig. 16, the side force coefficient is a result of the ducted fan in a crosswind. When the angle of crosswind is zero degrees, there is no lateral force. These side forces for the ducted fan in every free stream magnitude converge at the angle of crosswind $\approx 90$ degrees. In addition, the side force is affected by the angle of crosswind. The magnitude of the side force coefficient is the largest at a 60-degree angle of crosswind under all crosswind conditions and subsequently decreases. The side force depends on the angle of crosswind and the velocity magnitude.

Figures 17–19 show the moment coefficients of the ducted fan. These moments are important to control a ducted fan UAV. The pitching moment increases up to 110, 100 and 90-degree angles of crosswind for velocity magnitudes of 3, 6 and 9 m/s, respectively, as shown in Fig. 17, and decreases because of the duct lip stall. The peak pitching moment decreases when the angle of crosswind increases. These results have similar tendencies as the results of Ohanian and Karni\(^\text{10}\) and Mort and Yaggy.\(^\text{23}\) A positive pitching moment is generated by the crosswind. The strong nose-up pitching moment originates from the asymmetric force of the duct lip, which is significantly affected by the crosswind. To improve the stability of the ducted fan, the positive pitching moment must be reduced. The control vanes of the ducted fan at the exit flow are commonly adopted to trim the UAV.

Figure 18 shows the yawing moment coefficient of the ducted fan.
means that the swirl velocity component is removed by the stator. The yawing moment coefficient becomes unstable at 80-degree and 70-degree angles of crosswind for \( V_\infty = 6 \) and 9 m/s, respectively. The free stream velocity magnitude has a smaller effect than the angle of crosswind.

As shown in Fig. 19, the rolling moment coefficient of the ducted fan is \( -0.0172, -0.0177 \) and \( -0.0184 \) for \( V_\infty = 3 \), 6 and 9 m/s, respectively. The rolling moment is unstable at strong free stream velocities, particularly when the angle of crosswind is 45 degrees. When the angle of crosswind is 90 degrees with \( V_\infty = 9 \) m/s, the rolling moment greatly increases.

Figure 20 shows the z-axis center of pressure of the ducted fan. The location of the center of pressure is calculated from the pitching moment divided by the normal force. The \( z_{cp}/D \) is not plotted at the zero-degree angle of crosswind. The duct lip stall is observed at \( V_\infty = 9 \) m/s and an angle of crosswind of 90 degrees. The distance between the center of pressure and center of gravity significantly affects the pitching moment because this length acts as a moment arm. To improve stability, the moment arm must be reduced.

4.3. Flow field analysis

The Reynolds number for the ducted fan unit is \( 9.71 \times 10^4 \). The laminar boundary layer separation, transition and reattachment could be determined in the present study. To evaluate the aerodynamic characteristics, the flow fields around the ducted fan were computationally simulated.

Figure 21 shows the effect of the inflow velocity magnitude with streamlines on the side view (\( y = 0, zx\)-plane) for the ducted fan. The separation point is located on the outer surface of the duct during hovering, as shown in Fig. 21(a). The separation point is moved to the leading-edge of the duct, as shown in Fig. 21(b)–(d), because of the free stream velocity. The velocity magnitude is close to zero around the inlet and behind the hub. This region adversely affects the vehicle performance because of the momentum loss. The separation bubble occurs near the separation point and trailing-edge of the duct. The velocity magnitude is the smallest on the leeward side of the duct and increases on the leading-edge of the duct.

Greater suction occurs on the windward side as shown in Fig. 22(c). The velocity magnitude is the smallest on the leeward side of the duct and increases on the leading-edge of the duct.
duct. The asymmetric lift force is generated at the duct lip, where the dynamic pressure difference is confirmed. A strong nose-up pitching moment is generated. Therefore, the pitching moment increases due to the crosswind. The suction peak point moves to the inner side of the duct when the angle of crosswind increases. The thrust vector is bent due to the crosswind at the exit of the ducted fan. In other words, crosswind affects the duct lip separation on the duct lip and the trailing-edge. The pitching moment is caused by the asymmetric lift force of the duct lip.

Figure 22(d) shows a very complicated velocity magnitude contour and streams of the ducted fan. The crosswind

![Images of velocity magnitude contours and streamlines with different conditions](image-url)

Fig. 21. Velocity magnitude contours and streamlines of the ducted fan with $\alpha_{\text{cross}} = 0$ degrees, at $y = 0$, $zx$-plane.

Fig. 22. Velocity magnitude contours and streamlines of the ducted fan with $V_\infty = 9$ m/s, $\alpha_{\text{cross}} = 30 - 120$ degrees at $y = 0$, $zx$-plane.
interrupts the jet of the ducted fan. The separation bubble occurs near the trailing-edge of the duct on leeward side. The thrust coefficient decreases at this angle of crosswind.

5. Conclusions

In this study, to enhance the stability of main ducted fan UAVs, the aerodynamic characteristics and flow fields around the ducted fan were analyzed. The ducted fan unit for lifting/propulsion of a VTOL UAV was calculated using commercial software that solves the RANS equations.

Wind tunnel testing was performed to verify the CFD results. From this investigation, the following conclusions can be derived:

(1) The thrust, normal and side forces are affected by the magnitude of free stream velocity; the angle of crosswind. The thrust coefficient is almost constant under edgewise flight conditions and increases as the angle of crosswind increases.

(2) A positive pitching moment is generated by the angle of crosswind. Asymmetric force from the duct is generated by the crosswind and creates a strong nose-up pitching moment.

(3) Flow separation occurs from flow fields around the ducted fan. The separation point is located on the outer surface of the duct during hovering. The separation point is moved to the leading-edge of the duct because of the free stream velocity.

(4) Non-uniform flow fields occur at the inlet of the ducted fan and are strongly contorted by the crosswind. Inlet distortion is affected by duct lip separation on the leading-edge of the duct. The suction peak of the duct lip is confirmed from duct lip separation on the windward side of the duct. Therefore, the breathing area is reduced.

(5) The lowest velocity magnitude occurs behind the leeward side of the duct. The difference in the suction velocity magnitude on the duct lip creates asymmetric lift force. A strong nose-up pitching moment is generated on the duct lip, which is significantly affected by the distance between the center of pressure and the center of gravity. In other words, the pitching moment increases because of the crosswind.

The pitching moment must be reduced for stable flight. Furthermore, the cross-section of the ducted fan needs to be optimized to improve aerodynamic performance.

The flight characteristics of the vehicle will be discussed in future works. The full vehicle has three ducted fan units: twin main ducted units for the lift/propulsion and a subducted fan unit, which can be used to control the vehicle. In order to overcome unstable flight conditions, the control effect of the subducted fan unit should be analyzed.

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