An optimization and test method for ducted fans based on CFD

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Abstract. Some unmanned aircrafts with ducted fan systems are characterized by high efficiency, structural safety and good stability. As a major part of such aircrafts, the ducted fan plays an important role in performance. However, changes in the fan blade structure will influence the fan action. First, from a manufacturing point of view, materials and gate positions were selected. The injection molding process parameters were optimized based on an orthogonal testing analysis method, and this optimization process reduced the warpage by 36.4%. Then, the flow fields of the ducted fans in the theoretical and deformed models were compared and analyzed with SolidWorks computational fluid dynamics (CFD). Finally, the wind velocity values at different distances from the nozzle outlet of the ducted fan were obtained using a wind speed measurement experiment system. The results from the model comparisons showed that fan blade deformation reduced the wind speed by approximately 5%.

1. Introduction
An unmanned aerial vehicle (UAV) with a ducted fan system as the main source of flight power is a type of drone with vertical takeoff and landing functionality. Due to its safe structure, high propulsion efficiency and fast maneuverability, this type of aircraft has been used in many fields. However, the ducted fan structure must be able to satisfy additional requirements, including low weight, high stability and high energy efficiency [1]. The aerodynamic shape and structural design of the fan blade will influence the energy conversion efficiency. To achieve good aerodynamic performance, the blade requires an efficient airfoil shape, a reasonable installation angle, an appropriate lift-drag ratio, a proper tip speed ratio, high-quality materials and advanced technology [2]. Fan blades typically exhibit warpage during molding, which seriously affects the characteristic parameters of the blade. This deformation leads to the loss of flight efficiency and even affects the dynamic characteristics of the ducted fan.

Kovács et al. presented a novel method for the analysis and measurement of the deformation of injection-molded plastic parts [3]. Fatihah Kamarudin et al. used the Taguchi method to identify the parameters that caused product defects, and this method was also able to decrease the cost of creating the product [4]. To improve the underground ventilation performance, Ziyun et al. designed an integrated device for a wind turbine used for underground ventilation [5], and this work effectively reduced warping. Panigrahi et al. focused on one of the key design factors of mine ventilation fans by analyzing the selection of an appropriate airfoil blade profile for the fan blades to enhance the energy.
efficiency of axial-flow ventilation fans using computational fluid dynamics (CFD) simulations [6]. Jihyeong et al. used a computational analysis tool to characterize the flow structure in an S-shaped intake, and the relationship between the inlet shape and angle of incidence was determined [7]. The research showed that CFD technology could be used to analyze the flow field and design and to evaluate the performance of ducted fans.

The ideal model was used without considering the manufacturing error. In this paper, a method of structural optimization and testing for ducted fans was proposed from a manufacturing point of view. First, the effect of deformation on the aerodynamic properties of the fan is analyzed by leaf element theory. Model reconstruction was carried out via reverse engineering. The optimum mold-forming parameters and the minimum deformation model were obtained through orthogonal experiments. Then, the numerical simulation results of injection molding and the CFD results of aerodynamics were used for a joint simulation analysis. Finally, a wind speed measurement system was constructed, and comparisons were drawn between the simulated data from the original model, the simulated data from the reconstructed model, and the experimental measurements. Through this comparison and analysis, the influence of fan blade deformation on wind speed was obtained.

2. Method and experiments

2.1. Research method based on CFD and reverse engineering
To ensure that the numerical simulation results are similar to the test results, noncontact 3D structured light technology and point-cloud reconstruction technology are used for reverse engineering. Using Geomagic Design Direct, forward and reverse hybrid modeling is carried out to obtain a 3D model similar to the real object. The 3D model is simulated with the injection molding simulation software Moldflow, and the optimal injection molding process parameters are determined through an L_{16} (4^5) orthogonal experiment. These parameters include the injection molding time, holding time, holding pressure, mold temperature and melt temperature. The optimal combination of process parameters for minimum warpage is obtained via range data analysis. After the deformed model is reconstructed, the effect of warpage on fan blade performance is studied from a manufacturing perspective by comparing the wind speed-distance curve measured on the inlet and outlet sides of the ducted fan, which have separate theoretical models, deformable models and material objects. The overall flow chart is shown in Figure 1.

![Flowchart of the test method based on CFD and reverse engineering.](image)

2.2. Momentum theory and blade element theory
When air is flowing in a pipe, if the cross section of the pipe perpendicular to the airflow direction remains unchanged along the pipe axis, then the gas parameters will be uniform. The continuity equation of gas under one-dimensional steady-flow conditions can be obtained using the law of
conservation of mass. The thrust of the ducted fan involves not only the velocity of the inlet and outlet sections of the fan but also the angle between the velocity and the axial direction. Slip flow theory plays an important role in calculating the stress state. The axial force acting on the blade can be obtained by controlling the momentum Equation (1) along the X-axis:

$$T_p = \frac{1}{2} \rho \left( v_2^2 - v_0^2 \right) A$$

Here, $T_p$ is the thrust of the ducted fan, $N; \rho$ is the density of air, $kg/m^3; v_2$ is the outflow gas velocity of the duct, $m/s; v_0$ is the average flow velocity of $v_1$ and $v_2, m/s; and A is the cross-sectional area of the culvert, $m^2$.

An airfoil fan is adopted herein, and the specific parameters of the fan are calculated and analyzed. According to the classical blade element theory (BEM), the thrust and angle of attack are closely related to the lift and drag coefficients, and the solidity cascade changes with respect to the distance from the propeller axis. The thrust of the fan blade is determined using the following expression:

$$T_{fan} = \int_0^\infty \frac{1}{2} N_b \rho \omega_p^2 c C_L(\alpha) r^2 dr$$

Here, $T_{fan}$ is the thrust of the fan blade; $N_b$ is the number of propeller blades; $\rho$ is the density of air, $kg/m^3; \omega_p$ is the rotational angular velocity of the propeller, $rad/s; c$ is chord length of the propeller blade, $m; r$ is the curvature radius; and $C_L(\alpha)$ is the lift coefficient, which is a function of the attack angle $\alpha$.

$$C_L = 2\pi \left[ \alpha + \frac{1}{\pi} \int_0^\infty \frac{dz}{dx} \left( \cos \theta_0 - 1 \right) d\theta_0 \right]$$

Here, $\theta_0$ is a dummy variable.

2.3. Material and geometry

Engineering plastic, such as acrylonitrile butadiene styrene (ABS), is suitable for ducted fan blades. In this paper, ABS was supplied by LG Chemical Industries (material ID 8920, density 1.3406 $g/cm^3$, melt flow rate 1.7 $g/min$, melting temperature 195°C, and glass transition temperature $-20^\circ C$). As shown in Figure 2, the ducted diameter is 70 mm, and an isometric fan with an angle of 30° between the two blades was studied. The turbine cascade has several basic geometric parameters, such as the row line, grid axis, grid pitch, wing chord, and setting angle. The blade section shape of the airfoil fan is similar to that of an aircraft wing. Studies have shown that airfoil blades have low wind resistance and large lift coefficients, which makes them excellent for use in aviation fields. This type of fan is typically produced via a controlled molding process. To study the simulation of the fan, it is necessary to remodel it.

To shorten the research and development cycle, remodeling can be done through structured light and reverse engineering design. Figure 3 shows the COMET L3D system based on structured light. Geometric software was used to take the measurements, and a 3D model was reconstructed by implementing a combination of forward and reverse engineering techniques. Then, based on the simulation results, the structure can be improved through testing and optimization.

Figure 2. Ducted fan and its blades. Figure 3. Flowchart of COMET L3D system and the model reconstruction process.
2.4. Injection molding and orthogonal experimental design method

As previously mentioned, the injection molding process has an influence on the performance of the fan. Based on Moldflow MPI, simulations with different parameter choices were carried out. Experimental and simulation analyses of the filling, holding pressure and warpage were carried out with MPI software. The orthogonal test method was used to find the optimal injection process parameters, reduce the computational load and produce an accurate solution. Orthogonal experimental design is a method used to study multiple factors and levels to determine an optimal combination [4]. The analysis in this study considers five factors, each of which has four levels. The key process parameters include the injection molding time, holding time, holding pressure, melt temperature and mold surface temperature. An L₁₆ (4⁵) Taguchi orthogonal table is established with these parameters, as shown in Table 1. In this table, No. 14 is the combination of injection molding process parameters that produces the maximum warpage, whereas No. 3 is the parameter combination that produces the minimum warpage.

Table 1. Orthogonal test table of the injection molding process conditions.

| No. | A/s | B/s | C/% | D/°C | E/°C | Q/mm maximum deformation |
|-----|-----|-----|-----|------|------|--------------------------|
| 1   | 1   | 1   | 1   | 1    | 1    | 0.2930                   |
| 2   | 1   | 2   | 1   | 1    | 1    | 0.2889                   |
| 3   | 1   | 3   | 1   | 1    | 1    | 0.1975                   |
| 4   | 1   | 4-14| 1   | 1    | 1    | 0.3457                   |
| 5   | 2-2.5 | 1-8 | 2-80| 3-250| 4-240| 0.3457                   |
| 6   | 2-2.5 | 2-10| 1-70| 3-240| 4-70 | 0.3078                   |
| 7   | 2-2.5 | 3-12| 4-100| 1-270| 2-75 | 0.2047                   |
| 8   | 2-2.5 | 4-14| 3-90 | 2-260| 1-80 | 0.2107                   |
| 9   | 3-3.0 | 1-8 | 3-90 | 4-240| 2-75 | 0.3465                   |
| 10  | 3-3.0 | 2-10| 4-100| 3-250| 1-80 | 0.3342                   |
| 11  | 3-3.0 | 3-12| 1-70 | 2-260| 4-65 | 0.3389                   |
| 12  | 3-3.0 | 4-14| 2-80 | 1-270| 3-70 | 0.3520                   |
| 13  | 4-3.5 | 1-8 | 4-100| 2-260| 3-70 | 0.3387                   |
| 14  | 4-3.5 | 2-10| 3-90 | 1-270| 4-65 | 0.4256                   |
| 15  | 4-3.5 | 3-12| 2-80 | 4-240| 1-80 | 0.3415                   |
| 16  | 4-3.5 | 4-14| 1-70 | 3-250| 2-75 | 0.3093                   |

Figure 4. Fan deformation in the Z direction: (a) minimum deformation state and (b) maximum deformation state.

Figure 4 shows the maximum and minimum deformation states of the parts in the Z direction. The material characteristics led to variation in the structural parameters of the ducted fan. The whole fan
shrank toward the center, and the outer blade bent in the Z direction. The total minimum warpage was 0.1975 mm, whereas the maximum warpage was 0.4256 mm. After optimization, the Q value under the optimal process conditions was approximately 2.15 times that under the worst process conditions.

After obtaining the data by the orthogonal experimental method, range analysis was used to analyze the data according to the experimental results to determine the sequence of several factors affecting Q and the optimal scheme. The equations involved in the range analysis are as follows:

\[
\bar{k}_i = \frac{K_i}{S}
\]

(4)

\[
R = \max \{k_1k_2k_3k_4\} - \min \{k_1k_2k_3k_4\}
\]

(5)

Here, \(K_i\) is the sum of Q simulated by some factors at level i; \(\bar{k}_i\) is the arithmetic mean value of \(K_i\); \(S\) is the number of occurrences of a factor at various levels; and \(R\) is the range.

Using the MPI injection-pressure-warping analysis sequence, the warpage Q was calculated in the simulations. The range analysis of the results determined the response of the target Q to the process factors A, B, C, D and E. Table 2 shows the degree to which each process parameter affected Q, and Figure 5 shows that the parameters had the following order of influence (from greatest to least): A>E>B>D>C. The injection time had the greatest effect on the maximum warpage because, the longer the material stays in the mold, the more strain or stress is released inside the part. As a result, longer injection/cooling times result in less warpage. The influence of the mold temperature and melt temperature was complex, and warpage was mainly caused by temperature in different positions. For a low melt temperature or mold temperature, the temperature variation between different positions should be larger, resulting in greater warpage. The holding pressure had the least influence among all the process parameters.

**Table 2.** Range analysis data sheet.

| factors | A    | B    | C    | D    | E    |
|---------|------|------|------|------|------|
| \(K_1\) | 1.1251 | 1.314 | 1.249 | 1.2753 | 1.1794 |
| \(K_2\) | 1.1059 | 1.3565 | 1.3182 | 1.1772 | 1.1494 |
| \(K_3\) | 1.3716 | 1.0826 | 1.1803 | 1.1768 | 1.196 |
| \(K_4\) | 1.4151 | 1.2177 | 1.2177 | 1.3415 | 1.446 |
| \(k_1\) | 0.2812 | 0.3285 | 0.3122 | 0.3188 | 0.2358 |
| \(k_2\) | 0.2118 | 0.3391 | 0.3295 | 0.2943 | 0.2873 |
| \(k_3\) | 0.3429 | 0.2706 | 0.2950 | 0.2942 | 0.299 |
| \(k_4\) | 0.2830 | 0.3044 | 0.3353 | 0.3353 | 0.3615 |
| \(R\)   | 0.1311 | 0.0684 | 0.0403 | 0.0411 | 0.1256 |

**Figure 5.** Main effect plots of the maximum deflection.
2.5. *Comparison based on CFD numerical simulations*

Even if the warpage is minimized by optimization, it likely changes the inclination impeller blade tilt angle, shape and dynamic characteristics. We reconstructed the deformed models according to Figure 4. Then, the flow field was simulated via CFD simulations to obtain the results of the wind velocity. Figure 6(a) shows the velocity flow field of the minimum deformation model when the fan speed was 10000 RPM, which is compared with that of the maximum deformation model shown in Figure 6(b). Similarly, as shown in Figure 6(c) and 6(d), the movement of air was restricted within a more concentrated space by the ducts; thus, the air speed had better directivity, and the ducted fan produced a greater axial velocity. From Figure 6(a) and 6(b), we can see that the air velocity at the inlet and outlet sides of the ducted fan both changed, and this change can also be seen in Figure 6(c) and 6(d). In particular, the velocity near the center of the rotating shaft had a large velocity gradient.

![Figure 6. CFD simulations of the wind velocity and flow field diagrams: (a) minimum deformation model; (b) maximum deformation model when the fan speed is 10000 RPM; (c) minimum deformation model; (d) maximum deformation model when the fan speed is 15000 RPM.](image)

The wind speed fields of the minimum deformation model and the maximum deformation model were obtained through CFD simulations. The wind speed measurement data are represented by a waterfall diagram, as shown in Figure 7. By comparing the wind speed changes in the two models, we can see that the velocity of the air in the maximum deformation model was relatively low, indicating that the efficiency of the fan was reduced. In addition, from the perspective of velocity change, it is obvious that the fluid velocity field gradient after deformation was smaller, which negatively affected the stability and dynamic performance of the duct, and near the center, the air velocity changed the most. Thus, the deformations in the Z direction mentioned above may have an important effect on the blade shape, which affects the aerodynamic performance of the fan. According to the characteristic formula of wind power, the average fan thrust is related to the square of the average inlet and outlet velocities. The simulation analysis shows that the deformations of the injection fan have a negative effect on the characteristics of the ducted fan.

2.6. *Wind speed measurement system*

The experimental conditions were consistent with the simulation. The temperature was 26.2°C, and the air humidity was 67%. The fan measurement system consists of four components: a mechanical
structure system, a motor drive system, a control system and a data-acquisition system, as shown in Figure 8. The whole mechanical structure system is composed of several aluminum profiles with a scale, support units and clamping units. The distance between the fan and the anemometer can be adjusted by loosening the screw. Since the motor generated a torque when rotating at a high speed, to provide balance, we added an aluminum sheet to the aluminum profile for fixation. The motor drive system is composed of a 4S lithium battery, UBEC (Ultra Battery Elimination Circuit) and ducted fan components. The UBEC can adjust the working voltage of the motor. The control system is composed of a remote-controlled handle and a wireless receiver module. Through the communication setting, the wireless receiver received the commands issued by the remote control, and then the PWM (pulse width modulation) parameters of the electronic control system were adjusted. The data-acquisition system consists of an anemometer, an anemometer display and a laser tachometer. The anemometer is connected to a computer via a USB port for data transmission. The measurement range of the laser tachometer is 100–30000 RPM, the resolution is 0.1 RPM, the measurement error is ±0.5%, and the sampling time is 0.8 s. An anemometer was used to measure the position of the simulated diagram. The velocity measurement range of the digital anemometer is 0–45 m/s, with a measurement accuracy of ±2.5%. It was necessary to accurately operate the remote control to adjust the PWM value, while closely observing the data from the laser tachometer. Error and contingency factors were excluded, and the average value was taken as the result.

![Simulation1, minimum deformation model, fan inlet](image1)
![Simulation2, maximum deformation model, fan inlet](image2)
![Simulation1, minimum deformation model, fan outlet](image3)
![Simulation2, maximum deformation model, fan outlet](image4)

**Figure 7.** Wind velocity at a certain distance when the fan speed is 10000 RPM.

To verify the performance of the fan at the same speed, it is necessary to simultaneously measure the following data: voltage, fan speed, measured distance and wind speed. During this process, the fan was operated by remote control. The speed of the fan was measured in a direct contactless way so that accurate data could be obtained.
First, a random position was selected, the laser tachometer was aligned with the fan blade, and the voltage value was recorded at fan speeds of 10000 and 15000 RPM. Next, after adjusting the distance between the ducted fan and anemometer from 36 mm to 76 mm, the anemometer reading at this voltage was recorded. Finally, after testing the ducted fan, the fan blade part was disassembled and replaced with the deformed fan generated by rapid prototyping. Then, at the same position, the wind speed test was repeated on the new ducted fan. The experimental data revealed the influence generated by the fan post-deformation.

With the simulation data in Figure 7, a comparison of the two sets of fans verified the trends of the prediction results, as shown in Figure 9. However, there is a significant amount of simulation data on the fan deformation effect.

![Wind speed measurement system of the ducted fan](image)

**Figure 8.** Wind speed measurement system of the ducted fan: (1) laser tachometer; (2) hygrothermograph; (3) ducted fan; (4) UBEC; (5) anemometer; (6) remote control; (7) 4S lithium battery; (8) wireless receiver module; (9) anemometer display; (10) aluminum profiles with a scale.

![Experimental data from the wind speed measurement system](image)

**Figure 9.** Experimental data from the wind speed measurement system: (a) 10000 RPM; (b) 15000 RPM.

### 3. Conclusions

This study introduces a test method for ducted fan structures and carries out injection simulations. The following conclusions are drawn from this study:

1. Through a simulation analysis of the injection molding process of the ducted fan blades, the injection molding process parameters were optimized, and the maximum warpage was reduced from 0.4256 to 0.1975 mm, which is a reduction of 36.4%.

2. A fan wind speed measurement system was designed and developed to accurately analyze the speed, distance and wind speed of the fan under different voltages. The results show that the wind speed at the outlet and inlet decreased by approximately 5% on average after the fan blade was deformed.
(3) By referencing experimental data, CFD software was used to perform a simulation analysis, and the flow field conditions of the deformed models were compared and analyzed. The results show that the deformation after injection molding should not be ignored when analyzing the comprehensive performance of a ducted fan.

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