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Design of a ducted propeller system for a tail-sitter type vertical take-off and landing vehicle using computational fluid dynamics

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Abstract

The tail-sitter type unmanned aerial vehicle (UAV) is attracting a lot of attention because it has a simple structure and can fly vertically and horizontally. However, even in horizontal flight, the same low pitch propeller for vertical flight is used, which has the disadvantage of not securing sufficient thrust during forward flight. Ducted propellers have the effect of improving thrust by 30-50% compared to open propellers at static or low speed, but in forward flight mode, they act like drag bodies, so an optimal aerodynamic design is essential. In this study, simplified computational numerical simulations were applied to parameterized ducts and the effect of duct shape on the performance of the propulsion system was evaluated. After analyzing about 2,000 cases, it was found that ducts with shorter lengths in the wake region and converging or straight ducts showed relatively higher efficiency. And the results were compared by varying the pitch and chord length distributions. Increment in both pitch and chord length produced more thrust, but the chord length resulted in better efficiency in terms of specific thrust.

Keywords: tail-sitter, ducted propeller, vtol, uav, openfoam

1 Introduction

A tail-sitter type UAV is an aerial vehicle capable of both vertical flight like a multicopter and horizontal flight like a general fixed-wing aircraft. Although it has received a lot of attention for a long time, it has rarely been developed as a manned vehicle due to its difficulty of vertical flight control, take-off, and landing. In the

2000s, with the development of unmanned aerial vehicles, various tail-sitter type UAVs were developed. Pixhawk and Ardupilot, which are open-source flight controllers, also provide tail-sitter airframes as standard. The tail-sitter is particularly advantageous in its structural simplicity and the propeller used for vertical flight is also used for horizontal flight. However, in this case, the low pitch propeller in vertical flight does not generate sufficient thrust in horizontal flight. A duct can be used to increase the propulsion efficiency in a static state, and it is well known that the duct can produce an additional thrust of about 30-50% in existing studies. However, the duct has a disadvantage in that it generates drag during the forward flight, consequently, hinders high-speed flight. In this study, the optimal design of the ducted propeller considering both the vertical and horizontal flight modes of the tail-sitter type unmanned aerial vehicle is performed using computational fluid dynamics.

2 Methods

A simplified CFD analysis was performed to confirm the effect of the duct on the aerodynamic performances of the propulsion system. First, the duct shape was parameterized as shown in Figure 1, and the parameter test was performed numerically to see the performance change with the parameters.

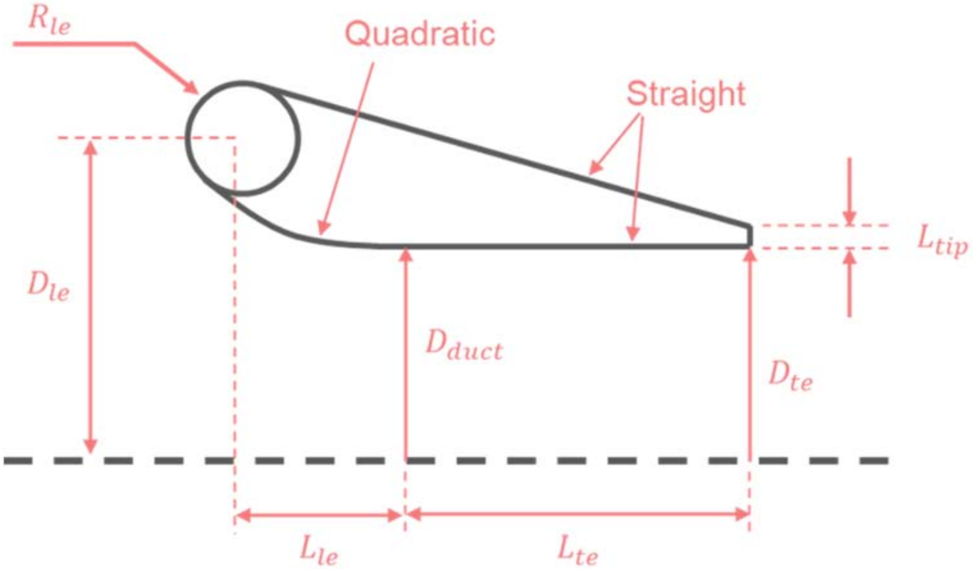

Figure 1: Parameters to define a duct section

Based on the basic characteristics of the duct identified through the simplified simulations, the duct shape was designed, and higher fidelity simulation was carried out. At this time, the flow field was initialized using MRF and the performance of the ducted propeller was evaluated using the sliding mesh technique. In particular, the performance between the open propeller and the ducted propeller were compared to see how much the thrust was increased. In the case of propellers, the aerodynamic performance was predicted by changing the pitch and chord distribution. The target thrust was set to 500N in a 30-inch-class propeller system to apply to a tail-sitter UAV with 25kg payload for the ducted propeller design. OpenFOAM, an open source CFD analysis tool, was used and a modified incompressible inviscous flow solver with improved stability and efficiency was developed and applied. The wedge type computational domain was used to run the simulation and cyclicAMI boundary condition was applied to both side patches, as shown in Figure 2. Once the parameters are given by a user, the mesh is generated automatically so that the entire parametric test process can be automated.

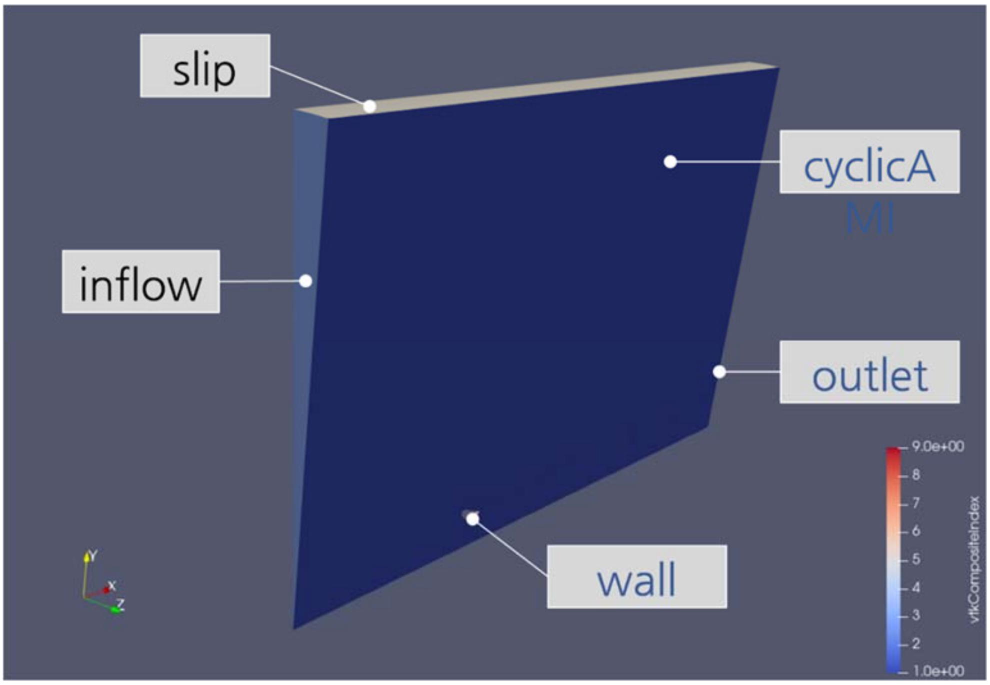

Figure 2: Computational domain

3 Results

Figure 3 shows the automated parameter test process.

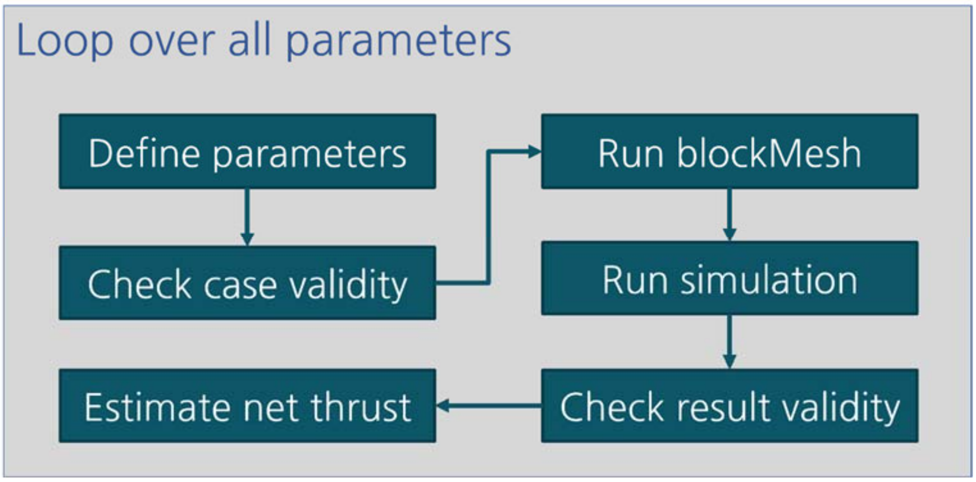

Figure 3: Parametric study process

We obtained analysis results for a total of 2,175 cases, and Fig. 4 shows an example of the flow field distribution around the duct section in the flow analysis. Depending on the duct geometry, recirculation areas may be found on the inlet side and at the blade tip. Figure 5 shows the relative total thrust with respect to the duct thrust ratio. In some cases, the performance of the thruster is deteriorated by the duct.

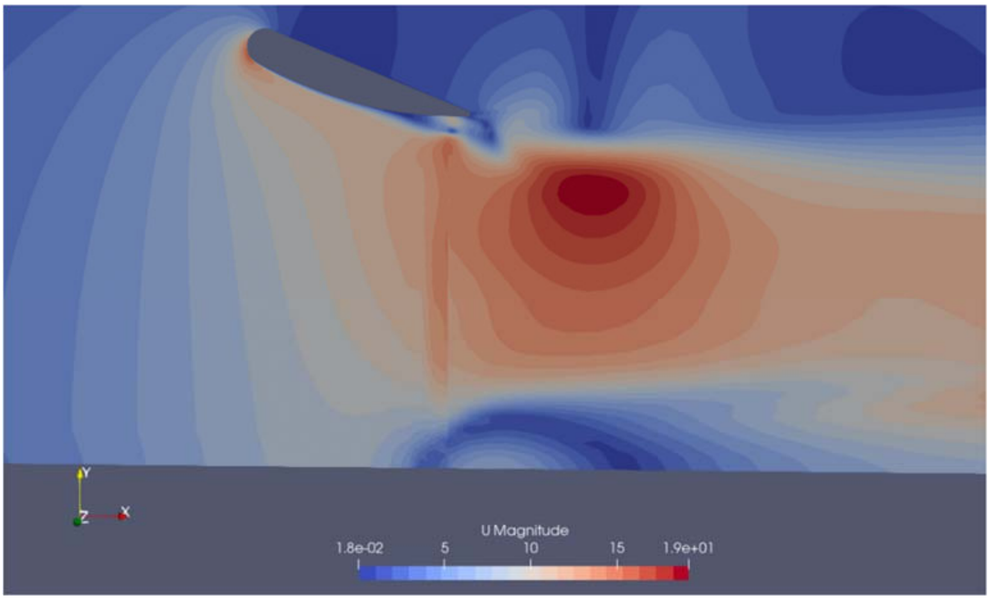

Figure 4: Estimated flow field around the ducted propeller by using the simplified analysis tool

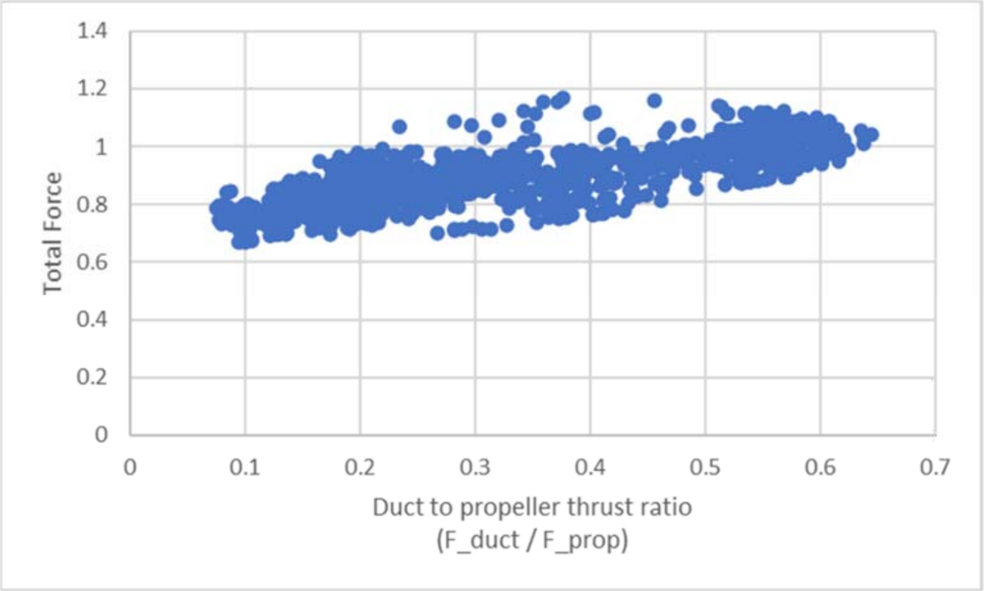

Figure 5: Comparison of total thrust with respect to duct thrust ratio

From the simplified results, we selected the optimal design candidates and applied the higher fidelity simulations to get the final ducted propeller design. In this case, we changed the blade pitch and chord distributions to find the optimal combination of a propeller and the selected duct. We saw that increasing pitch distribution may generate higher thrust but less specific thrust due to higher tip loading and heavy recirculation region near the tip from Table 1. Instead, increasing the chord distribution showed similar increment in thrust with better specific thrust.

RPM	Model	T N	Q N-m	P W	T/P g/W
3,000	Ref.	135.4	7.743	2,433	5.68
3,000	Inc. Pitch	157.2	11.027	3,464	4.63
3,000	Inc. Chord	157.4	9.720	3.054	5.26

Table 1: Comparison of ducted propeller with different propeller configurations

4 Conclusions and Contributions

The optimal design of the ducted propeller for vertical take-off and horizontal flight was performed. OpenFOAM was used for computational numerical analysis, and an incompressible and viscous flow solver with improved stability and efficiency was developed and applied. First, a simplified analysis model was applied to see the effect on the flow field according to the shape of the duct. Analysis was performed on about 2,000 cases, and the entire process was automated. As a result, it was found that the performance deteriorated rather than the open propeller under some conditions, and the duct length in the outflow direction was short and the converging or straight type duct was more efficient. Based on these results, an optimal duct candidate group was selected, computational numerical analysis was performed, and the performance of the ducted propeller was analysed. At this time, the thrust and efficiency according to the change of the propeller's chord and pitch distribution were compared, and more positive results were obtained when the chord was increased rather than the pitch distribution change.

Acknowledgements

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