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Design and Test of a Ducted Fan VTOL UAV

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Abstract. A 30-kg-class ducted fan UAV has been developed in this study, which has two ducted fans and one tail rotor. The transmission system, including several gearboxes, was designed for driving ducted fans by a combustion engine. For the attitude control of this UAV, a control concept has been proposed. The aerodynamic performances of ducted fan in hover condition have been investigated with the unsteady CFD method and ground test. A full-scale prototype was fabricated and hover flight tests have been carried out.

Keywords. ducted fan, UAV, transmission system, flight test

1. Introduction

The objective of this study is to develop a concept of vertical takeoff and landing (VTOL) unmanned aerial vehicle (UAV) which can be carried by ground vehicle and operated in scenarios not accessible to fixed wing UAV. The conventional helicopter UAV fulfill this requirement, but its exposed rotor ans high noise make it is not the optimal solution. Electric multi-rotor UAV is also not a preferred scheme for its short endurance time. Therefore the ducted fan UAV is selected as one of the preferred solutions for this application, with less danger to the operator and lower acoustic signature than other VTOL UAVs [1,2].

In this study, a kind of ducted fan UAV has been designed, which has two ducted fans and one electric driving tail rotor. For this UAV is used in tight quarters accompanying with ground vehicle, and hovering in one location to provide surveillance data continuously over a single area, the ducted fans are not needed to tilt to obtain high flight velocity [3,4]. The aerodynamic performance of designed ducted fan for this UAV has been investigated through numerical flow calculation, and a duted fan ground test system was also constructed for validating the calculated results. A full-scale prototype was fabricated and some preliminary hover flight tests were carried out.

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2. Configuration Design

2.1. Configuration of UAV

The specification of this ducted fan UAV is showed in Table 1, and in order to fit into transport vehicle and take off and land from its roof, the dimensions of this UAV are limited to carriage size. To meet the requirements of not less than two hours of endurance, internal combustion engine is needed to be the major power for this UAV.
Figure 1 shows the configuration of this UAV, and the dimensions of it is shown in Figure 2. This UAV have two duted fan for providing major flight lift, which is arranged on both sides of the front fuselage. It have a tail rotor, which is surrounded by a rigid protective annular ring, for pitch and yaw control and provide about 10% total lift in hover.

Table 1. Specification of Ducted Fan UAV

Parameters	specification	Parameters	specification
Length	≤1.8m	Max flight speed	≥80km/h
Width	≤1.8m	Endurance	≥2h
Payload	≥6kg	Gross Weight	30kg

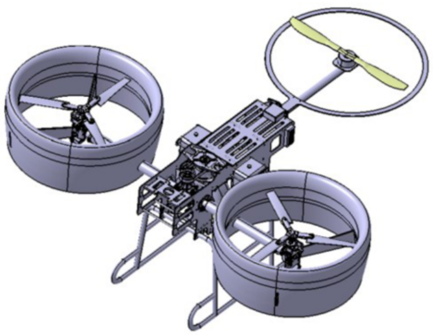

Figure 1. Configuration of ducted fan UAV

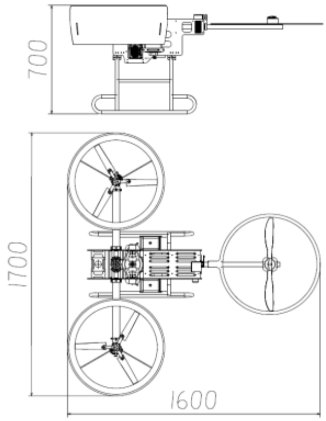

Figure 2. Dimensions of ducted fan UAV

2.2. Power System

To achieve the requirements of more than 2 hours endurance time, two ducted fan are driving by a 80cc two-stroke piston engine through mechanical transmission system, and the engine is mounted at the middle of the fuselage. The maximum engine power is about 5.51kW. The transmission system, as shown in Figure 3, consists of a pair of belt wheels, a transfer gearbox and two propeller driving gearboxes. The engine power is first transmitted to the upper input port of transfer gearbox through the belt wheel and synchronous belt, because of the belt drive can decrease the vibration from piston engine. The transfer gearbox transmits the input power to output ports on either side, through a pair of bevel gears. Two rigid shafts and four elastic couplings are used to connect the output ports of transfer gearbox and input ports of two propeller driving gearboxes and transmit the driving power. Each of the two propeller driving gearboxes contains a pair of bevel gears inside, they have the same gear ratio but different layout, to ensure the rotation direction of two ducte fan propellers is opposite. The working speed of engine is 7000 rpm, and the working speed of propellers is 6000 rpm, so the total transmission ratio is low, and the overall efficiency of this transmission system is assumed to be great. For the purpose of reducing transmission system complexity, the tail rotor is driving by a isolated electric motor instead of the piston engine. The electric motor is powered by a Li-ion battery, and because of the low tail rotor thrust requirement and small disc load, the tail rotor and driving motor are working in a high efficient condition, the battery weight is about 3kg for 2 hours flight and is acceptable.

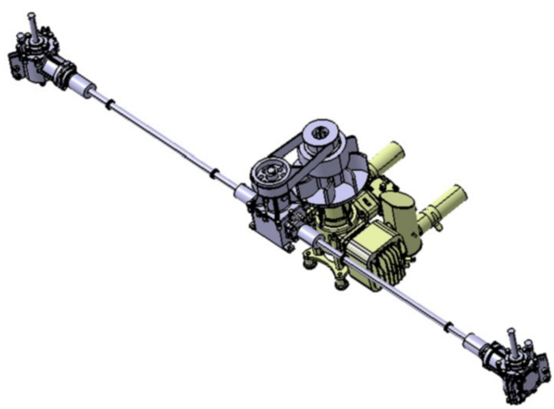

Figure 3. Transmission system of ducted fan UAV

2.3. Control Concept

As shown in Figure 4, the roll control of this UAV is realized by change the thrust of each ducted fan differentially, in the case of keeping the total thrust of this UAV unchanged. The speed of the ducted propeller is constant, and the thrust adjustment is achieved by varying the collective pitch of propeller blades. The pitch control is realized by change the thrust of ducted fans and tail rotor differentially, and the tail rotor thrust adjustment is achieved by changing the driving motor speed, just unlike the ducted fan. The tail rotor and its driving motor can tilt around the mounting tube, which is parallel to the longitudinal axis of the fuselage, by the control of tilt servo. So the yaw control is realized by tilt the tail rotor to generate horizontal yaw moment, in the case of keeping the vertical thrust of tail rotor unchanged.

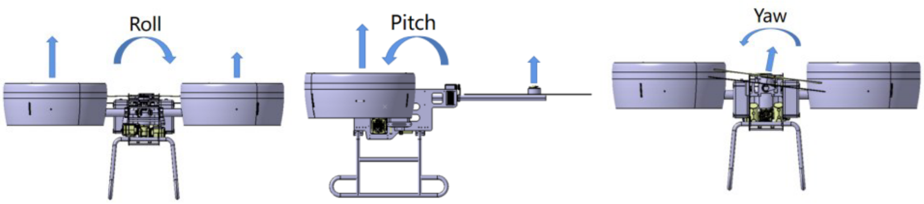

Figure 4. Control concept of ducted fan UAV

3. Design and Test of Ducted Fan

3.1. Ducted Fan Design

A ducted fan with three blades is used in this UAV, the geometric parameters is showed in Table 2.

Table 2. Specification of Ducted Fan

Parameters	Value
Duct outside diameter	620mm
Duct inside diameter	526mm
Disk diameter	520mm
Hub diameter	140mm
Duct length	250mm
Blade twist angle	22°

3.2. Numerical Analysis Methodology

By using the sliding mesh technique to simulate the propeller rotation, the aerodynamic performances of this designed ducted fan in hover condition have been investigated with the unsteady CFD method[5]. The whole flow field has been divided into static and dynamic parts and an interface was created to connect the two parts. The static domain contained the outer flow field and the duct, and the dynamic domain was the rotary inner part containing the propeller. As we wanted to evaluate the hover performance of the ducted fan, the boundary conditions of inlet, open and outlet were both set to pressure outlet with similar parameters to atmospheric environmental values. The structured mesh was used for the external static zone, the unstructured mesh was used for the internal rotational zone, and the prism mesh was applied to the duct and blades to simulate the viscous effect in the boundary layers. Figure 5 presents the meshes of the static and dynamic zones, in which the total numbers of mesh nodes are 3 million and 4 million, respectively. The k- ω SST turbulence model was adopted for better capture of the flow characteristics. For the boundary conditions, Figure 6 exhibits the settings in the static domain and the dynamic domain.

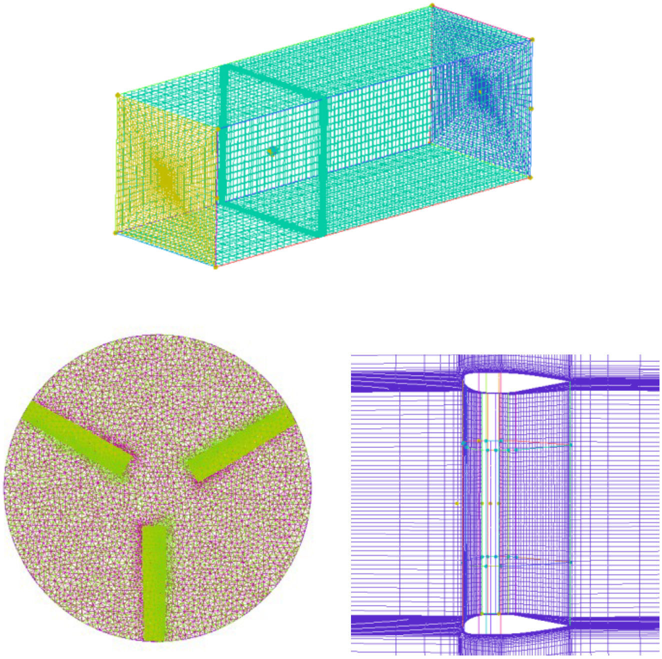

Figure 5. Mesh for numerical analysis of ducted fan

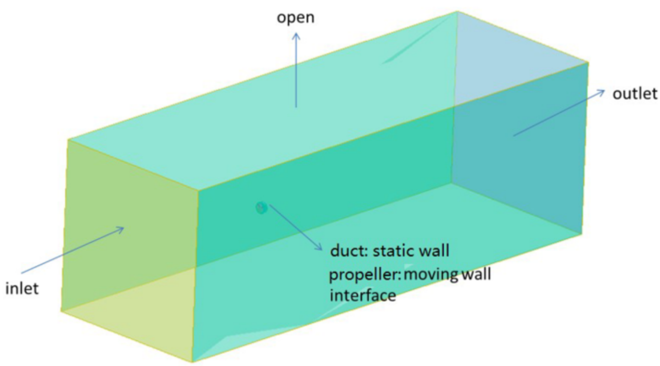

Figure 6. Boundary conditions for numerical analysis of ducted fan

3.3. Ground Test Platform

A ground test platform, which is shown in Figure 7, was established for validating the numerical calculated results for designed ducted fan. The platform was supported by aluminum profiles and the measured ducted fan was placed vertically. There were two types of sensors used to record the test data in real time,including the over all thrust and the torque of the driving motor. The speed of the ducted propeller is constant, which was controlled by the motor ESC (Electronic Speed Controller), and the collective pitch of propeller blades was adjusted by the servo.

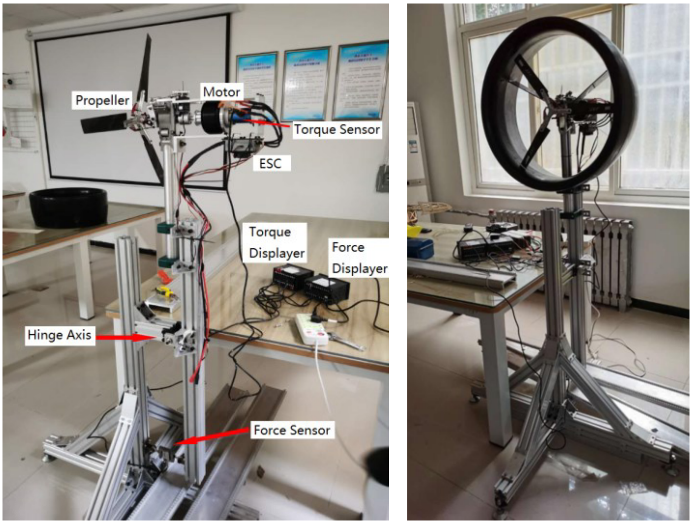

Figure 7. Ground test platform for ducted fan

3.4. Aerodynamic Performance of Ducted Fan

Figure 8 compares the numerical calculated results with test data for the ducted fan in hover, and the propeller rotate speed is 6000rpm. It can be seen that the numerical results agree well with the test data, and the maximum error does not exceed 5%. One possible reason for errors is the duct support and hub are ignored in the simulation.

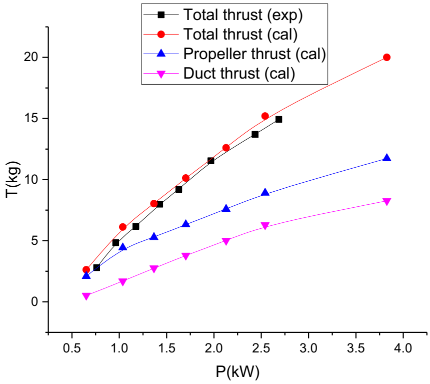

Figure 8. Power vs. thrust of the ducted fan.

It also can be seen that, the thrust required in hover condition for single ducted fan is about 12.6kg and the power required is about 2.2kw. The total power required for two ducted fans is less than the maximum continuous engine power, and the engine power also has certain surplus to meet the needs of maneuvering flight under the consideration of transmission efficiency.

4. Flight Test

A full-scale prototype of ducted fan UAV was fabricated after the design of power system and the ground test of ducted fan were finished. Figure 9 shows this prototype with a fuselage shell, and Figure 10 shows the mounting of transmission system gearboxes.

Figure 9. Full-scale prototype of ducted fan UAV

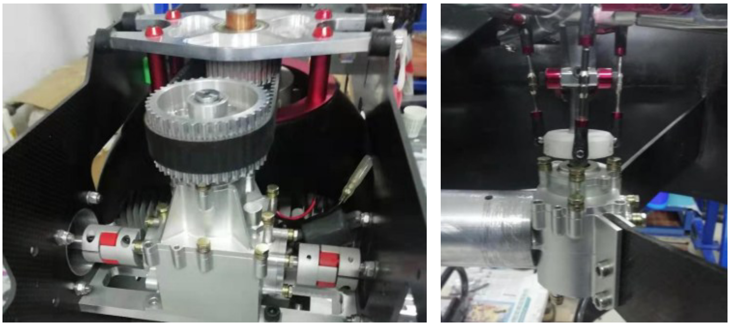

Figure 10. Mounting of transmission system gearboxes

Hover flight tests for this prototype with flight control system have been carried out, and it could takeoff vertically and hover stably without the safety line as shown in Figure 11. The feasibility of control concept, which has been described in section Ⅱ, and the loading capacity of this UAV were validated by hover flight tests. The flight tests are still in progress and further flight tests, including forward flight and endurance flight, are planned.

Figure 11. Prototype hover test

5. Conclusion

A small ducted fan UAV has been developed in this study, which can been carried by ground vehicle and operated in tight quarters. It has two ducted fans and one tail rotor for pitch and yaw control. For driving two ducted fans by one piston engine, the transmission system consists of several belt wheels and gearboxes has been designed. The ducted fan was designed for providing required thrust within engine power supply. The aerodynamic performances of ducted fan in hover condition have been investigated by using the sliding mesh technique to simulate the propeller rotation, and the calculated results were validated by ground test. A full-scale prototype was fabricated and some preliminary hover flight tests with the assistance of flight control system were carried out. The feasibility of control concept and the loading capacity of this UAV were validated by hover flight tests.

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