Design and analysis of ducted fan for multi-rotor VTOL UAV

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Abstract: The aim of this article is to analyse the use of electric drive ducted propeller in the vertical take-off and landing UAV objects. This paper is a typical design report focused on aerodynamic calculations. The main purpose of the project described in this article was to design a considerably more efficient electrical propulsion system for multi-rotor VTOL UAV units.
The first chapter describes the concept of a ducted fan drive for a multi-copter, our experience in propulsion systems design and an experimental VTOL unit which will be tested during flight tests.
The second chapter is devoted to the aerodynamic calculation methods used in design work. The used calculations methods like the panel method, the lifting line method with the Betz' law which allows to determine the maximum propeller efficiency, and Fluent CFD calculations are explained
The third chapter presents the results of calculations and the conclusions.

1. Introduction

Ducted propellers date back to the late fifties of the twentieth century. Alexander Lippisch built the first prototype named "Autodyne" The main body of the aircraft was a ducted fan itself. To eliminate resistive torque, two counter-rotating propellers were used. "Aerodyne" had the ability to l take-off vertically. Later on, there were many constructions using that kind of propulsion. Each case was different and showed all advantages and disadvantages of ducted propellers. The helicopter named "Gazelle 341" from the Aerospatiale consortium may serve as an example. The tail of that rotorcraft was equipped with a ducted fan. Ducted fan is used in the machines of this type due to the danger of damaging the propeller tail while the helicopter is close to the ground.

In 2002 in Toronto, at an international congress (ICAS 2002), Nikola de Divitiis, PhD, gave a speech about modeling and performance analysis of a specific type of UAV. The modeled object was very similar to the UAV produced by Sikorsky under the name Cypher. The axially symmetric model had two contra-rotating propellers in the centre of the UAV. The body of the vehicle was covering propellers, making duct-like geometry. The total weight of the UAV was 80 kilograms. One part of de Divitiis' task was to design the UAV's static thrust with the use of analytic methods. His analytic calculation showed that the ducted propeller in this case produced a lift force equal to 70% of the weight. The resulting values of the lift force and the drag force were equal to 30% of the UAV weight.

Summing up, it can be observed that ducted propellers have their advantages but also limitations. Basing on Hovey's work (Hovey, 1977) and our experience, we have prepared the following list of drawbacks and benefits:

Advantages:

1. Thrust can be increased by optimizing the section of the duct.
2. A duct forms a physical barrier, which protects the surroundings from the propeller's blades as well as the propeller from its surroundings
3. To achieve a performance comparable to that of a ducted fan, the simple propeller's diameter must be 30% larger
4. While the propeller's diameter decreases, the blade's tip speed decreases, therefore the rotation speed can be increased.
5. A duct functions as a sound barrier in some space surrounding the propulsion
6. The increased efficiency of the propeller is due to the increased effective aspect ratio of the blade

Disadvantages:

1. A ducted fan can be used only up to a certain velocity. If a certain velocity is exceeded, then the duct is just a drag source. That velocity depends on the duct's geometry.
2. The slot between the duct and the blade's tip is an important element. If the slot is too large, it negates all the advantages of using the duct. If it is too small, then it results in the blade hitting the duct when the duct vibrates and, therefore, it may damage the duct.
3. To eliminate friction, caused by a small gap, rigidness of construction should be increased. That results in the increase of the total mass of this type of propulsion system.
4. Production technology is highly complicated because of the axisymmetric duct. It is very difficult to find the ideal axis during the assembly of the duct, the propeller and the central body. Additional i tools are needed and, therefore, the production of a propulsion system is more expensive.

Fig. 1. Research object "SKYN8" in flight

1.1. Previous experience

1. A ducted fan design for the "PW-5" glider as an attempt for a moto-glider design – a Bachelor's Thesis
2. A ducted fan design for the "Uszatek" UAV moto-glider as a Master's Thesis
3. An analysis of a ducted fan for application in the multi-rotor UAV.

1.2. Research objectives

For the future flight tests we have designed and built a multi-rotor UAV. It is equipped with eight brushless, 230 watt motors. We have used 11.2 volts Lithium-Polymer accumulators and an IMU unit for flight stabilization.

2. Methods

Aerodynamic design of ducted propeller typically consists of four phases:

Firstly, based on J.W. Hovey's book (Hovey, 1977), duct for the propulsion system is designed. Hovey, basing on numerous field data, wrote an algorithm to design the initial geometry for ducted fan design. The algorithm determines the limits of the inlet, the outlet and the chord of the duct. After the selection of base geometry characteristics, the next step is to choose airfoil. Profile selection and analysis is made with the use of the XFoil program.

In propulsion system design of VTOL UAV the minimization of power consumption by the propeller is significant. It means that the airfoil section with a high Lift to Drag ratio and the optimal geometry of the propeller and the duct are the key elements for efficiency. The airfoil section analysis is performed in XFoil 6.9.

In the aerodynamic calculations of the low Reynolds numbers we also need to check the possibility of laminar bubble occurrence, which could be a reason for a dramatic

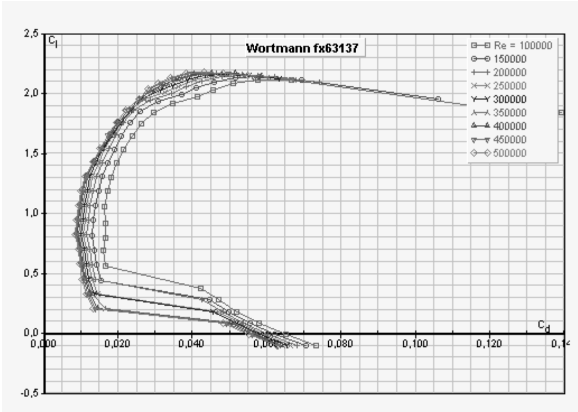

Fig. 2. Wortmann FX63-137 CL(CD) graph in design Re numbers

performance drop under real world conditions. In this case 12% thick Wortmann FX63-137 airfoil has been chosen due to its good aerodynamic characteristics in design of the Re number.

In the third phase we were using the Mark Drela DFDC 0.70 code, which has been written specially for ducted propeller optimization. It is a simple two dimension code where duct is modeled with the panel method scheme similar to the XFOIL method, and the propeller blade performance is determined by combining of blade element and vortex theory. Vortex theory with the Betz' and the Glauert law is used to optimize blade geometry for entering thrust, power, or torque.

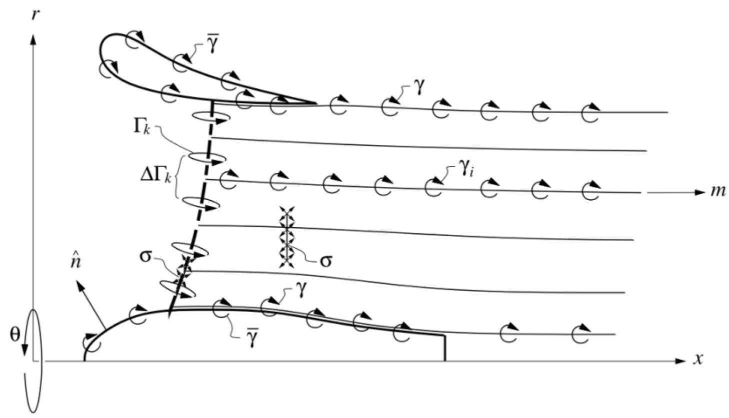

Fig. 3. Vortex representation of duct, center body, and propeller

The fourth phase consisted of a verification in ANSYS Fluent 12. Numerical representation of the problem consisted of two areas, namely of the far-field area

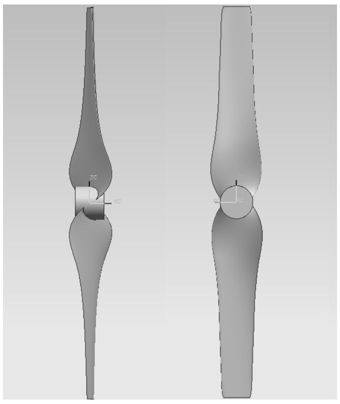

Fig. 4. Geometry of designed propeller

where the ducted fan and the central body were placed and of moving the reference frame of the propeller.

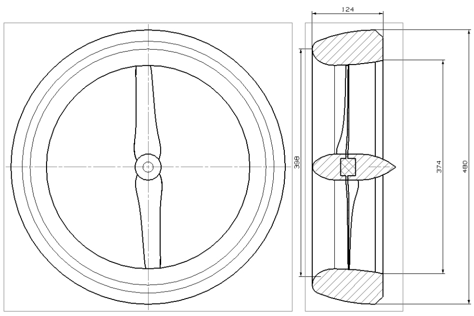

Fig. 5. Drawing of designed propulsion system

In order to verify the DFDC model we used the Realizable k-ε turbulence model, the Simple Pressure-Velocity scheme, the Least Squares Cell Based gradient discretization, the PRESTO! pressure discretization and the second order method for momentum, turbulent kinetic energy and dissipation rate.

3. Results and conclusion

Design of propeller for ducted fan propulsion system was performed in the DFDC code. Propeller geometry optimization is based on the Betz law. There are two variables for optimization: blade section angle and chord, optimization goal is to achieve the maximum thrust from a given power. As a result of calculations a 14" diameter propeller has been designed. Geometry was created in the Siemens UG NX6

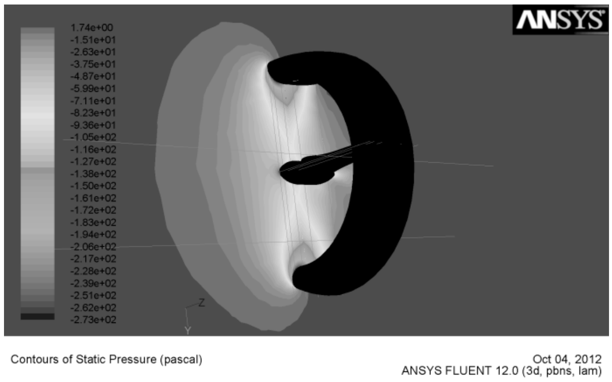

Fig. 6. Plot of static pressure contours

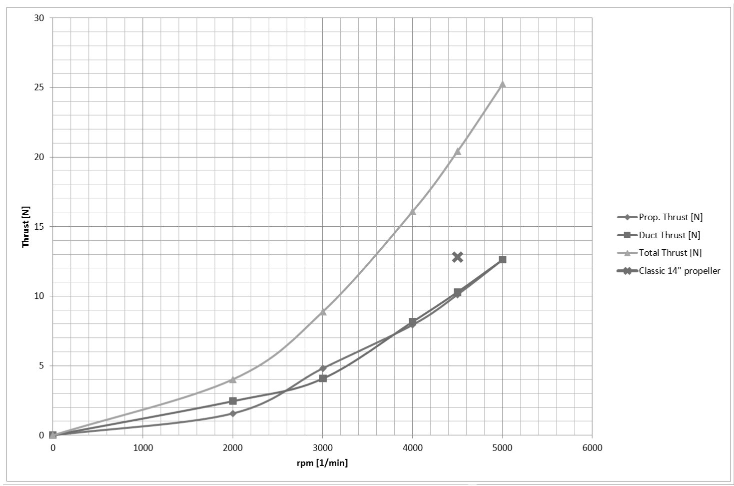

Fig. 7. Calculation results and comparison to classic propeller (x)

CAD system:

Initial geometry based on the geometrical proportions described in R.W Hovey's (Hovey, 1977) book. In the next step, duct geometry has been iteratively modified to achieve the maximum value of duct thrust in static conditions.

As a result of aerodynamic design, a project of a ducted drive has been created:

This type of ducted fan is specially designed for static and hovering conditions of flight and low speed flight, which is typical for the UAV VTOL objects like multi-rotors. Verification of design assumptions has been done with the use of Fluent CFD software.

The CFD calculations results confirmed the earlier calculations done in the DFDC code. We achieved a significant gain in static thrust in comparison to the classic propeller configuration. The improved performance of ducted fan is the result of minimizing induced drag in the propeller tip area and of the occurrence of high vacuum in the ducted fan inlet section. The additional pressure force which is formed at the duct inlet area is directed to thrust force so when we add these two vectors, we obtain a growth in total thrust. In this case, duct to propeller thrust ratio is 1:1.

The calculations described in this article, have confirmed the initial hypothesis concerning the validity of application of a ducted fan propulsion system in the UAV VTOL units. The obtained results were considerably better than expected. The main advantages of using of this drive include gaining a significant increase in static thrust - in comparison to the classic propeller we can achieve from 30 to 50% more of static trust. It is possible to reduce the electric power consumption, in hovering, by 35%.

There are also some disadvantages of ducted fan drive like structural complications, vibrations problems and weight gain, but modern composite materials could be a solution to these problems. Currently we are working on a ducted propeller prototype for flight tests and verification of our calculations.

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