

DESIGN AND OPTIMIZATION OF LOW SPEED DUCTED FAN FOR A NEW GENERATION OF JOINED WING AIRCRAFT

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Abstract

The Paper describes the process of design of a pusher ducted fan propulsion system for an unmanned aerial vehicle MOSUPS designed in a joined wing configuration.

Aerodynamic design followed by real time results obtained from tests in a wind tunnel have been described. Everything is summarized with conclusions showing what has been learnt from the whole design and research.

1 General Introduction

Ducted propellers and fans have been used since the 1930s. They have gained popularity in the 1960's, usually being used in experimental aircraft. Nowadays they are still quite popular in UAVs and VTOLs [1]. The main advantage of using ducted fan is the reduction of the induced drag, if the distance between propeller tip and duct is small enough. If properly designed it provides noise reduction compared to conventional propellers. The shroud also enhances safety. What is more the efficiency of such propulsion unit is higher for velocity of up to 45m/s.

The paper describes the overall design process and furthermore optimization of a ducted fan unit for a dynamic model of MOSUPS aircraft. MOSUPS program is a unique concept of a joined wing aircraft utilizing a ducted fan in a pusher configuration (Fig. 1).

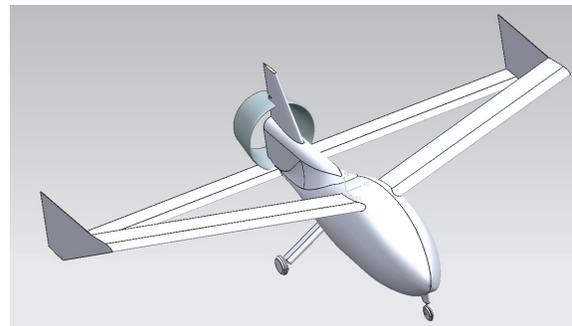


Fig.1 MOSUPS aircraft.
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2. Aerodynamic Design

2.1 Duct Design

This chapter describes aerodynamic design procedure of a ducted fan unit. Main task of the design work was to optimize propulsion system performance for aircraft's cruising speed flight condition. It was considerably difficult to determine optimization points, because at the beginning of design process weight of the airplane and values of angles of attack of lifting surfaces have not yet been fixed. After a careful analysis of the performance of the aircraft, expected design point has been defined for a cruising speed: $V_{\text{cruise}} = 25 \text{ m/s}$.

In the first stage of design work, duct geometry has been determined. Several 2D axisymmetric simulations of duct geometry for flight cruising speed velocity have been performed. Main goal of this stage was to achieve best values of vacuum in duct inlet area.

The curvature of the streamlines (Fig 2.) and the pressure drop at the inlet of the tunnel translates to obtainment of additional thrust on the inlet duct surface.

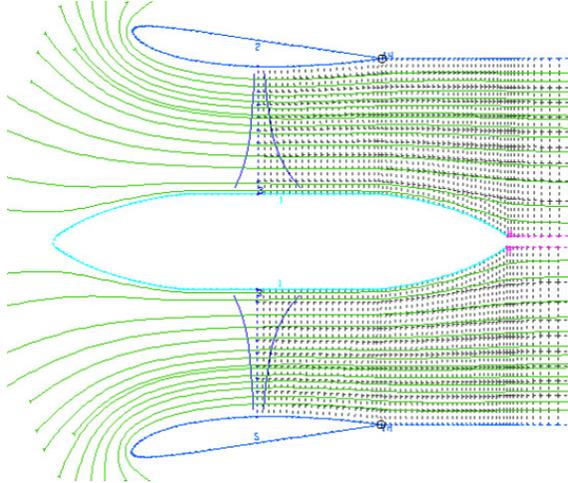


Fig.2 Curvature of the streamlines

For the development of duct geometry, research of Mr. RW Hovey [2] has been used. The author of the research has noted that for the same power, ducted propeller can achieve same value of thrust as an unshrouded propeller but with a square root smaller diameter of the propeller disk. Based on this data we were able to determine the optimal diameters of propeller disk, inlet and outlet sections. Typical inlet section contains between 1,05 to 1,15 of propeller's disc diameter, outlet section contains between 1 to 1,05 of propeller's disc diameter.

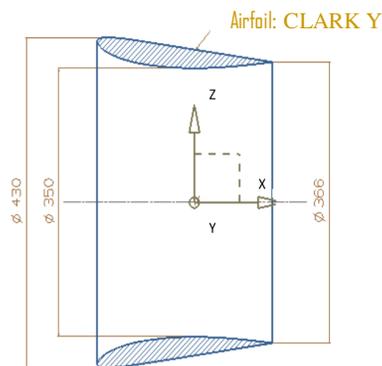


Fig.3 Final geometry of the duct

Fig. 3 shows final geometry of duct, which will be designated for structure prototyping and prefabrication.

2.2 Blade design

Second stage is blade design and verification loop. First iteration of design process starts with motor data and optimal airfoil search. There were two concepts of blade geometry, first one assumed typical “single solid” blade geometry with standard thickness airfoil. After weight analysis, we have decided to design single blades with thick airfoils (second concept). Such process is being presented in Fig.4

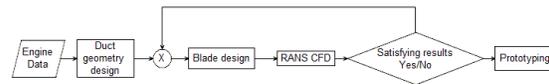


Fig.4 Typical blade Design loop.

The blade design of the ducted propeller stage lies between classical vortex/blade-element methods of Betz and Glauert, and a general 3-D vortex-lattice method. The chief advantage of the presented method is that it is extremely computationally cheap and has simple inputs, making it ideal for interactive design work. Such algorithms are implemented in prof. Drele's DFDC software.

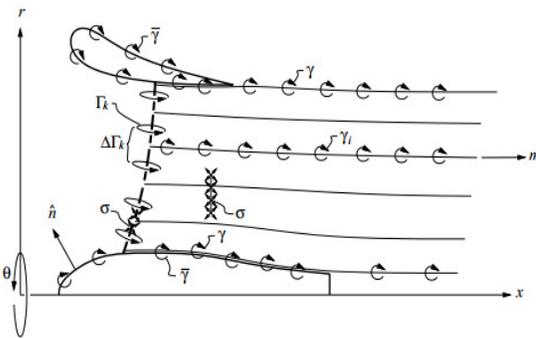


Fig.5. Flow modeling method with lifting line representation of propeller blades and panel method for duct and center body geometry

Blade geometry is optimized for prescribed design point which consists of free stream velocity, optimum motor rotational speed (RPM), airfoil data, brushless motor power and torque curve. During the design process, the influence of the number of blades and blade tip shape on the propulsion performance has been studied. There were several test cases. At the beginning 3-blade

propellers, with different blade tips have been tested. In the following steps 4 and 5- bladed rotors have been calculated. Best thrust to power ratio were given by 5-bladed configuration, which has been decided to be the final version.

Each blade configuration has been calculated using RANS CFD method. Numerical representation of problem consists of two areas: far-field area where ducted fan and center body is placed and a moving reference frame in which the propeller is placed. For verification of DFDC model we used Realizable $k-\epsilon$ turbulence model, Simple Pressure Velocity scheme, Least Squares Cell Based gradient discretization, PRESTO! pressure discretization and second order method for momentum, turbulent kinetic energy and dissipation rate.

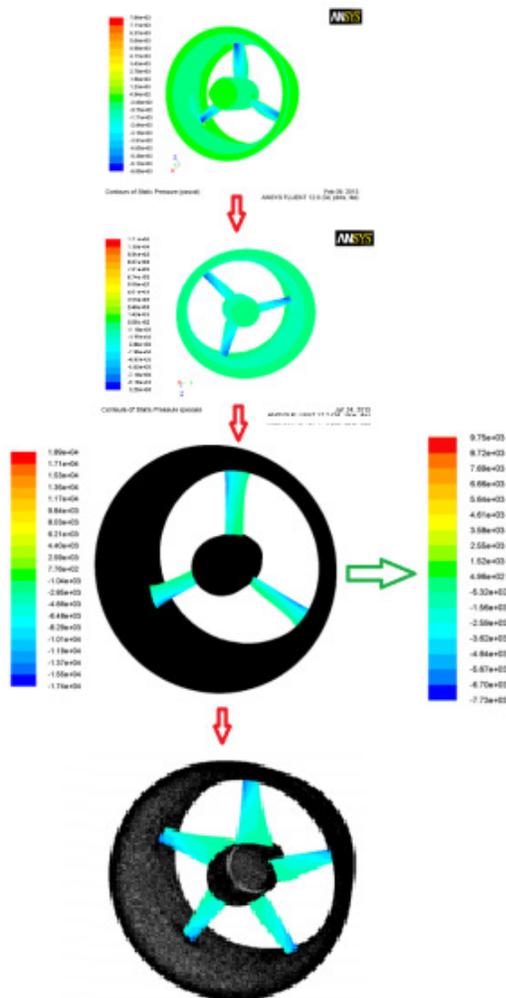


Fig. 6 Evolution of the design.

3. Tests of the propulsion system.

3.1 Ducted fan's internal structure

General concept of the ducted fan is shown in Fig. 7. The main parts are: The fan with a diameter of 0,35m, which consists of five composite blades (turquoise), lightweight composite duct with 12% CLARK Y airfoil (green), cylindrical casing for 3 kW electric motor (yellow), four control surfaces for vectoring the stream (red), aft fairing of the central body and two sets of cantilevers made out of CFRP tubes (blue) for fixing central body structure with the duct.

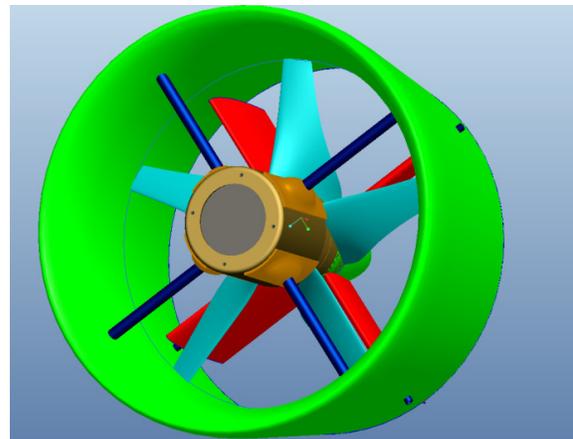


Fig.7 3-D view of the ducted fan

The duct is made from thin CFRP shells. In order to obtain sufficient stiffness, the structure of the duct is reinforced by 3 circumferential spars and additionally stiffener of the leading edge (Fig.8)

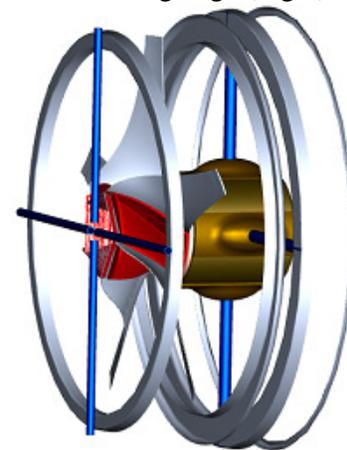


Fig.8 Internal structure of the Duct

3.2 Test stand

In order to fully assess the performance of the propulsion system a special test stand (Fig.9) has been designed. It enabled the acquisition of such data as motor torque (reaction force) and thrust. An Eagle Tree logger has been used in live mode to acquire the data from the load cells and additionally it measured the rotational speed of the motor's shaft, battery voltage and current (electric power).

What is more the test stand is equipped with a system which limits the maximum motor torque disabling the possibility of damaging the load cell.

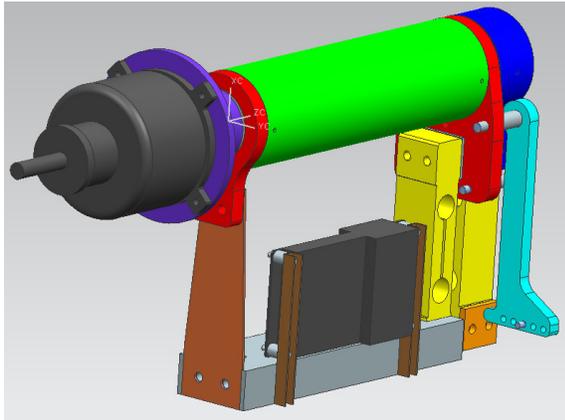


Fig.9 Test stand

3.3 Wind tunnel configuration

To simulate the conditions in which the propulsion system will be working in the aircraft, last 0,4m of the rear fuselage together with the vertical stabilizer have been modeled. What is more aft wing has been included with about one third of the wingspan. The front has been closed with nose. Additionally to the test stand and the wind tunnel's load cell, model also contains a National Instruments hub and batteries to power the motor and measuring instruments.

The load cell of the wind tunnel has been placed in such way as not to exceed its limits during the tests. Figure 3 shows the model placed in the 1,5m T-1 wind tunnel of the Institute of Aviation in Warsaw.

For power, a 3kW brushless electric Turnigy motor together with 120A Electronic

Speed Control unit has been used. Battery setup composed of 24 LiFe cells in 12s2p configuration (12 cells parallel, 2 in series) giving 44,4V fully charged.

As several different configurations have been considered, repeatability of the tests was necessary to get comparable data. A special program for running the motor has been made using the Lab View software.

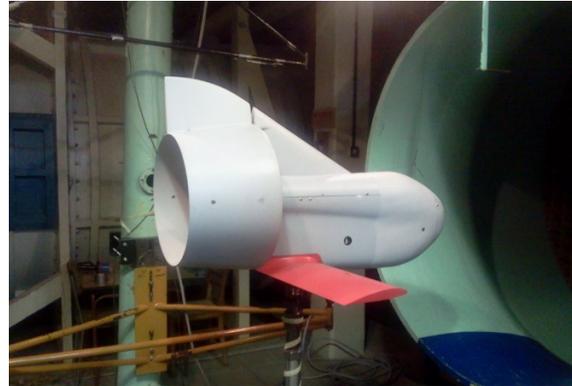


Fig.10 Wind tunnel test model

4. Tests

Due to the fact that several different configurations of the ducted fan have been considered such as the model with a typical propeller, the duct alone, with internal control surfaces, with a tail cone a carefully planned list of tests has been made.

As to fully test and compare the different configurations, few scenarios have been developed. An example of such is a full throttle test with the changes of angle of attack (AOA) ranging from $\alpha=-10^{\circ}$ up to $\alpha=+15^{\circ}$. In such scenario the model has been adjusted to one value of the AOA with the constant airflow (free stream velocity $V_t=25\text{m/s}$) and after the flow adjusted to steady-state the electric motor of the propulsion system has been turned on to maximum RPM for about 7-8s. Afterwards the AOA has been changed and the motor turned on again until every value of the AOA has not been tested.

Besides full throttle tests, 25%, 50% and 75% of the input signal, free spinning (wind-milling) with and without the electronic speed control brake and constant RPM have been tested. It all summed up to nearly 60 tests, not

taking into consideration the tare and measurements with erroneous results.

The acquired data from the wind tunnel's load cell is presented in Fig.11. This is an example of thrust in the function of number of samples for a single angle of attack. The final calculated value is the difference between the maximum value and the minimum steady (constant) value. Obviously the subtracted values have been averaged.

Similar results have been obtained from the load cells of the test stand. The differences between the values from the test stand and the wind tunnel load cells have not exceeded 10%, thus being self-validating.

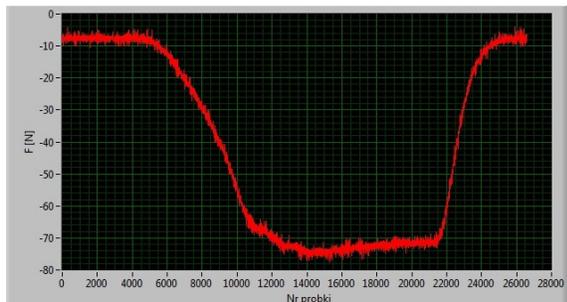


Fig.11. The result of the thrust data from the wind tunnel's load cell.

Fig.12 shows the final results of static thrust ($V_t=0$) and thrust at V_{cruise} ($V_t=25\text{m/s}$). As a comparison typical wooden propeller used in radio controlled model airplanes has been shown (20x10 Fiala prop). As can be seen, the unshrouded propeller has more thrust in both situations but with much greater input power.

		Test stand	Wind tunnel		
V_t [m/s]		Thrust [kG]	Thrust [kG]	Rotational speed (RPM)	Power [W]
0	20x10 prop	10	10,3	6950	2950
	Ducted Fan	8,5	8,4	6975	2675
25	20x10prop	7,2	7,1	7175	2850
	Ducted Fan	5,3	4,9	7275	2390

Fig.12 Test results for the base configuration

5. Summary and conclusions

It is essential to mark the fact, that the propulsion system has been designed without taking into account the influence of the fuselage and wing, which exist in front of the duct, it was designed as a stand-by unit.

Static thrust test results of just the ducted fan (without the fuselage body in the front of the duct) were about 25% greater than the results obtained with existence of the fuselage, and were almost the same as the ones of the 20x10 propeller.

It means that the flow around the fuselage and aft wing strongly affects the flow around the duct. In order to better design this specific propulsion system, a new more complex CFD model has to be evaluated.

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