Small Height Duct Design for 17” Multicopter Fan Considering Its Interference on Quad-copter

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Abstract

The 17 inch ducted fan with a 50mm height was studied in hover. Numerical simulations were provided by solving RANS equations with SST turbulence model using actuator disc with radial distribution of pressure difference according to numerical and experimental investigations of 17” propeller in hover. Optimal airfoil for axisymmetric duct was found. The 3D numerical simulations of four ducted fans interference were carried out. The geometry of duct was improved in term of power consumption considering interference of quad copter ducted fans.

1 Introduction

For the last decade multicopters became one of the most popular aircraft for the set of applications. These remotely piloted aircraft (RPA) can be used as cheap and safe devices for area monitoring from the air, security assistance, taking part in a rescue operations, inspection of defects in places that are difficult of access for human or robots. Moreover, multicopters are sufficiently stable, quiet and non-polluting aircraft with the low energy consumption in comparison with the other devices. One of the main features of such RPA is the ability to hover for a long time over same point. For the hovering time to be increased the energy consumption from the on-board energy source should be minimized while the propeller thrust remains constant. It could be provided by optimization of controllers and other electrical devises or increasing the propeller efficiency. The latter could be solved by installing the duct. Also duct protects propeller from contact with obstacles. For the study the 17 inch ducted fan with a 50mm height was chosen. Small height of the duct was chosen to satisfy the wind stability requirement. Thus the ducted fan thrust was set as 9N which is corresponding to the hovering regime.

2 Methodology

The principal functions of the duct are:

•Producing extra lifting force by the installing an airfoil at the appropriate incidence;

•Reducing the propeller induced drag;

•Protecting from contacts of the fan with surrounding obstacles.

Previous theoretical and experimental investigations give the following optimal parameters for a duct [1]:

•The front edge of the ring should be rounded and the rear edge must be sharp;

•Internal diameter of the duct should decrease firstly, then this diameter ought increase downstream;

•It is highly recommended to install the propeller in the narrowest part of the duct;

•The duct height b_a must be equal to 60% of propeller diameter D_p;

•The distance between duct front edge and propeller must be equal to 40% of duct height b_a;

•The optimal airfoil thickness is 18%;

•The airfoil incidence is 7°;

•The duct diameter D_d is equal to 1.26 of propeller diameter D_p.

The features described above are either represented in figure 1.

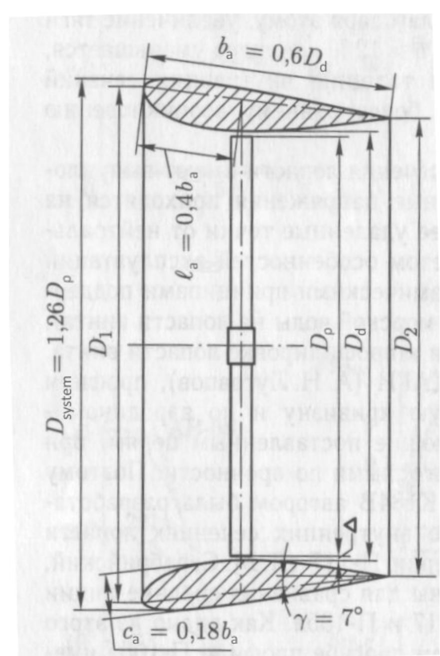

Figure 1: Features of a system.

However, these features are set for the high duct which is unacceptable for multicopters because of wind stability. It is very difficult for multicopter to balance sideforce, including side wind flow. Thus it was decided to consider the small height duct ($b_a \sim 10\%$) which combines rather acceptable wind stability and advantages of normal duct. Therefore the main objective of the investigation was to maximally decrease the power consumption for the constant ducted fan thrust.

Firstly the foil optimization was continued for the axisymmetric task. Previously found airfoil [2] was improved by 19% using neuronet methods of optimisation. The optimisation task was solved numerically using an actuator disk with a radial distribution of pressure difference which was found previously from the numerical simulation of the 17” propeller [3].

Next step is numerical study of the ducted fans interference on quad-copter and minor shape improvement. Numerical simulations were provided by solving RANS equations with SST turbulence model on 25mn structured mesh. Pressure difference radial distribution on the actuator disk was the same as in the airfoil optimisation task.

3 Axisymmetric task

Axisymmetric case was solved numerically using 2D structured mesh on the system of airfoil and actuator disc. The two-dimensional mesh which define 1 of the duct contains about 200 000 elements with wall cell thickness of 0.015 mm which provides maximum value of Y_{+}=0.932. As it was mentioned above the simulations were provided by solving RANS equations with SST turbulence model with the actuator disc. Surface of a duct was set as no slip wall. Every single simulation was stopped only after fixation of fourth significant digit in magnitude of the aerodynamic forces acting on a foil. The radial pressure difference distribution on the actuator disk was taken from the numerical simulation of the 17” propeller in hover [3]. The pressure difference on the quarter chord line of the propeller and approximation function is given in figure 2. Thus the approximation function was:

$$\triangle p = k*(23922*r^2-861*r+52)*(th(72,5r-0.21125)+1) \tag{1}$$

where r is a local value of radius. The maximum deviation of approximation function therefore is less than 0.5%. In each separate solver task the thrust remained constant at 9N by increasing or decreasing coefficient k of pressure difference on the actuator disk.

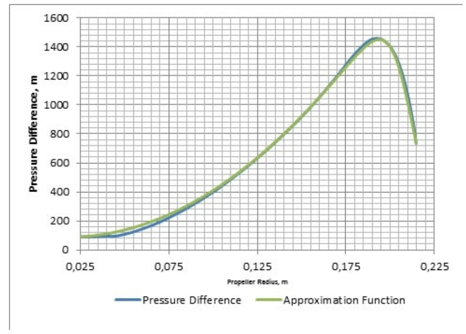

Figure 2: Pressure difference between upper and lower surfaces of the propeller on its quarter chord line.

During the previous and present studies, the main foil feature was understood. For such a small duct height it is not possible to develop a classical duct with an appropriate front edge to turn the flow and diffusor behind the propeller. Only one part could be used. If diffusor will be set alone the separation on its front edge will not allow diffusor to work optimally, moreover, in some cases, it is not working at all. Thus the main feature of the airfoil for small height duct should be turning of the flow to air ram on the propeller approximately perpendicularly.

Optimization task was based on varying of 51 parameters: one parameter is leading edge radius and other 50 are foils coordinate points. The optimization task was provided in 2D case with setting the mass flow, which corresponds to the mass flow obtained from the propeller simulation [3], over the upper surface of the airfoil. Airfoil which gives maximum thrust was chosen for the follow-up study. The foil obtained is shown in figure 3. This airfoil was also studied for two parameters: optimal position of the actuator disk along the chord and optimal incidence of the airfoil.

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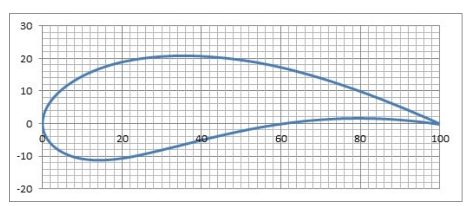

Figure 3: Airfoil obtained from the optimization task.

To find the optimal position of the actuator disk it was set consecutively from the front to the rear edge of the airfoil with a step of 0.1 of foil chord b_a. The results of the simulations are given in figure 4. According to the airfoil angle of incidence (23,56 for this case) the function of the power consumption is in good agreement with the postulation of the installation of the propeller in the narrowest part of the duct

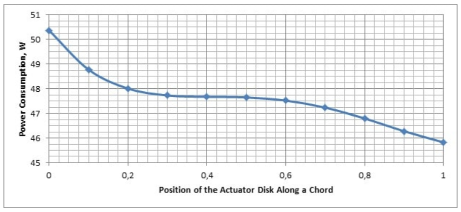

Figure 4: Power consumption as a function of actuator disk position along the airfoil chord.

Firstly airfoil obtained was set to the angle of incidence of 45.6 as a previously studied foil [2] and then was consecutively decreased with a step of 2 up to 17. The function of the power consumption is represented in figure 5.

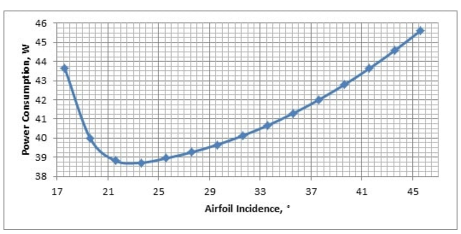

Figure 5: Power consumption as a function of the airfoil angle of incidence.

It is well enough seen that the minimal power consumption is 38.68W in comparison to 47.24W on the propeller alone. The power consumption decreases until the leading edge separation occurs on incidence of 21.6 then it significantly increases. The pressure coefficient distribution and separation on the leading edge depending on angle of the foil incidence is shown in figures 6-8.

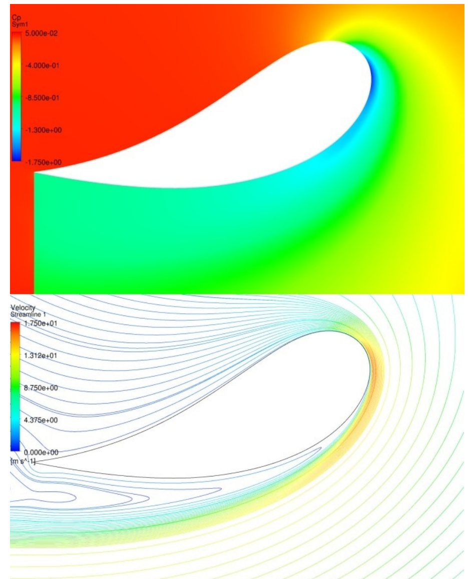

Figure 6: Pressure coefficient distribution (upper). Separation on front edge (lower). Angle of incidence 17,6°

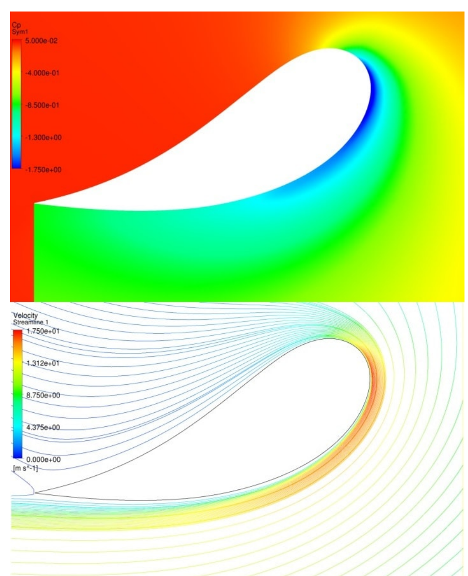

Figure 7: Pressure coefficient distribution (upper). Separation on front edge (lower). Angle of incidence 21,6°

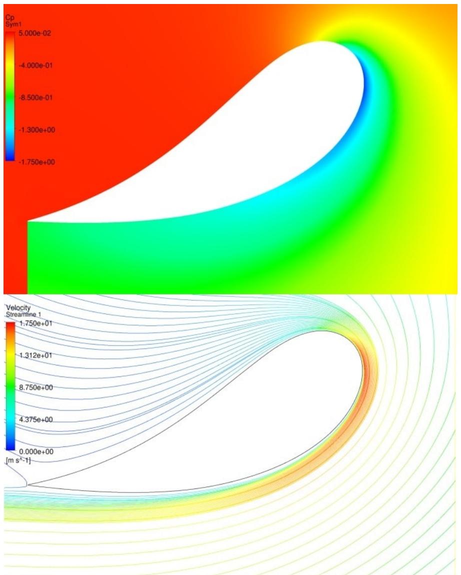

Figure 8: Pressure coefficient distribution (upper). Separation on front edge (lower). Angle of incidence 25,6

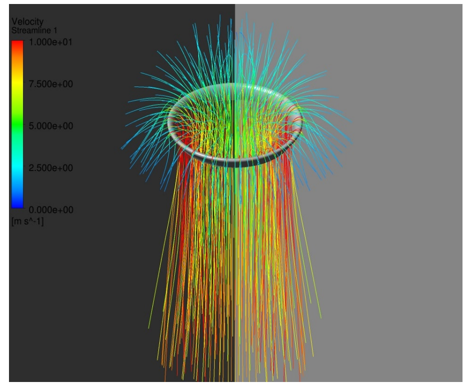

Figure 9: Streamlines that passes the actuator disc.

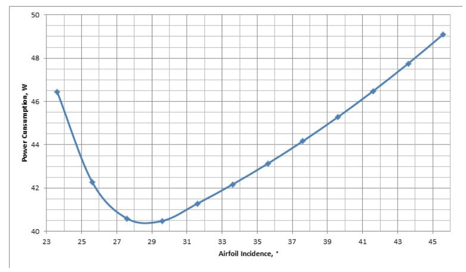

Figure 10: Power consumption as a function of the airfoil angle of incidence in 3D case.

4 Duct shape optimization considering its interference on quad-copter

The interference of four ducted fans was studied numerically using rotational periodicity symmetry conditions on the planes of geometrical symmetry. The structured meshes for the analysis have cylindrical C-H grid topology and contain about 25 million cells with wall cell thickness of 0.01 mm which provides maximum value of $Y_{+} = 0.759$. As it was mentioned above the simulations were provided by solving RANS equations with SST turbulence model with the actuator disc with radial pressure difference distribution. Surface of a duct was set as no slip wall. Every single simulation was stopped only after fixation of fourth significant digit in magnitude of the aerodynamic forces acting on a duct.

Axisymmetric duct with airfoil obtained was simulated. Due to the geometrical features of the case the flow pattern slightly differ from the 2D case. The local angle of attack averagely increases by 6 because flow that passes the actuator disc in this case comes from the quarter of the space above duct (figure 9) in distinction from the axisymmetric case where flow comes from the entire front half sphere. Thus the power consumption dependency from the foil incidence became to the following view (figure 10):

The dependency shows sharp decrease from 23.56 to 27.56 degrees of incidence. After that there is a steady growth of power consumption. The minimum power consumption for the case of interference increased by 1.8W up to 40.5W. In comparison the power consumption of propeller in the case of interference is 49.6W.

Figures 11-12 represents fast flow junction. Nearby in one diameter below the duct streams from all four ducts attaches to each other and then evaluate as a one stream.

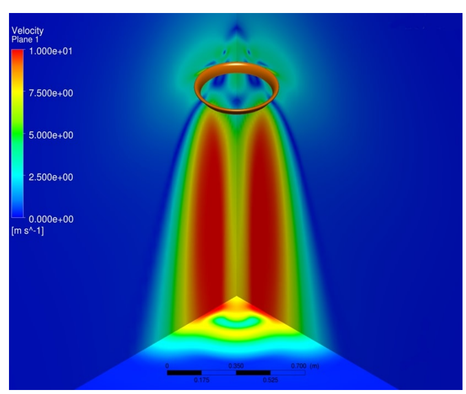

Figure 11: Velocity distribution on the symmetry plane and plane 1.5m under duct.

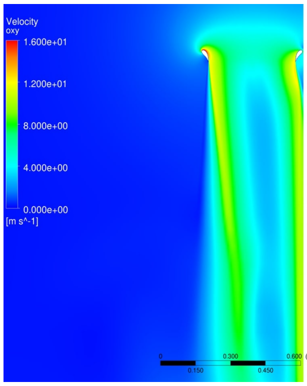

Figure 12: Velocity distribution on the plane parallel to XOY at the maximum radius placement.

The flowfield near the planes of symmetry necessitates varying the foil incidence in this area. The strong pressure increase occurs on the duct inside surface that lead to increase in power consumption to provide thrust of 9N. Typical Cp and velocity distributions in this section are represented in figures 13-14.

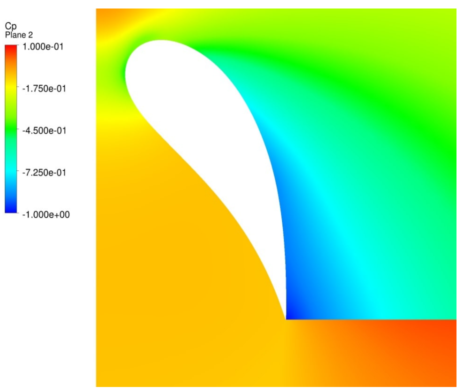

Figure 13: Pressure coeffitient distribution on the foils nearest to the symmetry.

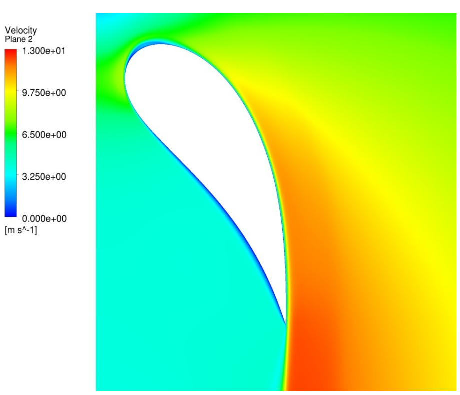

Figure 14: Velocity distribution on the foils nearest to the symmetry.

The resulting amounts of power consumption for the different angles of incidence of foil nearest to the symmetry plane are given below. Thus the optimal angle of incidence of the foils closest to the symmetries is 19.56 degree and the lowest power consumption appears to be 39.69 watts.

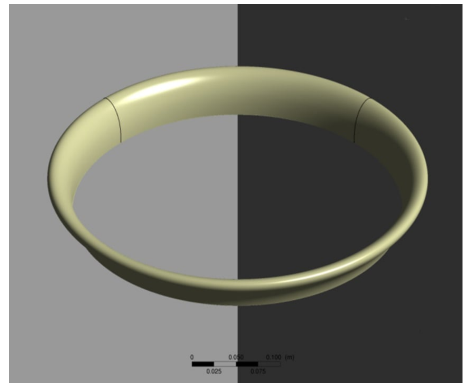

Figure 15: Airfoils nearest to the symmetry planes.

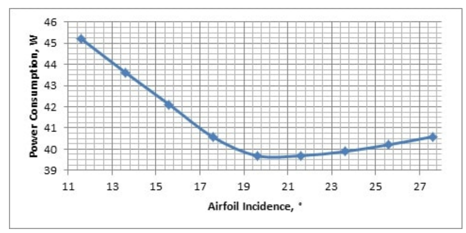

Figure 16: Power consumption as a function of incidence of airfoil nearest to the symmetry.

5 Conclusion

New airfoil for a small height duct obtained, the results of its simulation is in good agreement with an experimental data and represent an improvement over the previously published. The method of radial pressure difference distribution showed better agreement with an experimental data previously published. The method is thus very promising.

The optimal position of the propeller and foil incidence are found. The behavior of the flow for a different foil incidences described.

The power consumption on quad-copter in hover decreased by about 20%. The methods of the future study of the ducted fan interference are found.

References

[1] S.P. Ostrouhov. *Propellers and Ducted Fans Aerodynamics*. FIZMATLIT, Moscow, 2014.

[2] Arkhipov M.E., Serokvhostov S.V., Semelin A.E., Ageev N.D., and Volkova A.O. Design of ducted fans of small

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[3] Arkhipov M.E., Serokhvostov S.V., and Streltsov E.V. Experimental and numerical study of propeller in hover. In *2nd Extremal and Record-Breaking Flights of the RPAS and the Aircraft with Electrical Power Plant*, 2014.