Design of Ducted Fans of Small Height for Multicopter

*Arkhipov M.E., Serokvhostov S.V., Semelin A.E., Ageev N.D., Volkova A.O.**
** Moscow Institute of Physics and Technology, Department of Aeromechanics and Flight Engineering*
16, Gagarina str., 140180, Zhukovsky, Moscow Region, Russia

Abstract
Investigated is the ability of the usage of small height ducted fans in multicopters for increase in the hover time and protecting the propellers and surrounding. A set of numerical and experimental investigations concerning duct aerodynamics and efficiency of electrical part (drive, speed controller, accumulator) was conducted. The effects of interference between two ducted fans situated close to each other are also investigated.

1. Introduction

Multicopters are promising aircraft for the set of applications. These remotely piloted aircrafts (RPA) can be used as cheap and safe devices for taking pictures from the air, security assistance, coordinating 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 aircrafts with the low energy consumption in comparison with helicopters. The main feature of such RPA is the ability to hover for a long time over some point. From this point of view one of the main multicopter characteristics is hover time. It implies that the energy consumption from the onboard energy source must be minimized. For a number of reasons, electrical drives are used in multicopters and the energy source is the accumulator. The energy consumption minimization implies the efficiency maximization of each part of powerplant and a powerplant as whole. For the set of applications, the multicopter propellers as well as the surrounding environment must be protected from the contacts with obstacles and from rotating propellers, respectively. One of the solutions is to use the so-called “ducted fans”. On the one hand, the mass of the duct increases with the height increase. In addition, the high duct has worse performance in the presence of wind. On the other hand, with the duct fan height decrease the aerodynamical efficiency of the ducted fan decreases. The ducted fan must also fit the electrical part of the powerplant to provide the maximal efficiency. The outer diameter of the duct was set as 17 inch and the height of the duct was chosen as 5 cm for the investigation, and the thrust of the ducted fan was set as 9N.

2. Methodology

There are two main parts of the ducted fan. One of them is the duct or the "ring". The other part is the fan or propeller.

The principal functions of the ring are

1. Producing extra lifting force.
2. Reducing the tip vortex of the propeller due to the small gap between the propeller and the duct.
3. Protecting from contacts of the fan and surrounding obstacles.

Experimental and calculating research carried out previously permits to formulate some features of the duct shape that makes it possible to increase efficiency of the ducted fan:

1. The front edge of the ring should be rounded and the rear edge must be sharp.
2. Internal diameter of the duct should decrease firstly, then this diameter ought increase along the flow direction.
3. It is recommended to install the propeller in the narrowest part of the duct.

However, these features are made for the high duct (the duct height is about from 50 to 80 per cent of the propeller diameter). Small value of the ring height gives an insignificant contribution to efficiency of the ducted fan. So, the short duct was not investigated much before. The high duct is unacceptable for multicopters. Therefore, the "short" duct is considered as the ring for the multicopter propellers.

The main purpose of the investigation was to minimize the power consumption for the fixed thrust of ducted fan. The other way to compare two ducted fans is to use so called “figure of merit” or “hover efficiency” η defined as

$$\eta = \sqrt{\frac{2}{\pi\rho}}\frac{T^{1.5}}{PD}$$

where ρ – air density, *T* – thrust, *P* – power consumed, D – outer diameter of the system.

3. Numerical investigation

In the numerical investigation it was assumed that propeller was modeled as the "actuator disc" to increase the calculation speed. The actuator disc is the simplest model that simulates the working propeller. However, this model is capable to produce practically meaningful results. This disc is the infinitely thin disc that provides an axially symmetric pressure difference between two sides of the disc. There are only two components of air velocity that can be produced by the actuator disc: axial and radial. That means that there is no the axial twist. Thrust of the actuator disc was equal to 9 N.

In the research the duct cross-section shape, the angle of the duct installation and the actuator disc position were varied and optimized to provide maximal efficiency.

Firstly, flow created by the actuator disc without the duct (the diameter is 17 inch) was computed for better understanding of the flow character. Then, some airfoil sections were selected for the duct section and flow around the duct was calculated.

It was decided to consider the "two dimensional" problem. The model of the ducted fan was constructed as a sector with the angle equaled 1°. The computational domain of the flow around the ring contains structured mesh that was built using software ANSYS ICEM. Fig. 1 illustrates the mesh used in the calculation.

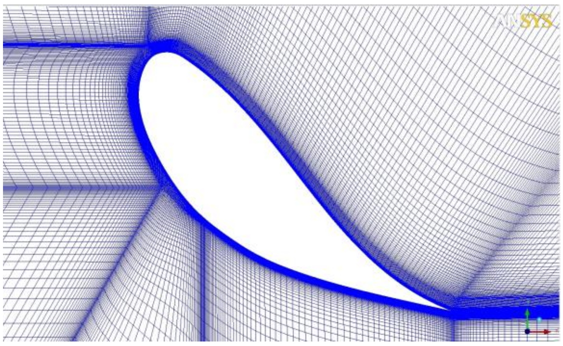

Fig.1. The mesh that is used.

The size of the cells on the model surface along the air stream does not exceed 1 mm. Also, the size of the cell thickness near the duct surface is 10^{-3} mm. The cell size growth ratio is 1.1, which provides sufficiently detailed simulation. The total 2D grid has about 150 thousand nodes. Designed mesh provides Y+max = 0.42.

The boundary conditions on the walls of the computational domain are set up as: all the walls except for the duct, the actuator disk and the symmetry are opening walls where the temperature and pressure equaled 297 K and 1 atm respectively. The duct surface is the no slip wall and the actuator disk is the interface with the pressure difference that supplies thrust of the disc (9 N). RANS system of governing equations with the SST turbulence model was calculated by the solver ANSYS CFX. Solving was conducted with a incompressible viscous fluid model of air (Ideal Gas).The problem was solved as the transient problem with the advection scheme (High Resolution), the transient scheme (Second Order Backward Euler) and the turbulence numerics (High Resolution). Time step equaled $2\cdot10^{-3}$ s that provided Courant Number equaled about 15 in average. One problem solving took 1000 iterations and the whole time of the process is 2 s. RMS residual for each equation was less than 10^{-5} at the end of solving. That means the solution was converged reasonably.

There are some possible negative phenomena in flow around the ducted fan:

1. Flow separation on the front ring edge.
2. Inefficiency of the front part of the duct.
3. Flow separation on the rear ring edge.
4. High flow compression after the disc.

It is necessary to carry out the analysis of the phenomena above mentioned and receive following information about the system "the duct − the disc":

1. Integral characteristics: thrust of the ducted fan *T* and power *P* that is spent to accelerate airflow through the actuator disc.
2. Streamlines (to make a diagnosis of a flow separation).

3. Distributions of pressure *p* and velocity *v* to analyze the air compression and estimate effectiveness of the front part of the duct.

If there is the pressure difference between front and rear sides of the actuator disc nearby the outer edge of this disc, there is backward flow of air through the gap between the disc and the duct. So, there is the toroidal vortex in the disc edge and it would be more acceptable if influence of this vortex on airflow is minimized. In order to realize this idea, the duct was designed with the groove which has the diameter 2 mm. The duct edge was located in the center of the groove. The shape of the duct and the position of the groove and the disc were varied.

4. Results of numerical investigation

At the first step, the actuator disc without the ring was considered and calculated in the numerical investigation. Efficiency of the disc equaled 78.09 per cent. The next step was to select several airfoil sections for the duct section (e.g., e385-il 8.41%, goe464-il, goe523-il, some sections were designed using streamlines). It is shown the velocity distribution for some duct shapes of this series in Fig. 3. The dark line in Fig.3 is the position of the actuator disc.

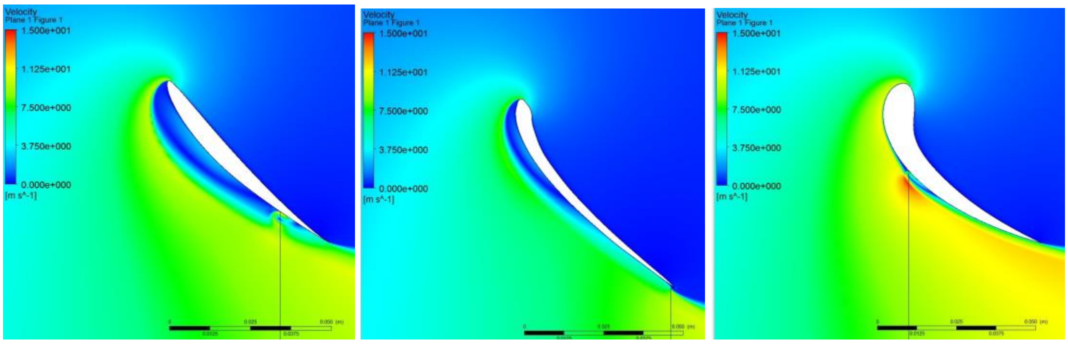

Figure 2: Velocity distribution of airflow for different shapes of the duct.

Further, the airfoil section goe523-il was chosen as it showed the best results at that stage of the investigation and calculated with variations of the disc position (0 mm, 12.5 mm, 25 mm, 37.5 mm and 50 mm along flow direction from the front edge of the duct) and the angle of the airfoil section (40°, 50° and 60°). Fig. 3 presents the velocity distribution of airflow around the duct (goe523-il) with the different disc positions and angles; and Table 1 demonstrates efficiency of each case for these variations.

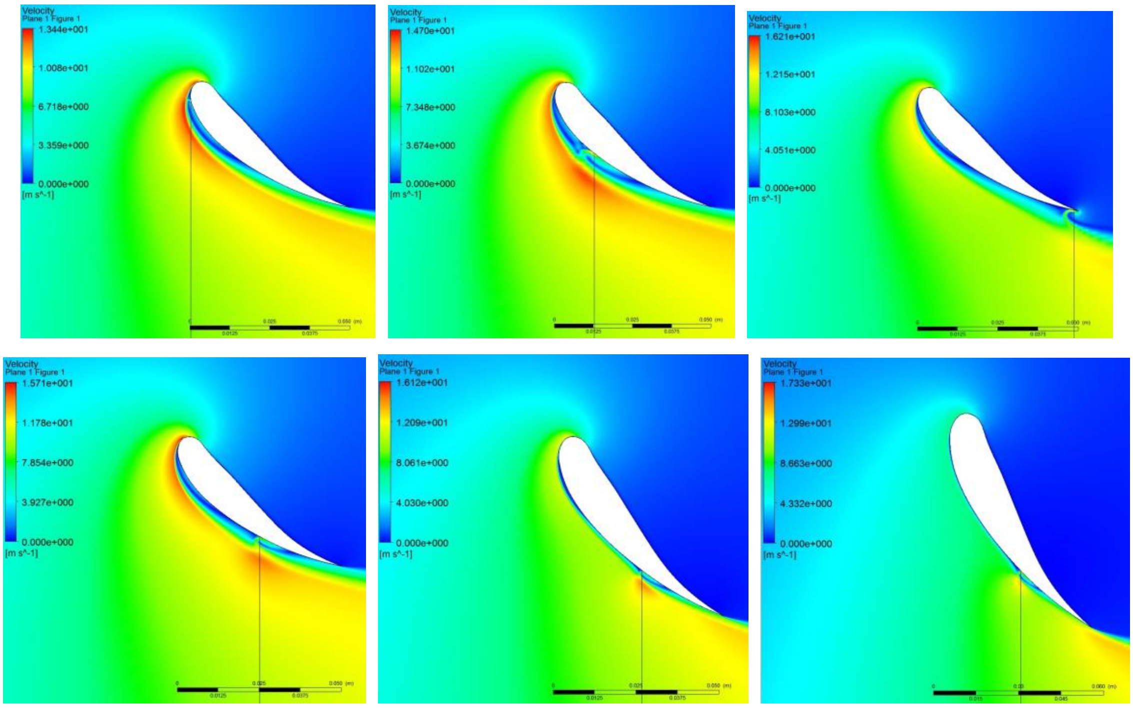

Fig.3. Velocity distribution of airflow around the duct (goe523-il) with the different disc positions (0 mm, 12.5 mm, 50 mm) and angles (40°, 50°, 60°).

Table 1: Efficiency η (%) of the ducted fan (goe523-il) in the variations

	0 mm	12.5 mm	25 mm	37.5 mm	50 mm
40°	77,28	76,97	76,96	74,00	72,93
50°	70,51	70,03	70,31	70,70	66,14
60°	60,51	59,95	59,99	60,50	57,44

It can be seen from the Table 1 that increase of the angle more than 40° leads to change for the worse of the ducted fan efficiency. The angle 30° was not considered because there would be a flow separation on the front edge of the ring according to Fig.3 that means low efficiency of the system. The acceptable actuator position for the duct (goe523-il) turned by 40° is on the front edge. However, the efficiency for this ducted fan less than the actuator disc efficiency without the duct.

In order to reach better results, the duct sections were obtained analyzing streamlines, velocity and pressure distributions of flow around the airfoil goe523-il. These ducts showed better effectiveness and some of them are illustrated in Fig. 4.

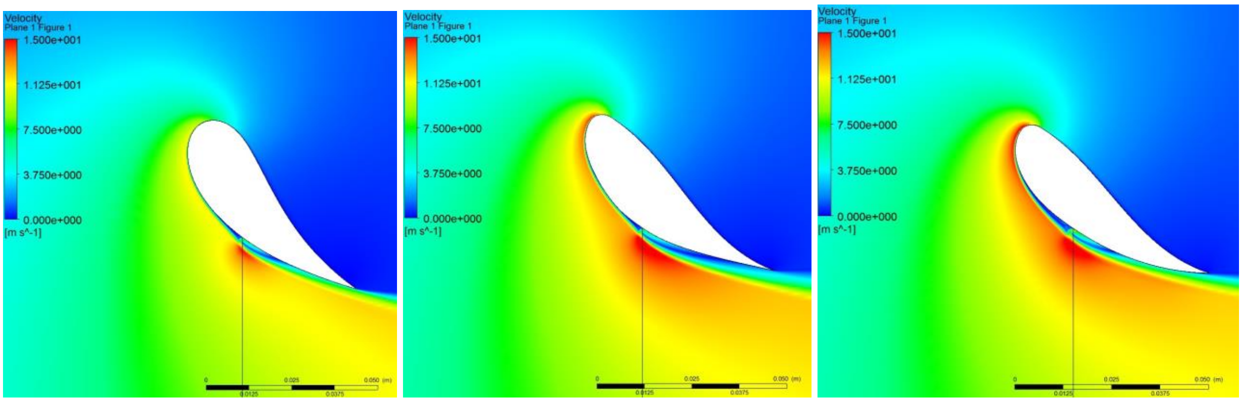

Figure 4:. Distribution of velocity around the ducts. Fan efficiency is 77.04, 77.9 and 78.8 per cent.

For the last duct in Fig.4, it was found the optimal position of the actuator disc. Table 2 presents dependence of this ducted fan efficiency on the disc location.

Table 2. Efficiency η of the third ducted fan in Fig.5 depending on the disc position x.

x, mm	10	12.5	15	25
η, %	78.6	78.71	78,8	77.69

One of the best duct shape, the actuator disc position (x = 15 mm) and efficiency (78.8 that is higher than the only disc efficiency 78.09) were found and shown in Fig.5.

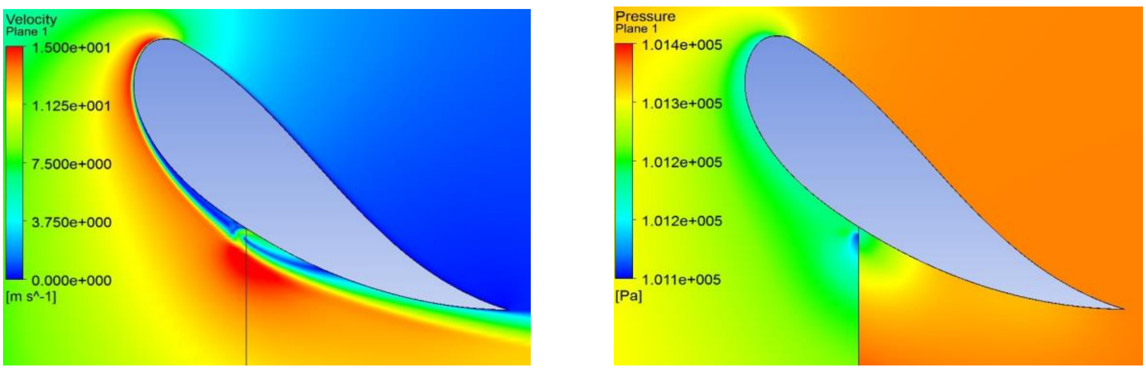

Figure 5:. Velocity and static pressure distribution of one of the best ducted fans (η = 78.8).

Reducing of the toroidal vortex influence on flow around the duct using the groove and careful analysis of recent results provided the ducted fan efficiency equal to 81.02 per cent that is much higher than the best one without the groove. This ducted fan is demonstrated in Figure 6.

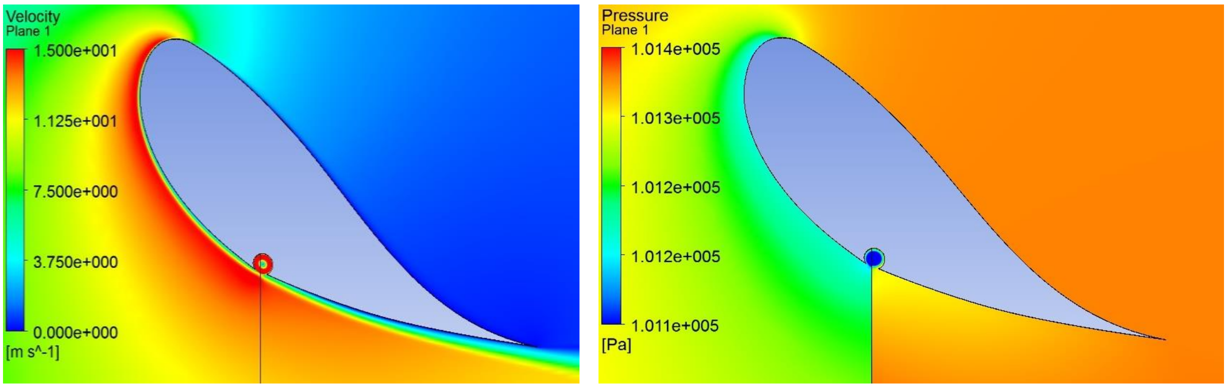

Figure 6. Velocity and static pressure distribution of the ducted fan with the groove (η = 81.02).

5. Experimental setup

On the basis of the mathematical model of the duct the experimental test duct was made with the help of 3D-printing technology, see Figure 3. In addition, a “thin” duct was made as the “inner” part of optimized duct (in this case the “experimental test duct” was used as mould), see Figure 4.

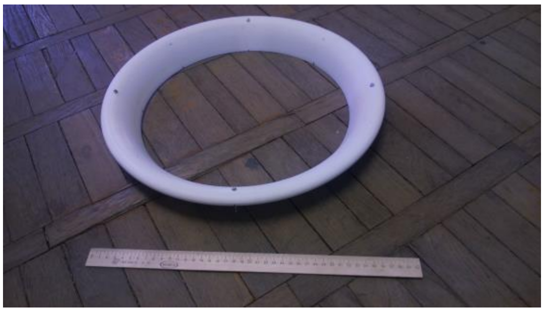

Figure 3: Duct made by 3D-printing technology

Figure 4: Thin duct.

The weight of the “thin duct” is about 45–50 gram. Then experimental setup was designed and made to measure the characteristics of the ducted fan, drive, speed controller and accumulators which enables to measure propeller rotational frequency, thrust, current from accumulator, voltage at the input of the speed controller.

6. Experiments and results

All the necessary data were obtained to calculate the total efficiency of a system and to define the efficiencies of its components. Experiments show that within the accuracy of the measurements there is practically no difference in the

efficiency between the ducted fan and the propeller of the same diameter. However, it should be mentioned that the authors are not sure that the elements of the ducted fan (propeller, fan and their combination) really have the best efficiencies among all the possible variants.
The interference influence of the two ducted fans was also investigated. The situation was modeled with the help of the “wall” situated in the vicinity of the duct. It was found that within the experiment accuracy there is no effect of interference.
After that, a set of experiments was conducted to define the dependence of the speed controller efficiency on its maximal current and voltage permitted and voltage of power source. A set of controllers (see Figure 5, Table 1) were tested for the case of 9N thrust of the powerplant for the different input voltages (12–18 Volt).

Figure 5: Controllers tested.

Table 1. Controllers tested

	Max. current, A	Max voltage, Li-Po
Jeti Advance 40 Plus	40	6
Multiplex Multicontrol 40	40	6
ZTW 40A	40	6
Hornet	60	6
Hobbywing Flyfun 60A	60	6
Maytech 50	50	6
T-Motor T40A 400Hz	40	6
Scorpion 45	45	3
Scorpion 35	35	3

First, it was found that for the current much more lower the maximal permitted (less than 30%) the controller efficiency is practically independent of the value of the maximal permitted current. This means that one can utilize the controllers with maximal permitted current of about 2–3 times higher than nominal current.
Second, the characteristic of the maximal permitted voltage does not affect the efficiency of the controller (at least for low current). Third, the efficiency of the controller decreases with voltage increase. For example, the increase of the voltage from 12V to 18V gives the increase of the current of about 10%. Finally, it was found that the mass of speed controller is proportional to the maximal permitted current and practically independent of the maximum voltage. The coefficient of proportionality is roughly about 1 gram per 1 Amper.

Conclusions

1. Numerical investigations of small height ducted fan were conducted. The acceptable duct shape and the propeller location were found. It was found out that the groove on the duct increase efficiency of the system by 2.4 per cent. Also, it was obtained that the efficiency of ducted fan without the groove is almost the same as for the propeller with the same diameter
2. Experimental setup was made. All necessary characteristics of ducted fan were obtained. It was found that the efficiency of ducted fan is nearly the same as for the propeller of the same diameter.
3. The characteristics of speed controllers were investigated. The dependence of controller efficiency on the maximal permitted voltage and current and input voltage were estimated.

References

[1] H. Glauert. The elements of aerofoil and airscrew theory Cambridge Science Classics Series. Cambridge University Press, 2 edition, 1983.

[2] F. R. Menter. Zonal two equation k-ω turbulence models for aerodynamic flows. AIAA Paper 93-2906, 1993.