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Numerical and Experimental Investigation of Ducted Fans Interference for Multirotor Copter-type Aerial Vehicle

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Abstract

The interference of 17 inch ducted fans with a height of 10% of propeller?s diameter was studied in hovering regime for the case as it was installed on a quad-rotor copter-type UAV/RPAS. 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 investigation of 17? propeller in hovering regime. The straight modeling of the ducted fan with propeller rotation was conducted to obtain higher quality resulting flowfield around the ducted fan. During the 3D numerical simulation of the interference of four ducted fans the improvements of duct geometry were provided in the term of the power consumption with a constant thrust. The wind stability of the quad-rotor copter with four ducted fans was studied by modeling the side wind of different velocities.

1. Introduction

For the last decade small multirotor copters became popular for the wide set of applications such as wild fire monitoring, rescue operations, monitoring of caves or inspection of building defects in places that are difficult to access for human. Two of the most significant features for such type of vehicles is ability to hover for a long time (or flight time that almost the same) and wind stability.

To increase the hovering time the power consumption from the onboard energy source of the copter should be minimized while the thrust remains the same. It was proposed to use ducted fans[4] as it is well known from the aircraft aerodynamics that usage of a duct around the propeller could increase the energy efficiency of the propeller by reducing its induced drag, moreover, duct provides an extra amount of thrust and protects the propeller from contacts with surrounding obstacles. According to the previous theoretical study and huge experimental database the following parameters of a ducted fan for an aircraft are optimal[3] (figure 1):

- The internal diameter of the duct should decrease firstly, then this diameter ought to increase downstream and propeller should be placed at the narrowest place of the duct
- The duct height b_a must be equal to 60% of propellers diameter D_p ($b_a = 0.6D_p$)
- The distance l between duct front edge and propeller must be equal to 40% of ducts height b_a ($l = 0.4b_a$)
- The airfoil incidence γ is equal to 7°;
- The external duct diameter D_{system} is equal to 1.26 of propellers diameter D_p ($D_{system} = 1.26D_p$);

The efficiency of the ducted fan could be up to 40% higher than the efficiency of the same propeller of the same diameter as the ducted fan at the same thrust. However, the ducts height of 60% of propellers diameter is inacceptable for multirotor copter from the point of view of the wind stability. Previous study showed that airfoil chord could be decreased up to 10% without significant increase in power consumption.[1]

The previously obtained optimal duct[1] was studied and optimized from the point of view of the interference with other ducts installed on the copter and finally copter behavior at the non-zero side wind velocity conditions was studied.

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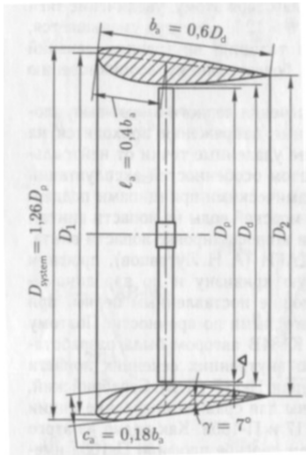

Figure 1: Optimal parameters of a duct.

2. Ducted fans interference

During the first flight tests of copter with axisymmetric ducted fans at the hovering regime, the unusual behavior was found. After some time after copter take off the vehicle started random angular motion that led to a crash or immediate landing. Testing the different types of autopilots, engines, regulators, accumulators and propellers, the hypothesis that this effect to be of duct aerodynamics nature has been done. The reason of such a supposition is that this effect appeares while every single electronic device and propeller are being tested, but it is never found when the vehicle is without a duct.

To find the reason of this random angular motion a set of numerical simulations were carried out. To provide the numerical simulations structured meshes of H-C topology were built, each mesh consisted of 25 million cells. To simulate propeller at the first step it was decided to use the actuator disc. Duct with actuator disc were placed between two perpendicular symmetry planes as it were placed on quad-rotor copter (figure 1). The symmetry boundary condition was set at the symmetry planes. The radial pressure change distribution that was taken from the previous numerical study of propeller in hover[2] was set at the actuator disc. Simulations were provided by solving RANS equations with SST turbulence model. For all the ducts, tested numerically overall thrust of the ducted fan was regulated by scaling pressure difference on the actuator disc to provide resulting thrust of 9N

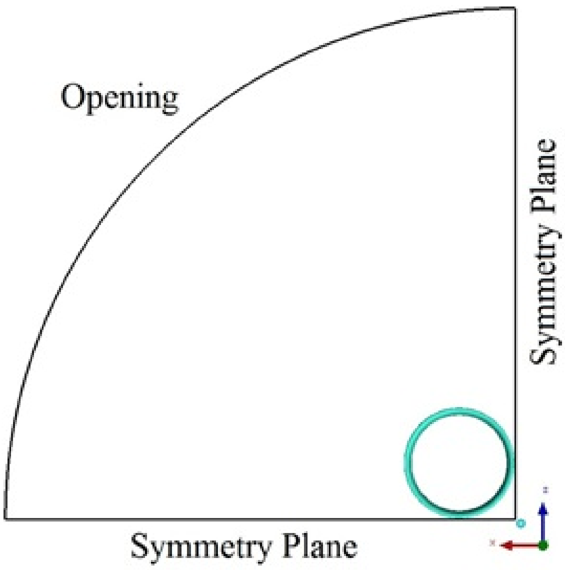

Figure 2: Computational domain for axisymmetric duct.

During transient simulation, the thrust oscillation was found with an amplitude of 0.4N, typical dependency of

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thrust as a function of time is shown in figure 3. The reason of this instability in thrust is system of independently oscillating vortices found around the duct that is shown in figure 4. Starting from the symmetry planes and washing the inner surface of the duct these vortices cause the low pressure zones on the ducts surface (figure 5) which are strongly affects the thrust.

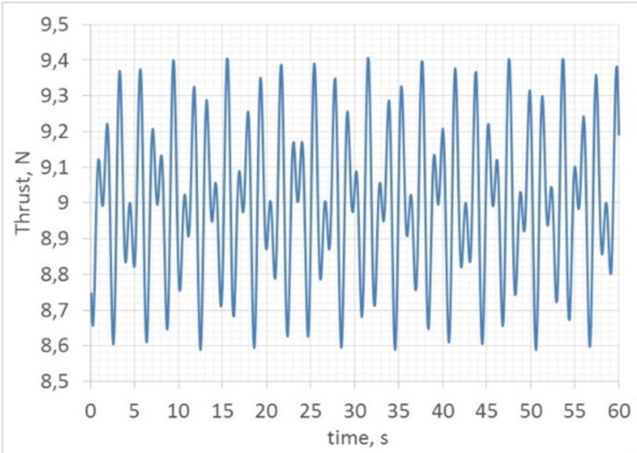

Figure 3: Typical dependency of thrust as a function of time.

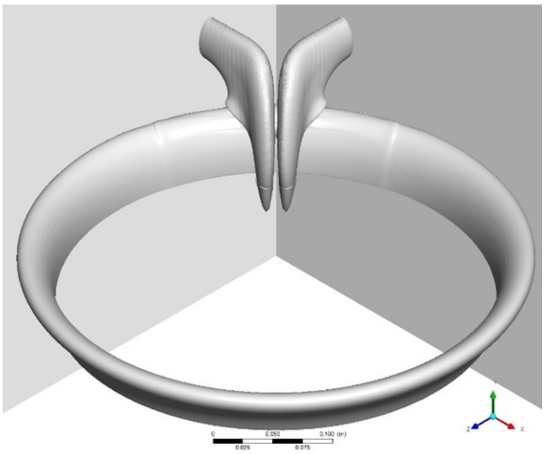

Figure 4: The vortices found. ω = 200 Hz.

The nature of these vortices is that ducts split the flow into two zones: between two ducts the flow velocity is directed upward and then at some height under the plane of ducts front edge turning downward while in the external space the velocity is directed downward. Vortices are forming between these two zones along the line where vertical component of velocity changes its sign. In other words, the presence of the ducts forms upwash that leads to the vortices forming. The distribution of vertical component of velocity is given in figure 6, the deeper the blue color the higher the vertical component of velocity: white color means the velocity is higher than 5 m/s and directed downward, deep blue color respects that velocity is higher than 5 m/s and directed upward.

To confirm that the vortices caused by the duct but not a mistake in the actuator disc the straight modelling of the ducted fan was provided. For that reason, the two-domain structured mesh, which is consisted of 15 million cells, was built. First domain around the duct was steady and second one containing propeller rotated around the propeller axis with a rotational speed of 3000 rpm. The disposition of two domains is represented in figure 7. To solve the propeller tip vortices clearly the additional value of cells were set between propeller and the duct, the distance between propellers blade is about 0.5 mm. The cross-section on the quarter-chord of the propellers blade near the duct is shown in figures 8 and 9. In addition, a number of nodes were added along the ducts circle to improve the quality of propellers blade simulation (figure 10). Around the propellers axis the cylinder with a diameter of engine was placed to avoid the zero radii simulation in the solver.

In straight modelling of the ducted fan the vortices appeared and behave in the same way (figure 11). Each

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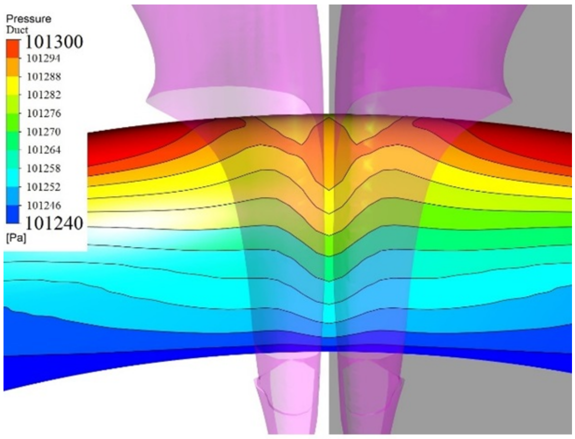

Figure 5: Isopressure lines on the duct surface.

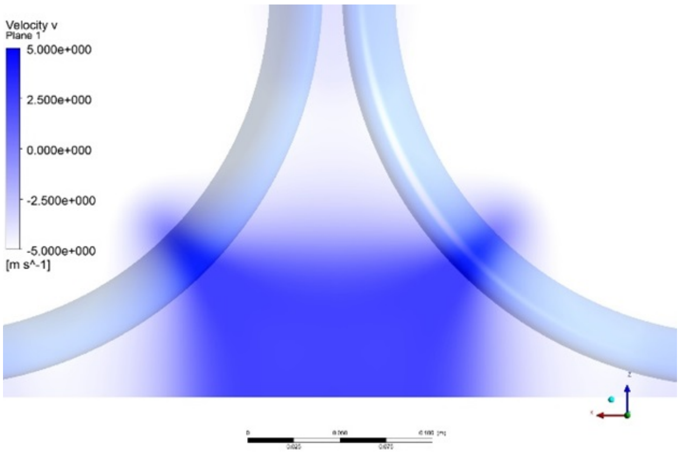

Figure 6: The distribution of the velocity vertical component.

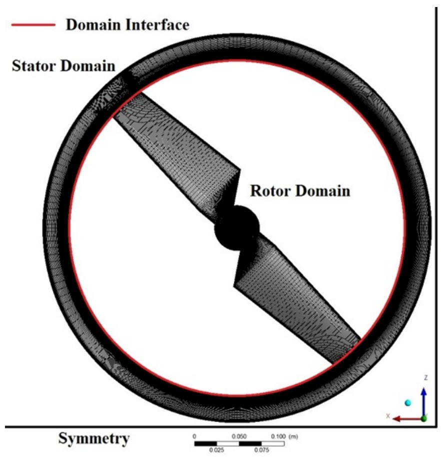

Figure 7: Computational domain for the strict propeller simulation.

vortex is destructing by the blade while blade is going through the vortex and then appears again. This brings to the high frequency oscillations of thrust on the duct surface in addition to the oscillations mentioned above. But this oscillations of the thrust are not affecting the whole thrust because of high angular velocity of the propeller.

To avoid these vortices oscillation two ways were proposed. First is to change the shape of the duct for the vortices to tend to a fixed position. Decreasing the incidence of the foil nearest to the symmetry plane, thus it shapes

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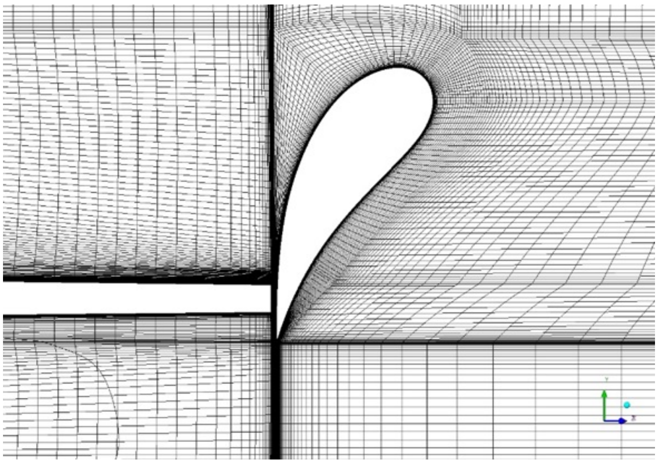

Figure 8: Propelleres balde quarter-chord cross section.

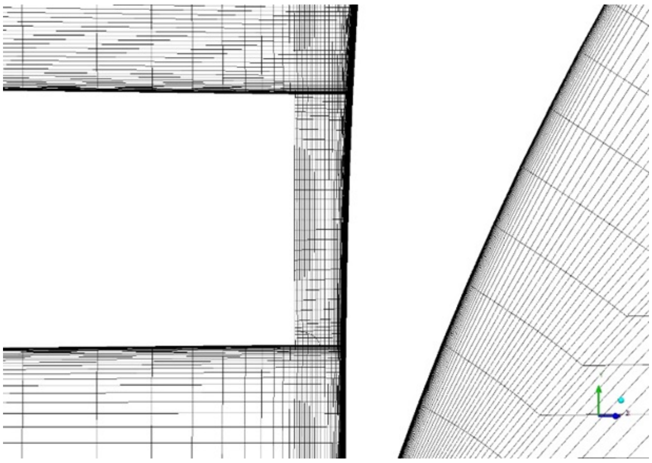

Figure 9: The mesh between duct and blade.

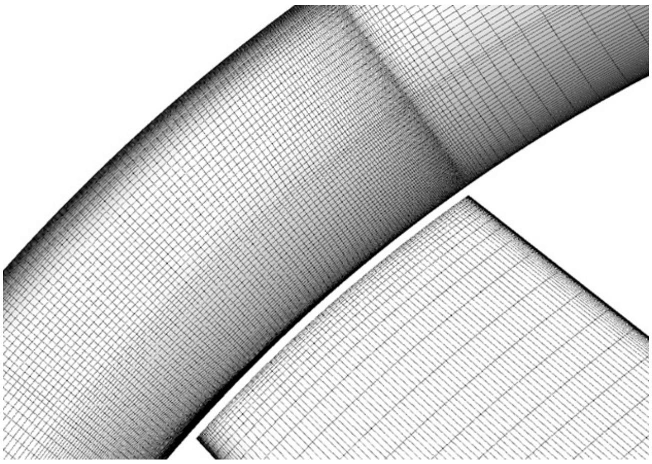

Figure 10: The mesh on the blade, planform view.

a special cavern for the vortex to be hard to leave it at the flight conditions and, moreover, this foil strictly divides the flow into two zones with different sign of vertical velocity components. The numerical simulation of such a duct showed that the amplitude of the vortex oscillation drops from 16% to 0.3% of the ducts circle and 0.1% in term of the thrust.

But the power consumption of such a duct slightly rises in comparison with the axisymmetric duct. It happens

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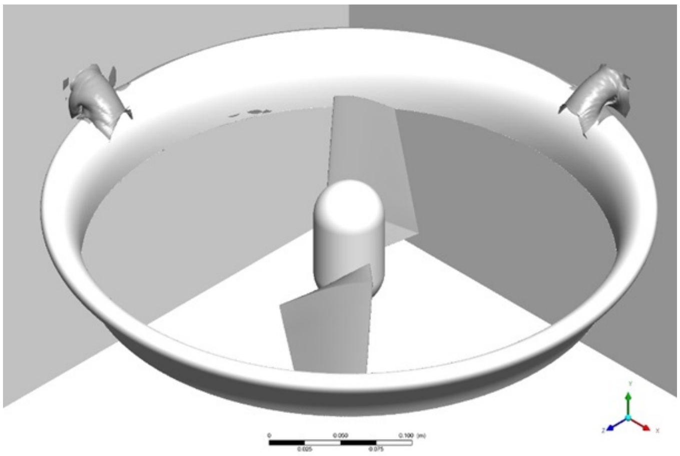

Figure 11: Vortices around the ducted fan. ω = 300 Hz

because changing the incidence of the airfoil closest to the symmetry the plane in which the propeller placed become not strictly round and narrowest in the inner space of the duct. To form the propeller/actuator plane strictly round and make it to be narrowest plane it is proposed the foil nearest to the symmetry to move down, the resulting view of the duct is represented in figure 12. The power consumption for this case is 1% lower and is equal to 39.2W, in comparison power consumption of the same propeller without duct in the case when it is installed on the quad-rotor copter is 49.6W. The vortices structure around the duct is shown in figure 13. In addition to the previously described vortices, two new appeared, but vortex structure became stable.

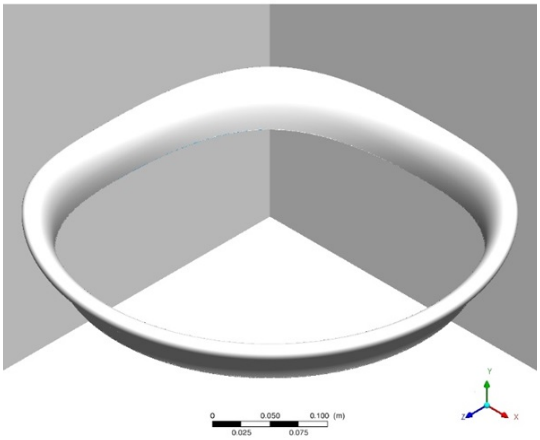

Figure 12: The duct with the airfoils nearest to the symmetry place rotated and moved down.

The second way to remove the oscillation is to remove the vortices. For this a set of meshes for a numerical simulations were built where the axisymmetric duct was consequently moved away of a copter center with a step of 50% of duct height. The power consumption as a function of the distance between two ducted fans is shown in the figure 14. The power consumption grows as a distance increases and then asymptotically decreases to the value of 38.7W which is corresponds to the power consumption of a single axisymmetric ducted fan.

3. Multirotor copter-type vehicle at side wind conditions

To study the ducted fans interference in the conditions of non-zero side wind velocity the mesh on two axisymmetric ducted fans with a symmetry plane was built. Full computational domain is shown in figure 15. The H-C topology structured mesh consisted of 50 million cells. The simulations were provided by solving RANS equations with SST turbulence model. The wind velocity of 2.5, 5 and 10 m/s were set on the domain external boundaries. In addition, the wind gust of bench-like and sinusoidal forms with a magnitude of 2.5 m/s were also simulated. The actuator discs were set with the same conditions as mentioned above.

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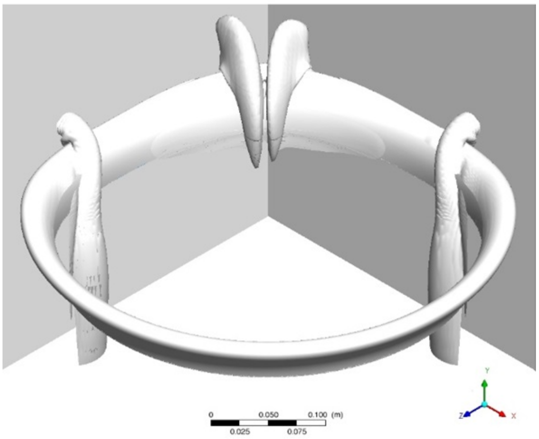

Figure 13: The vortices struture around the duct with changed incidence and moved down airfoils closest to the symmetries.

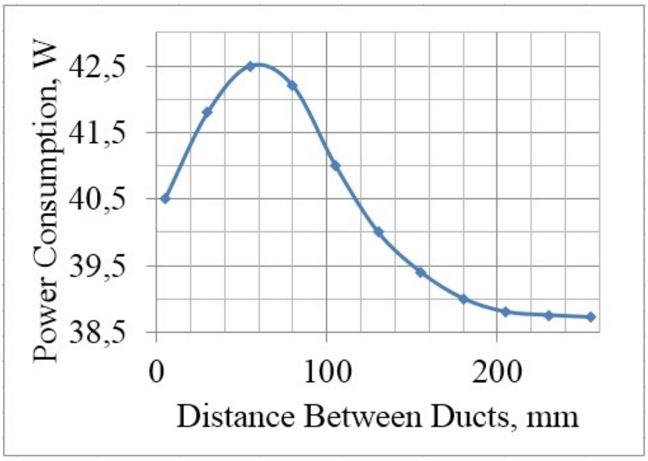

Figure 14: The power consumption dependency from the distance between two ducted fans.

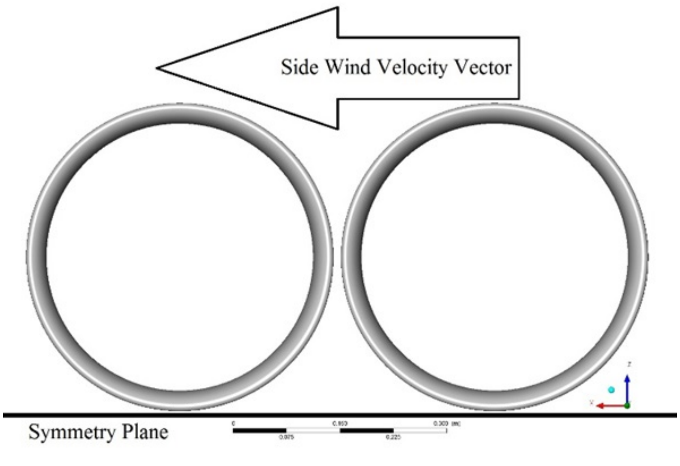

Figure 15: The computational domain for the study of interference in non-zero side wind velocity conditions.

With the appearance of side wind the size of the windward vortex increases while the size of leeward vortex decreases. If the wind velocity grows the effect goes more distinctly. The vorticity of vortices which cores are located along the wind velocity vector decreases as the wind velocity increases until the collapse which is shown in figures 16-18. The location of vortex cores along the actuator changes too. While side wind velocity grows the vortices are

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breaking down. With a constant side wind the pitch/roll moment acting on the copter is almost constant; it oscillates in a small range relative to constant value and the cause of this oscillation as described above. The pitch/roll moment dependency from the side wind velocityis represented in figure 19.

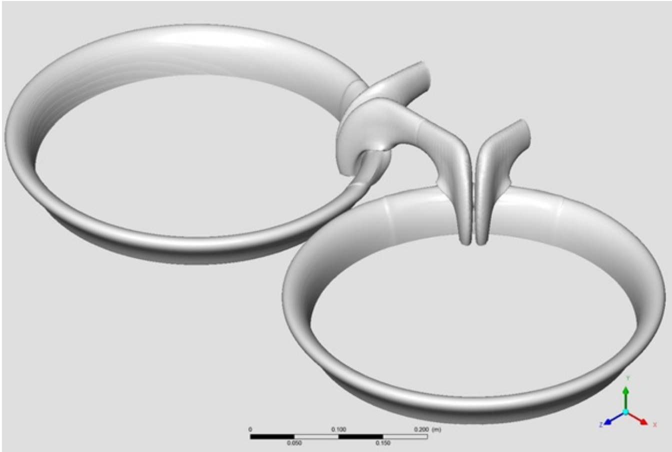

Figure 16: Vortex sheet around duct. Side wind velocity is equal to 0 m/s.

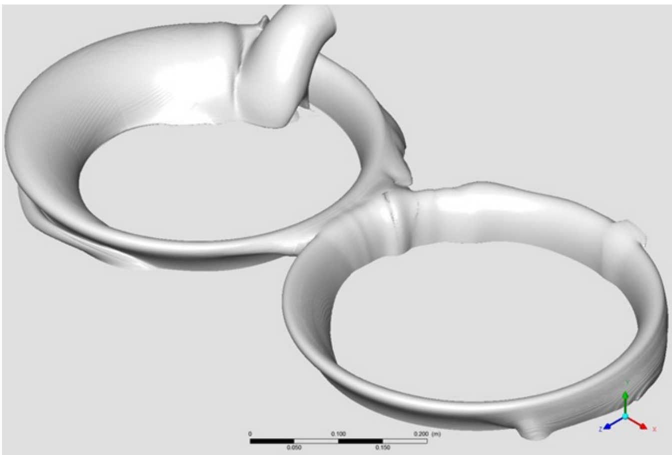

Figure 17: Vortex sheet around duct. Side wind velocity is equal to 2.5 m/s.

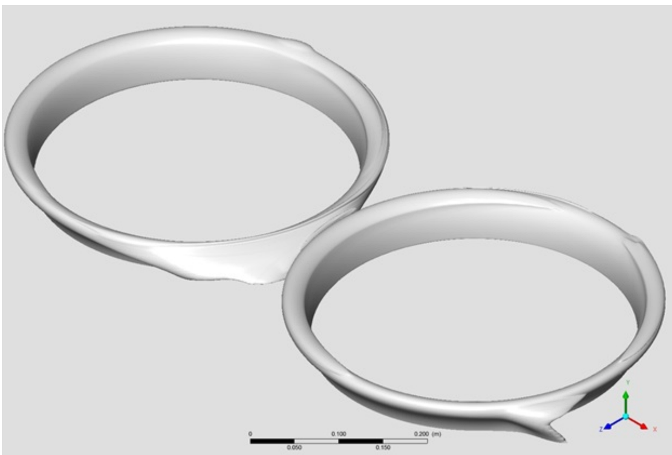

Figure 18: Vortex sheet around duct. Side wind velocity is equal to 5 m/s.

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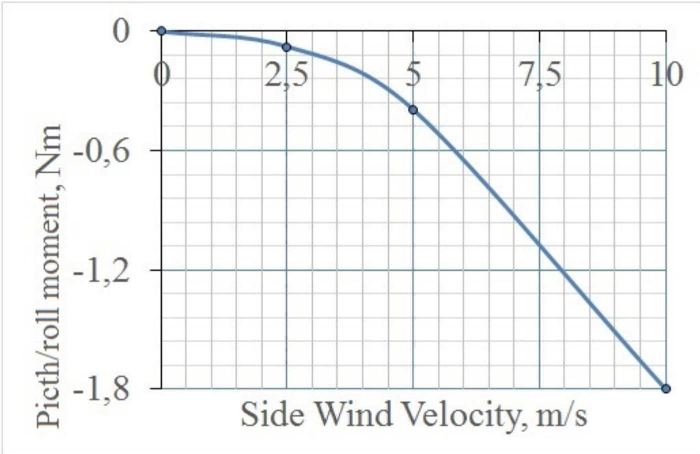

Figure 19: The pitch/roll moment as a function of time.

The transient simulation of ducted fan in the conditions bench-like and sinusoidal wind gust confirmed the steady one with 2.5 m/s wind velocity. The side wind velocity as a function of time is given in figure 20. Resulting pitch/roll moment is shown in figure 21. The thrust and the power consumption on both ducted fans obtained from transient simulation is given in figures 22 and 23 respectively.

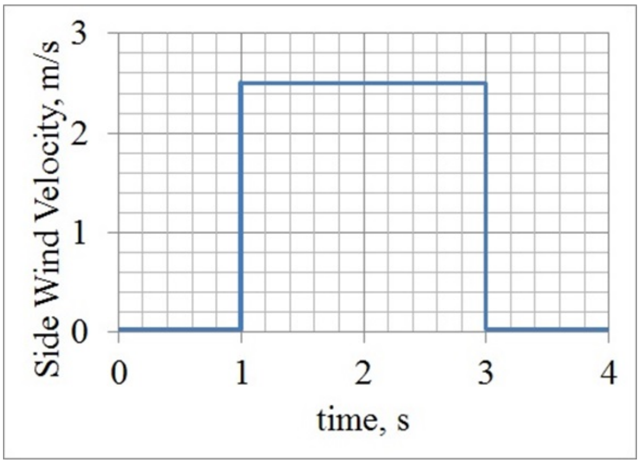

Figure 20: The velocity dependency from time of a bench-like wind gust.

In addition to the numerical simulations provided a simulation of two ducted fans in conditions of side wind gust with a same characteristics as above was carried out but with the regulations of the actuator disc thrust during the simulation. The actuator disc thrust has been regulated in the way that overall thrust of a copter remains constant at the level of 18N and pitch/roll moment is equal to zero. The resulting thrust and power consumption dependencies are shown in figures 24 and 25.

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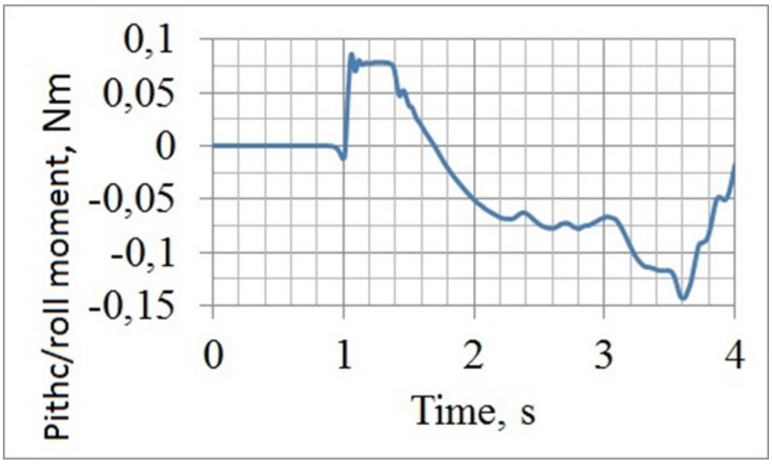

Figure 21: The pitch/roll moment as a function of time.

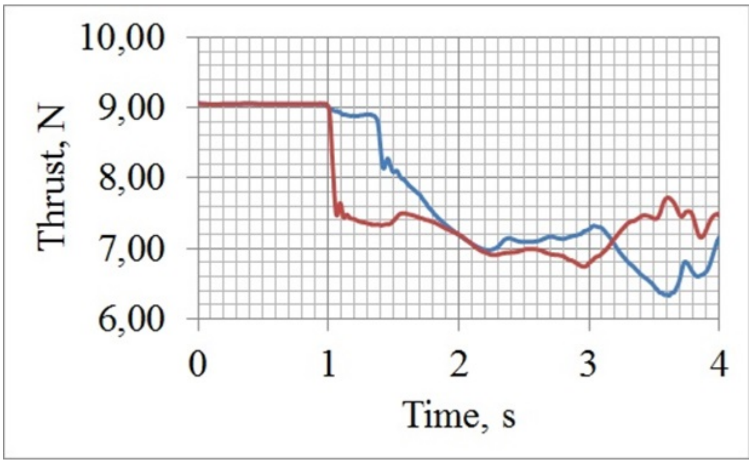

Figure 22: Time dependency of thrust.

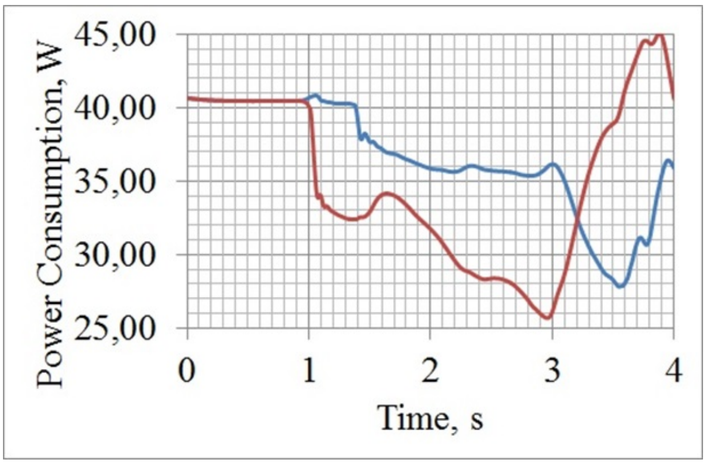

Figure 23: The power consumption as a function of time.

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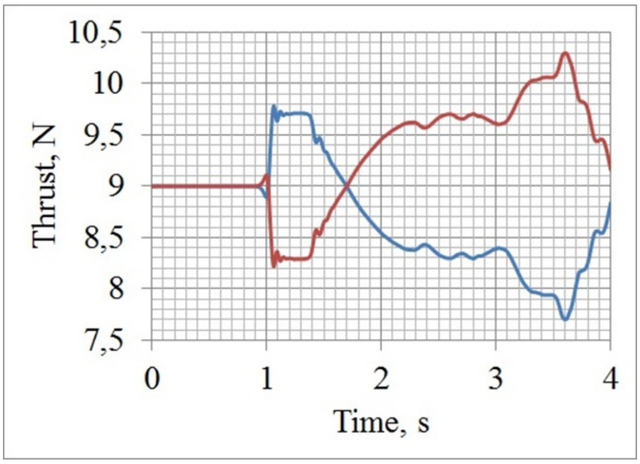

Figure 24: The thrust as a function of time while overall thrust remains constant and pitch/roll moment is equal to zero Nm.

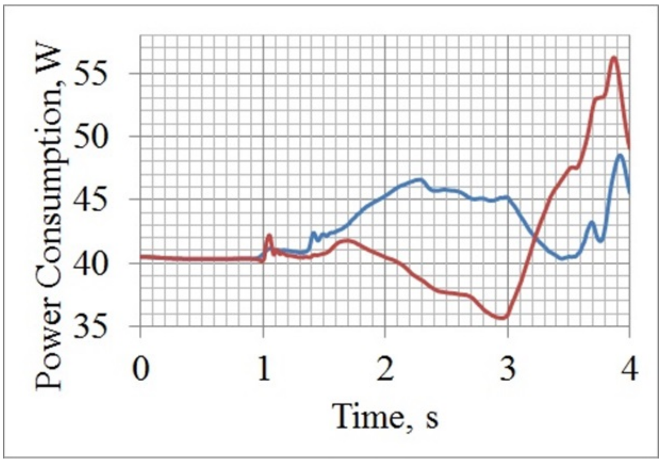

Figure 25: The power consumption as a function of time while overall thrust remains constant and pitch/roll moment is equal to zero Nm.

4. Conclusions

The set 3D numerical simulations were carried out to understand the strange behavior of the copter during the flight tests in hovering regime. The complex vortices structure was found. Each vortex is oscillating along the duct circle providing the thrust to be oscillating too. Thus the nature of pitch/roll moment occured during the copter flight was explained. The straight modelling of a propeller rotating in the duct confirmed the existance of these vortices, moreover during the blade passing the vortex the vortex is breaking down, and the blade thrust is oscillating as the ducts one.

To avoid negative effects caused by these vortices two approaches were developed. The first is to change the duct geometry and the second is to distant ducts from each other. For the first case the vortices were fixed in the same position by rotating and moving down the duct airfoils nearest to the symmetry planes. For the second case it was desided to distant the ducts until the vortices to disappear.

The numerical study of side wind of different velocities and wind gusts of different forms was conducted. The results show that while the velocity of side wind grows the windward vortex vorticity increases and the leeward decreases until both vortices breakdown. The ptich/roll moment, thrust and power consumption as functions of time were obtained.

The thrust and power consumption of windward and leeward ducts, while the overall thrust remains the same and the pithc/roll moment is equal to zero, as a function of time were found.

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