Study of ducted fans interference for copter type multirotor UAV/RPAS

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ABSTRACT

The interference of 17 inch ducted fans with a height of 10% of propellers 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

Since multirotor copter-type vehicles started to be in use for a wide set of applications, such as rescue operations or monitoring for an archeological excavations in mountains (for example Altai in Russia or Alps in Europe), the numerous requirements have been appeared.

The first strong requirement is the hovering time, the longer the flight time, the longer monitoring time is, for example, during the rescue operations iteration. To increase the hovering time the power consumption should be decreased while thrust remains constant. Previous investigations showed that the thrust of a single propeller could be increased by 40% by installing the duct of the same diameter (as single propeller) around the propeller (trimmed along the duct surface) [1]. Thus, the rpm of a propeller could be decreased and the rotor mast pitch/roll moment will be decreased too while the thrust remains constant that would cause the power consumption to drop. The optimal duct also has a height of 60% of the duct diameter that gives a huge side projection as for the copter and strongly affects the second requirement: wind stability. To satisfy wind stability requirements (ability to fly with a wind up to 10 m/s or wind gusts of the same velocity) earlier it was decided to use ducts of 10% of propellers diameter [2]. It was shown that optimal duct of such a height could decrease the power consumption by 20% but the propellers rpm should be slightly increased thus the total power consumption will be decreased by 16% (taking into account interference of the ducted fans on quad-rotor copter) [3].

To study the interference of the ducted fans the 17 inch ducted fan with a height of 10% of diameter obtained earlier during optimization [3] was chosen. The investigation was provided numerically and experimentally. It was decided that the quad-rotor copter to be the experimental vehicle to verify the numerical simulations. Thus the needed thrust was set as 9N which corresponds to the hovering regime.

2 DUCTED FAN INTERFERENCE AERODYNAMICS

The first series of flight tests showed a strange behavior of the copter in the hovering regime. After period since take off the vehicle started to move in roll divergence, such a situation led to a crash if not to land copter immediately. On testing the different types of autopilots, engines, regulators, accumulators and other electronic devices, different propellers the conclusion that this effect to be of duct aerodynamics nature has been done.

To find the reason of such a behavior the numerical simulations were conducted. To provide the numerical simulations on the set of different ducts a structured meshes with H-C topology that contains over 25 million cells and provides resulting Y+ variable of about 0.5-0.75. Duct with actuator disc were situated between two planes of the geometrical symmetry (as it is shown in figure 1) and the boundary condition of rotational periodicity on it. At the actuator disc the pressure change was set as a function of radius, this radial pressure change distribution was taken from the previous modelling of the propeller [4]. The simulations were provided by solving RANS equations with SST turbulence model.

As a result of the simulations the unsteadiness of the thrust was found. The thrust was oscillating with an amplitude of 0.4N while the average magnitude was 9N for all geometries of the duct. Typical dependency of thrust as a function of time is represented in figure 2. The reason of such a behavior is vortices found around the duct. These vortices are starting from the symmetry planes and washing the inner surface of the duct (figures 3 and 4). The vortices provide additional thrust by forming a low pressure zone on the duct surface (figure 5).

Moreover, exchanging the rotational periodicity bound-

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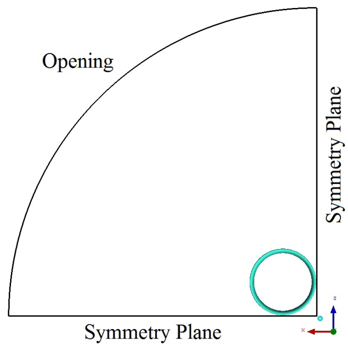

Figure 1: Computational domain for axisymmetric duct.

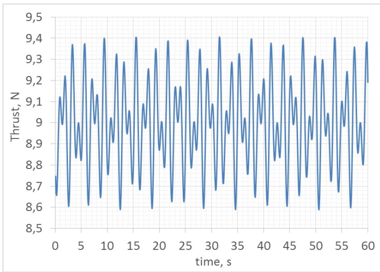

Figure 2: Typical dependency of thrust as a function of time.

ary conditions on the symmetry planes to symmetry boundary conditions it was found that these vortices could oscillate independently along the ducts circle (with an amplitude of 15% of the ducts circle). Thus this instability leads to the thrust and pitch/roll moment oscillations which were observed during the flight tests. The reason of these vortices to be is downwash caused by the duct presence. The vortices that occurs on a low set engine intake of the civil aircraft have the same nature.

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

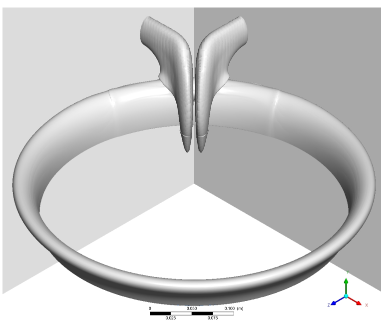

Figure 3: The vortices found. ω = 200 Hz.

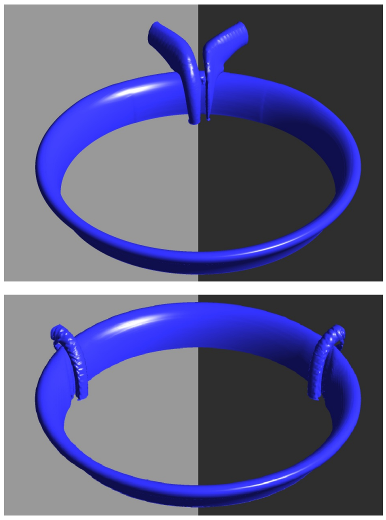

Figure 4: The vortices position at a different time moment. ω = 250 Hz.

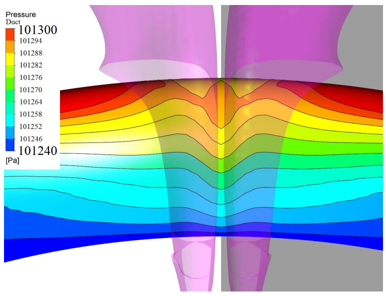

Figure 5: Isopressure lines on the duct surface.

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 6. 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 7 and 8. In addition, a number of nodes were added along the ducts circle to improve the quality of propellers blade simulation (figure 9). Around the propellers axis the cylinder with a diameter of engine was placed to avoid the zero radii simulation in the solver. The final mesh view is represented in figure **??**.

In straight modelling of the ducted fan the vortices appeared and behave in the same way (figure 10). Each 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.

To avoid these vortices oscillation two ways were proposed. First is to change the shape of the duct for the vortices

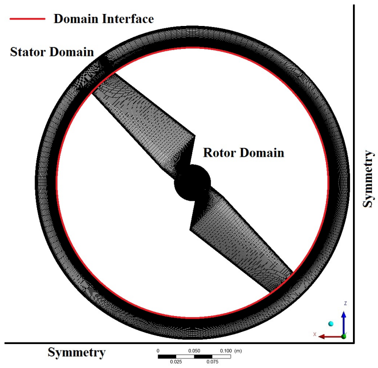

Figure 6: Computational domain for the strict propeller simulation.

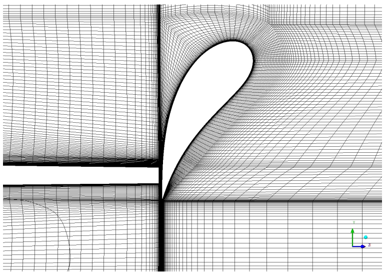

Figure 7: Propelleres balde quarter-chord cross section.

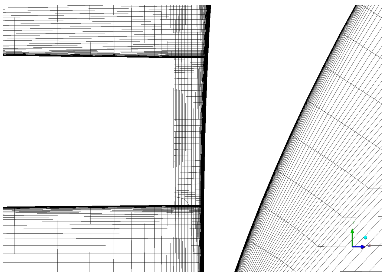

Figure 8: The mesh between duct and blade.

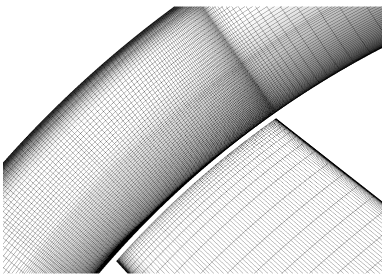

Figure 9: The mesh on the blade, planform view.

to tend to fixed position. Decreasing the incidence of the foil nearest to the symmetry plane, thus it shapes a special cavern for the vortex to be hard to leave it at the flight conditions.

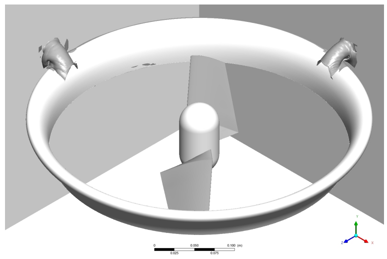

Figure 10: Vortices around the ducted fan. ω = 300 Hz

The numerical simulation of such a duct showed that the amplitude of the vortex oscillation drops up to 0.3% of the ducts circle and 0.1% in terms of the thrust. The typical view of such a duct is shown in figure 11. But the power consumption of such a duct slightly rises in comparison with the axisymmetric duct. It happens because changing the incidence of the airfoil closest to the symmetry the plane in which the propeller rotates 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 quadrotor copter is 49.6W. The vortices struture around the duct is shown in figure 13.

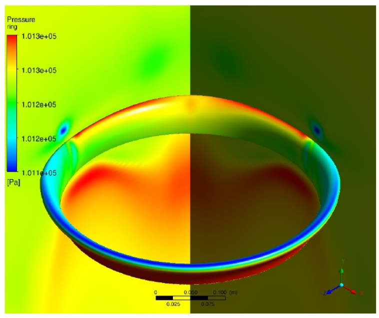

Figure 11: The pressure distribution on the duct with changed incidence of the airfoils closest to the symmetry planes.

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 preliminary results of power consumption as a function of the distance between two ducted fans is shown in the figure 14. Now the simulation of the last cases are ongoing and it is expected that power consumption will asymptotically take value of 38.7W which is corresponds to the power consumption of a single axisymmetric ducted fan.

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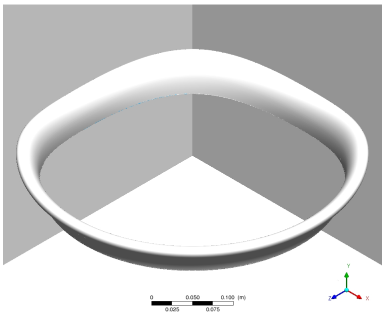

Figure 12: The duct with the airfoils nearest to the symmetry place rotated and moved down.

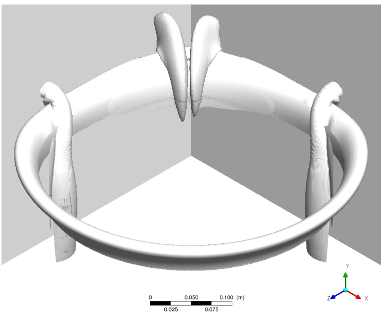

Figure 13: The vortices struture around the duct with changed incidence and moved down airfoils closest to the symmetries.

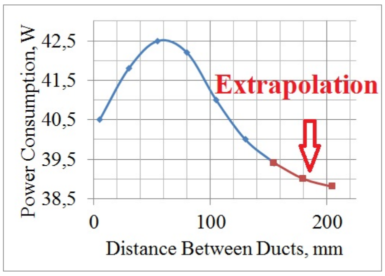

Figure 14: The power consumption dependency from the distance between two ducted fans.

3 Ducted fans interference with a non-zero side wind velocity

To study the ducted fans interference in the conditions of non-zero side wind velocity the mesh on two ducted fans with a symmetry plane was built. Shape of the axisymmetric ducts was taken from the previous study [3]. The H-C topology structured mesh consisted of 50 million cells. Full computational domain is shown in figure 15. 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 outer boundaries of the computational domain. In addition, the wind gust of bench and sinusoidal view with a magnitude of 2.5 m/s was also simulated. The actuator discs were set with the same conditions as mentioned above.

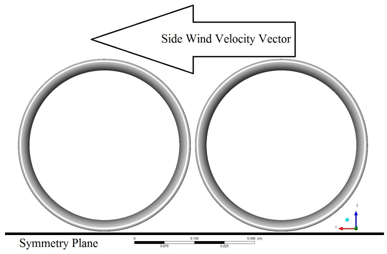

Figure 15: The computational domain for the study of interference in non-zero side wind velocity conditions.

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. With a growing wind velocity the vortices are breaking down.

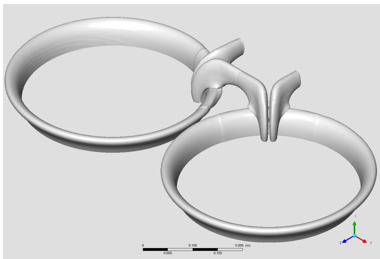

Figure 16: Vortex sheet around duct. Side wind velocity is equal to 0 m/s.

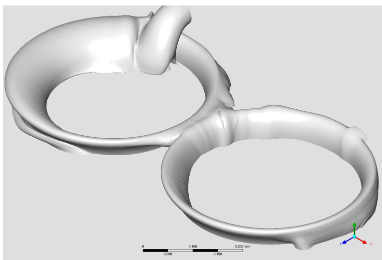

Figure 17: Vortex sheet around duct. Side wind velocity is equal to 2.5 m/s.

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

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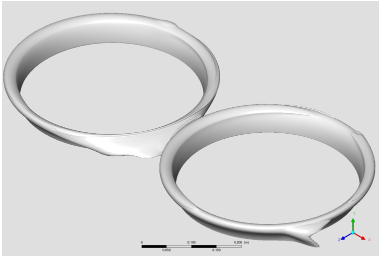

Figure 18: Vortex sheet around duct. Side wind velocity is equal to 5.0 m/s.

time while the wind gust is ongoing is represented in figure 19

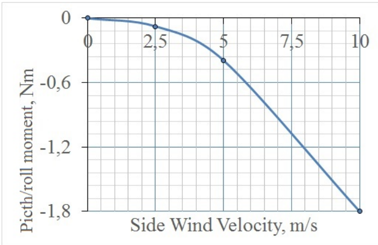

Figure 19: The pitch/roll moment as a function of time.

The transient simulation of working ducted fan confirmed the steady one with 2.5 m/s wind velocity. The form of the bench-like wind gust is given in figure 20. Resultin 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.

The modeling was carried out by providing the total two-duct thrust to be 18N while the pitch/roll moment is equal to zero. The power consumption as a dependecy of time in conditions of bench-like side wind gust of 2.5 m/s is represented in figure 25.

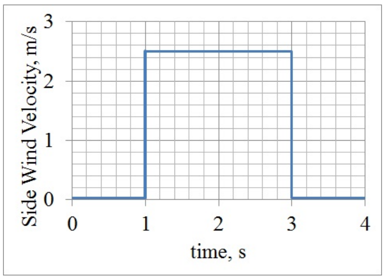

Figure 20: The velocity dependency from time of a bench-like wind gust.

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.

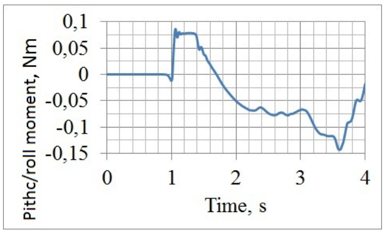

Figure 21: The pitch/roll moment as a function of time.

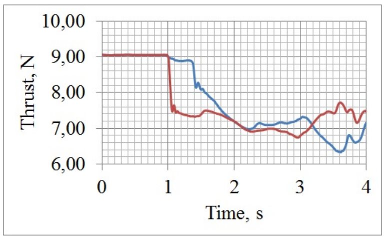

Figure 22: Time dependency of thrust

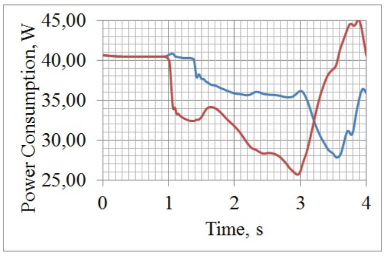

Figure 23: The power consumption as a function of time

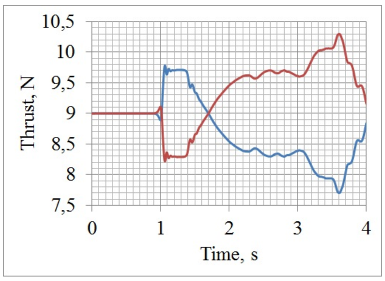

Figure 24: The thrust as a function of time while overall thrust remains constant and pitch/roll moment is equal to zero Nm.

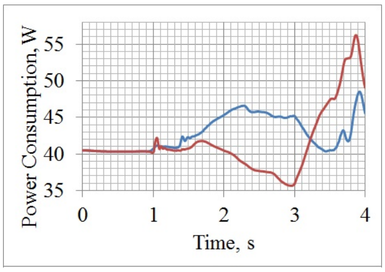

Figure 25: The power consumption as a function of time while overall thrust remains constant and pitch/roll moment is equal to zero Nm.

4 Conclusion

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.

References

[1] Ostrouhov S.P. *Investigation of the flow pattern near the propeller in the shaped ring and without it at thrust reversal*. TsAGI Science J., Moscow, 2009.

[2] Ageev N.D. Arkhipov M.E. Serokhvostov S.V. Investigation of ducted fans of small height for hexacopter. In *2nd Extremal and Record-Breaking Flights of the RPAS and the Aircraft with Electrical Power Plant*, 2014.

[3] Stremousov K.D. Arkhipov M.E., Serokvhostov S.V. Small height duct design for multicopter fan. In *30th congress of the international councill of aeronautical sciences*, 2016.

[4] Arkhipov M.E. Serokhvostov S.V. 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.