

PROGRESS IN THE GUST RESISTANT MAV PROGRAMME

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Abstract

Air turbulence is perceived as a major problem for Micro Air Vehicles (MAV) in outdoor applications. Researchers report trouble with attitude holding due to the turbulence and resulting problems with quality of images transmitted by MAVs. According to the literature, short duration vertical gusts may have velocity comparable to MAV airspeed, so brief periods of flight at very large angles of attack have to be considered. In these circumstances it seems reasonable to apply the design with as high stall angle of attack as possible. In particular the flow has to be attached to control surfaces to perform effective control in order to damp air turbulence effect.

Therefore an aircraft configuration was developed with cranked delta wing and propeller located inside the wing contour. To prove the value of the concept, wind tunnel experiment was undertaken, as well as flight tests programme. The prototype demonstrated ability to fly controllably at extremely high angles of attack. However few disadvantages were also noticed. For example the prototype was very sensitive to the motor settings, since every rpm change required immediate airplane trimming to maintain straight path of flight. This drawback can be eliminated by application of counter-rotating propeller.

The status of the programme is presented in the paper, including the most recent results, as well as currently undertaken experiments and plans for the nearest future.

1 Introduction

Micro Air Vehicle (MAV) is defined here as a small (hand launched, storable in portable container), light, and inexpensive unmanned flying vehicle for direct, over the hill reconnaissance. The focus is on fixed wing, forward thrust airplane since the ability to negotiate strong opposing winds is required.

Several prototypes of fixed wing MAVs were built to date [1-3]. They achieved good range and endurance performance. However, they suffer from near earth boundary layer turbulence, that creates high variations in angle of attack, as explained in [4]. The potential solution of this problem was noted in the course of the project described in [5], when one of the tested MAV configurations exhibited existence of leading edge vortex. Leading edge vortex is a well-known phenomenon [6, 7], that allows the design of super-maneuverable jet fighters, capable of flying at very high angles of attack. It was assumed that highly maneuverable MAV could be stable in the turbulent air, if equipped with a fast enough autopilot. Therefore, it was decided to apply cranked delta wing configuration, however, integration with propulsion system was not straightforward.

Propeller propulsion seems to be the most suitable for a fixed wing MAV. Propeller at the vehicle front would decrease the angle of attack locally, thus vanishing the effect of the leading edge vortex. On the other hand, pusher configuration would be dangerous for hand launching. Direct contact of the propeller with the hand of the launching person, could cause personal injury, as well as damages to the airplane. Therefore an airplane configuration,

with the propeller located in the slot, inside of the wing contour, was developed (Fig. 1). The propeller blows directly at the control surfaces in this configuration, which is perceived as an additional advantage, almost equivalent to the thrust vectoring of a modern fighter airplane.

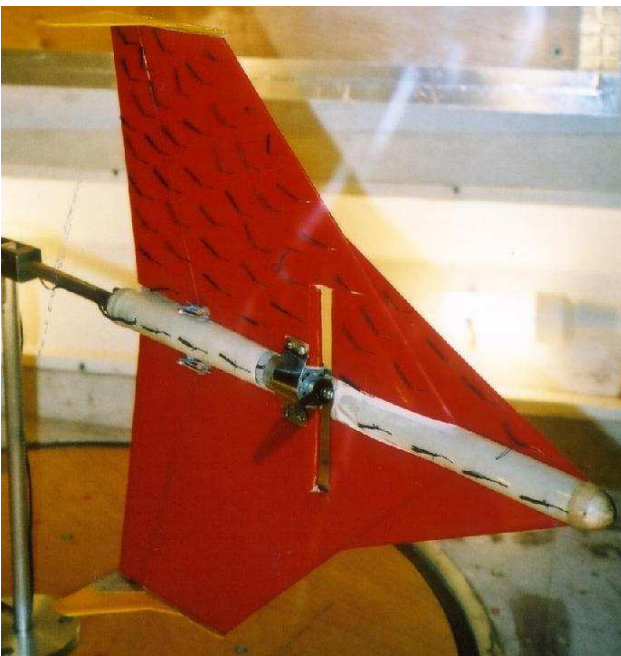
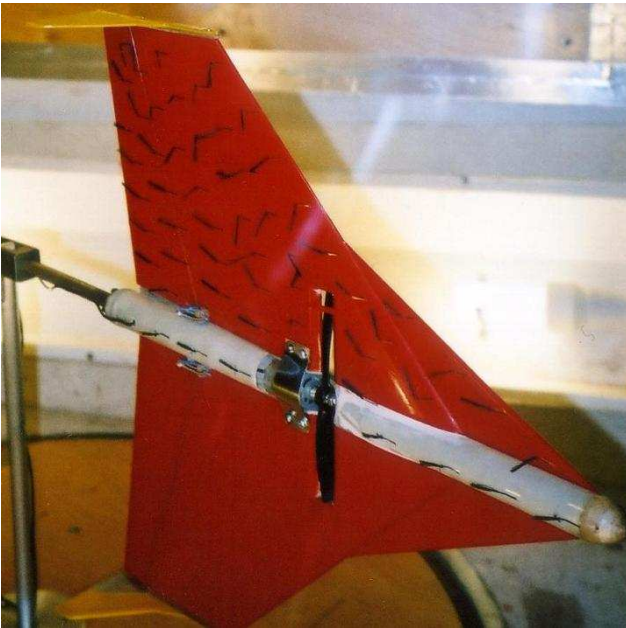


Fig.1 Propeller effect for angle of attack of 30°.

The model of this configuration was tested in the wind tunnel as described in [8], to investigate the co-operation of the leading edge vortex with the propeller stream. Results were

positive (Fig.2) since greater lift coefficient was achieved in wide range of angles of attack in the motor ON mode. Flow visualization confirmed this effect.

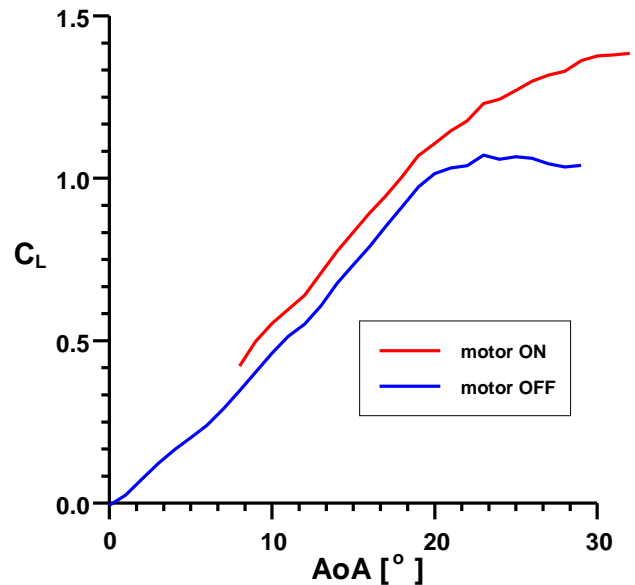


Fig. 2 Lift generated by the cranked delta wing MAV in motor ON and OFF modes, elevator in cruise position.

2 First prototype flight testing

Flight-testing is an ultimate method validating results, therefore, taking low costs of building flyable MAV prototype platform into consideration, the project was undertaken to make sure that positive results are not created by the wind tunnel effect [9]. Sufficient load factor achieved during rapid pull-up maneuver could exclude the possibility of this error.

The airplane was almost identical to the wind tunnel model applied in experiment described in [8]. The only differences were slightly increased fuselage to accommodate all necessary equipment and slightly thicker Leading Edge eXtension (LEX) root to accommodate avionics and experimental wiring. The main wing geometry was the same in both cases.

Airplane structure was based on the carbon torsion box in the nose part of the wing and ribs covered by flexible membrane in the remaining part of the wing. This structure was selected

because of greater flow stability as described in [10].

Electric motor MEGA Acn 16/7/8 with Jes 18-3P Advance controller and APC 5,7x3 propeller were selected for propulsion of the airplane. Motor was supplied from Li-poly batteries with capacity of 1250 mAh. Separate Li-poly battery was applied to supply the experimental equipment. PRP-J5 data acquisition system was used to conduct measurements together with a set of accelerometers and differential pressure velocity sensor. Fig. 3 shows the airplane before the test.

Experiments with large angles of attack began after initial airworthiness testing. Fig.4 shows the “cobra” like maneuver conducted to measure the maximum achievable load factor.

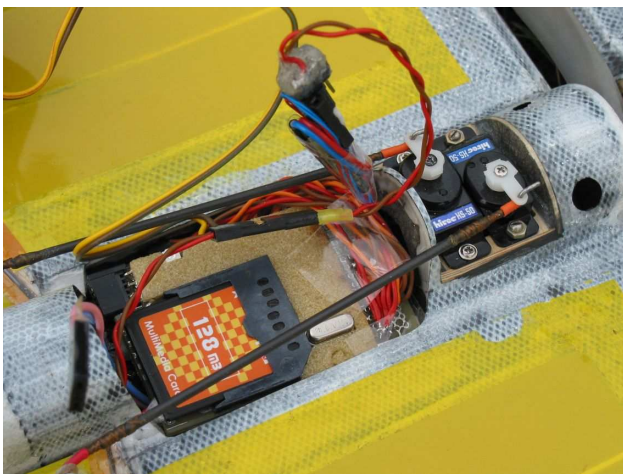


Fig.3 View of the MAV showing the data acquisition system.



Fig. 4 “Cobra” like maneuver

The aircraft was fully controllable when performing this maneuver. Fig.5 shows measured results compared with maximum load factor curves calculated from the wind tunnel measurement. As can be seen from this plot, load factors achieved in flight are greater than expected for powered flight. This can be explained by the fact that the highest angle of attack used for wind tunnel measurements was equal to 32° due to the constrained measurement volume. Both lift and drag influence the load factor measured orthogonal to the fuselage, so it increases due to the drag increase if lift remains at least constant. Therefore presented result proves that the investigated airplane is capable of coping with angles of attack greater than 32° . Lack of any tendency to autorotational roll or spin and full controllability during experiment support this statement.

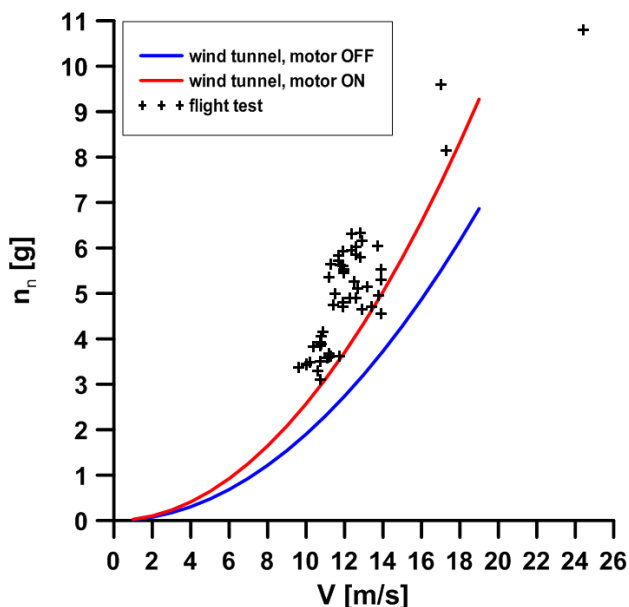


Fig. 5 Load factors measured in flight.

3 Contra-rotating propeller

Oversensitivity to the propeller torque forcing the pilot to trim the airplane after each change of the engine settings was discovered during flight test experiments. This oversensitivity was considered as a disadvantage, since the autopilot could be overloaded. Therefore it was decided to design

and test contra-rotating propeller to drive the MAV.

3.1 Contra-rotating propeller design

The computer code for design of the propeller was developed according to Theodorsen theory published in [11-16].

Designed propeller was then simulated with application of commercial software based on finite volume method [17]. This step in the project was undertaken to better understand phenomena connected with contra-rotating propeller operations. Figure 6 show examples of pressure distributions obtained from calculations, for various time steps. Rapid variations of the pressure distributions were observed at the moment, when the blades were passing each other. In critical moments the sign of the pressure was even switched. Short pressure peaks endurance ($\Delta t = 0.00012s$) influence only slightly the average thrust, moment and efficiency. Time histories of measured parameters are relatively flat [Fig.7]. It was possible to observe the most important advantages of the contra-rotating propeller. Cumulative moment of the propeller was very small ($-0,002Nm$), comparable to computations accuracy, in wide range of the cycle duration. Cumulative thrust of counter rotating propeller was slightly greater than the sum of thrust of two conventional propellers.

3.2 Contra-rotating propeller testing

Wind tunnel tests were undertaken to verify numerical results. They provided complete propeller characteristics, also out of the design point. Experimental comparison of the contra-rotating and conventional propeller was also possible.

Closed-circuit subsonic wind tunnel with open test section was used for this experiment. The test section has 1.5m diameter which allows investigating models with span as large as 0.7m with satisfactory accuracy. Tested propeller had maximum diameter of 0.18m, so it was considered small enough for this facility. Air

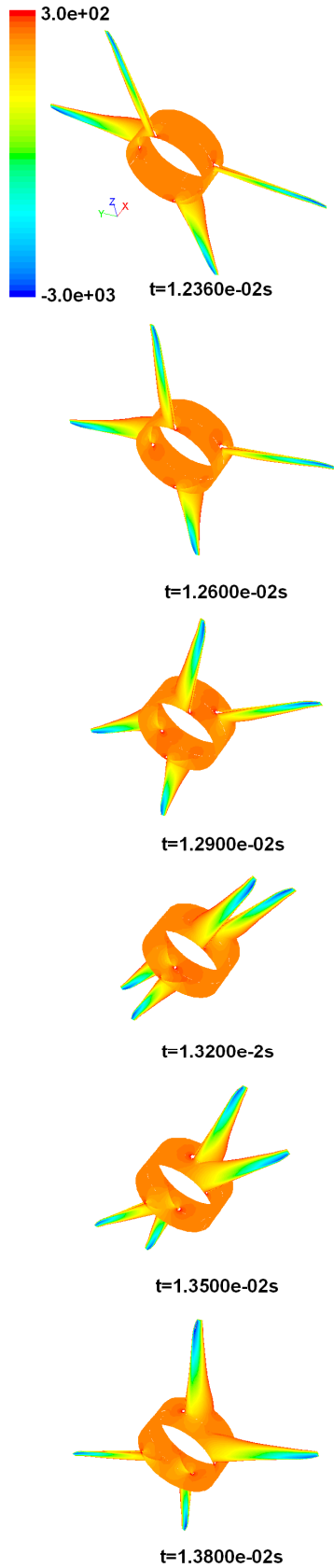


Fig. 6 Calculated pressure distributions.

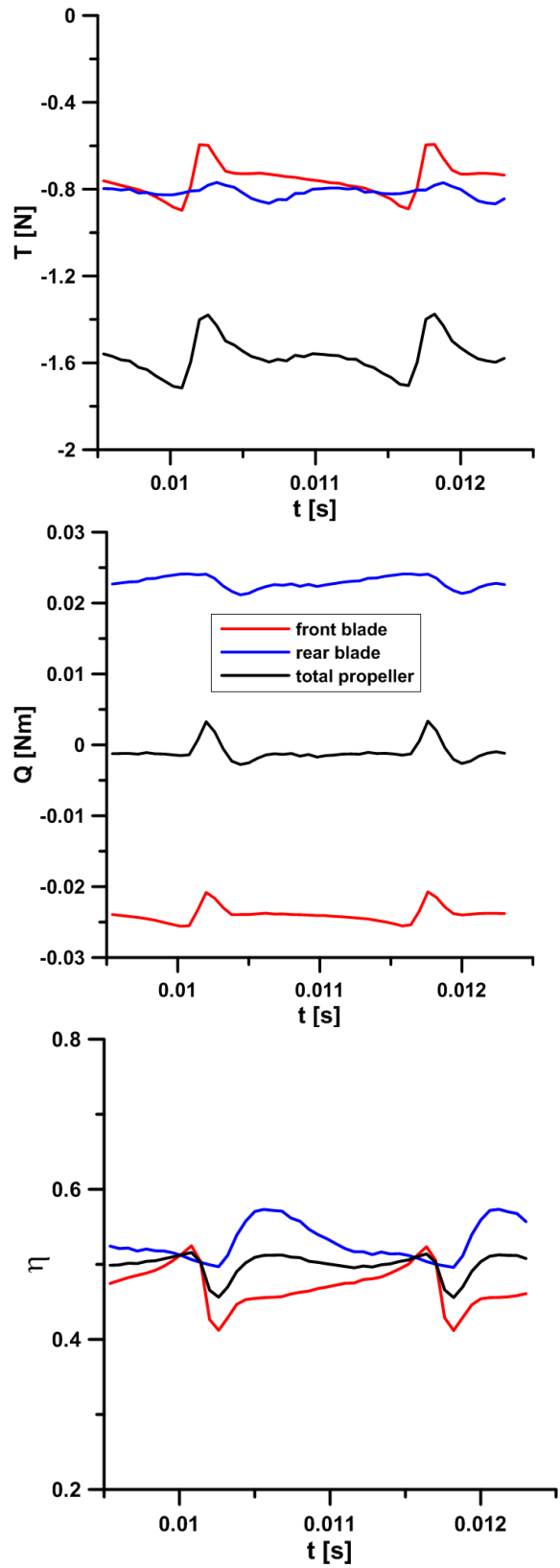


Fig. 7 Calculated propeller's set thrust, torque and efficiency.

velocity in the tunnel covered the whole range of MAV airspeeds. Propellers were made out of carbon fiber-epoxy composite. Commercial coupled contra-rotating brushless motor [18] was used to drive the propeller. Figure 8 shows the test stand.

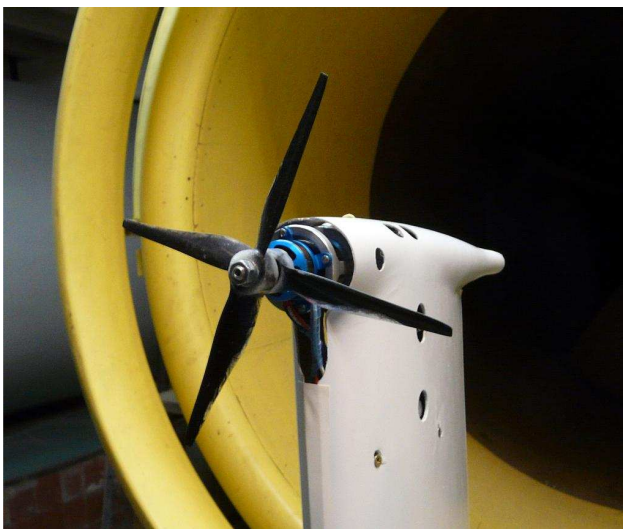
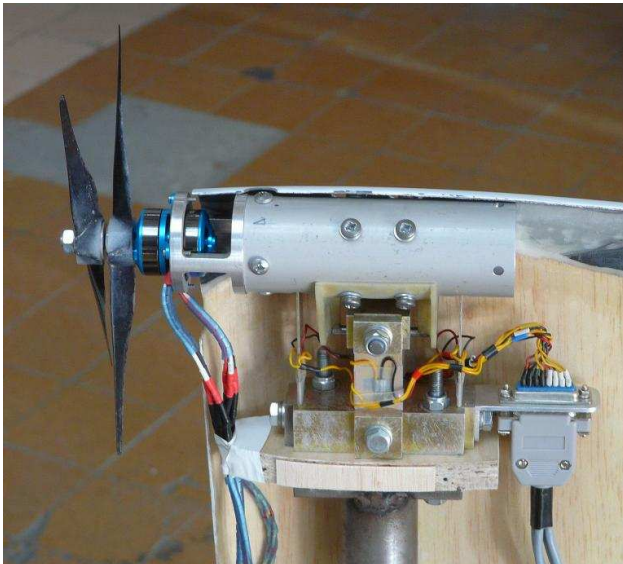


Fig. 8 Propeller test stand

The following parameters were measured in the course of the experiment: air velocity in the tunnel, propellers' RPM, thrust, torque, power supply voltage and current. Experiment was conducted for both contra-rotating and conventional propeller configurations, for different RPMs and different air velocities in the wind tunnel. Then the power supply to the propeller was calculated, as well as general

efficiency of the propulsion system and efficiencies of the propeller and the motor-controller unit. Figure 9 provides the results of the basic experiment. Thrust, and propeller efficiency, are presented here as functions of advance ratio $J=V/(nD)$. Values calculated in the course of design and simulation phase are presented for the comparison.

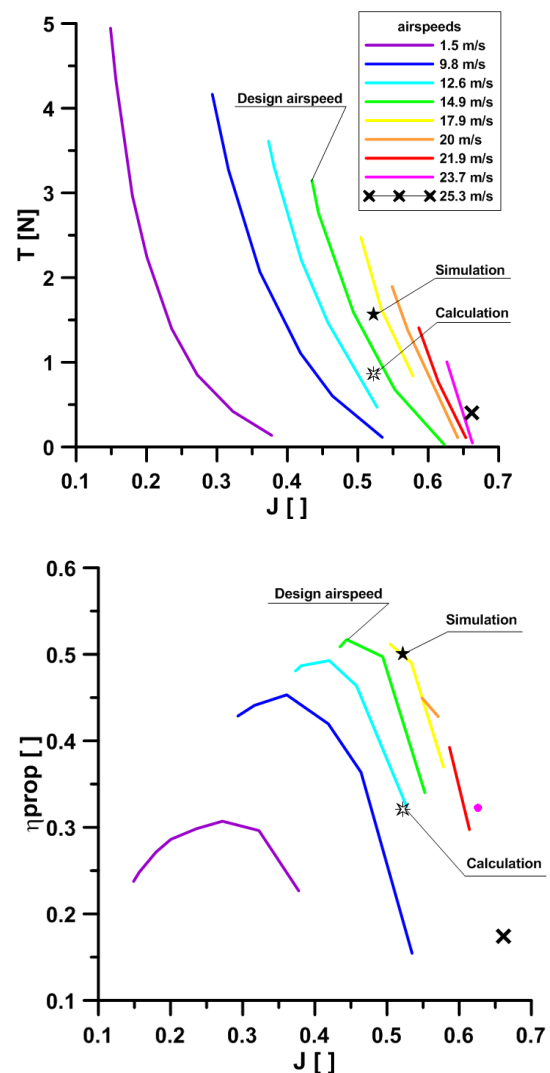


Fig. 9 Measured thrust and efficiency of the contra-rotating propeller

As can be seen experimental results were found in the middle between values calculated from the theory and from the numerical simulation, confirming usefulness of the theoretical results. The difference between experiment and calculated values is sometimes

quite big, because of steep characteristics, and small values measured. Theory gives underestimated values whereas numerical simulation provides overestimated results. The reason for simulation overestimation comes probably from inexact parameters assumed for turbulence model and boundary layer treatment at relatively low Reynolds number. On the other hand, during the design process, exact values of drag coefficients of propeller airfoils were difficult to acquire since they also work with low Reynolds numbers. They were obtained numerically and probably overestimated. Because of these arguments, obtained results can be considered as satisfactory. Experimental results can now be used to tune both methods.

Comparison of conventional and contra-rotating propeller also gave interesting results. Theory suggests that front propeller's wake energy is recovered by the rear propeller in the contra-rotating propeller and that the rear propeller's wake is not twisted as in the conventional propeller. Thus the contra-rotating propeller's efficiency should be higher than in the case of conventional one. This conclusion is true for large propellers of commercial airplanes. Figure 10 provides results obtained for measurements of conventional propeller characteristics. Rear propeller of the contra-rotating propeller with a half of the motor was used to simulate the conventional propulsion system in this experiment. Later on front propeller was also tested with the second half of the motor with the same results.

As can be seen from the comparison of Figures 9 and 10 maximum efficiency of the contra-rotating propeller is few percent greater than 50% whereas maximum efficiency of the conventional propeller is few percent lower than 50%. This result proves that the theory is correct also for small propellers working with relatively small Reynolds numbers. Measurements of the propeller torque also proved this conclusion since it was smaller than error of measurement in the course of the whole experiment with contra-rotating propeller. This result proved that application of contra-rotating propeller can eliminate the MAV's sensitivity to the motor settings, which was the main purpose of the

effort taken. It also provoked question if roll control can be augmented by different RPM's of the front and rear propeller of the contra-rotating propeller. Therefore brief experiment was undertaken to test this possibility. Control system was modified so that both parts of the motor were controlled by two separate controllers. As a result it was possible to increase the RPM of one propeller alone. The experiment began from approximately 9400 RPM for both propellers, which was assumed as the RPM's needed for stable, horizontal flight. RPM of the front propeller were gradually increased first. They were reduced again to 9400 RPM after all data were recorded. Then RPM of the rear propeller were also gradually increased and all parameters recorded. Result is presented in Figure 11.

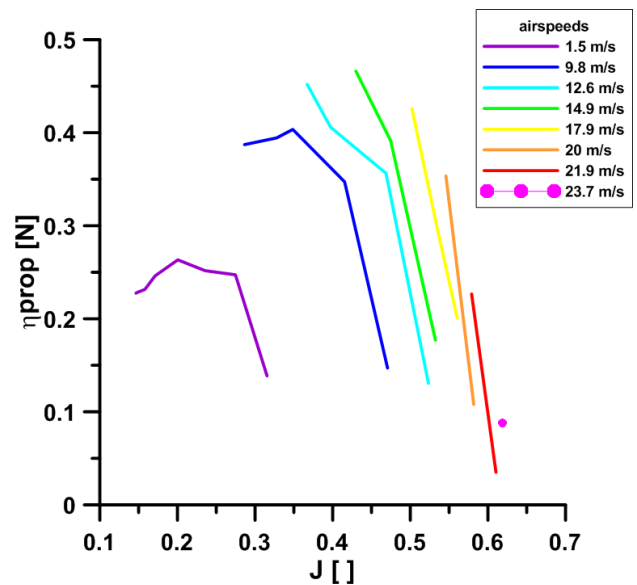


Fig. 10 Efficiency of the conventional propeller

As expected thrust was increased in both cases. Propeller torque was also increased, clockwise or anticlockwise depending on which propeller was running faster. This result suggests that MAV's roll control can be augmented with independent RPM control of the contra-rotating propeller; however this possibility requires further investigation, due to close interaction with the aircraft.

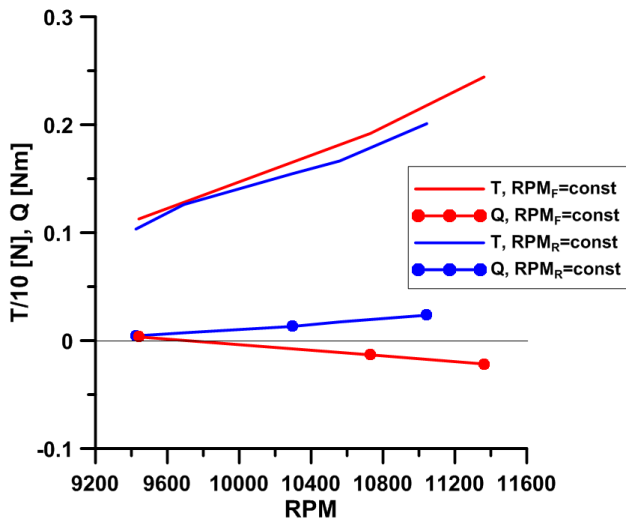


Fig.11 “Assymetric” thrust and torque of the contra-rotating propeller

4 Current tasks

There are two major tasks currently performed under the project. First of all, second prototype is built to check counter-rotating propeller interaction with plane in flight, in various possible aircraft mass configurations. Numerical study have been also undertaken to select possible simplifications to model of propulsion, suitable for further design and analyses.

4.1 Second prototype

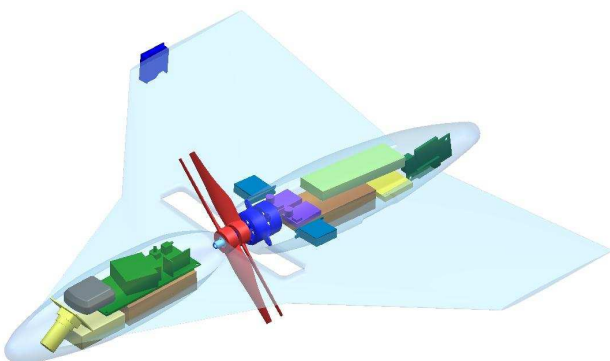


Fig.12 Avionics distribution in the second prototype

Avionics optimisation and weight analysis were performed at the beginning of the first

task. Figure 12 shows the avionics and propulsion distribution providing proper center of gravity position. Based on this analysis and experience with flying prototype, new shape of the fuselage was developed and structures designed. New moulds were built and work on the first structure of the new configuration is in progress (Fig.13). This effort is pointing also to experience practical operations and manufacturing of future fully developed MAV platform. The platform should be manufacturable, durable in terms of in-flight and on-ground handling, simultaneously assuring good flight characteristics. As a result the most effective structure in terms of manufacturability, strength, weight, cost and operations will be selected.



Fig.13 First structure of the second prototype

4.2 Numerical analysis

Numerical study was undertaken to select appropriate model of the propulsion system that is optimal for further design-analysis in terms of both accuracy and computing power requirements. Several grids with different propeller models are prepared. They represent different levels of simplification from complete model with rotating propeller blades (Fig.14) to

the disc plane with defined pressure gradient, with or without wake swirl. The goal of this task is to select the model which provides accurate result in the shortest time since it will be used for aerodynamic and stability numerical optimization. Many runs of aerodynamic calculations will be needed to obtain the most efficient MAV geometry, so they have to be as short as practical to finish optimization within reasonable time.

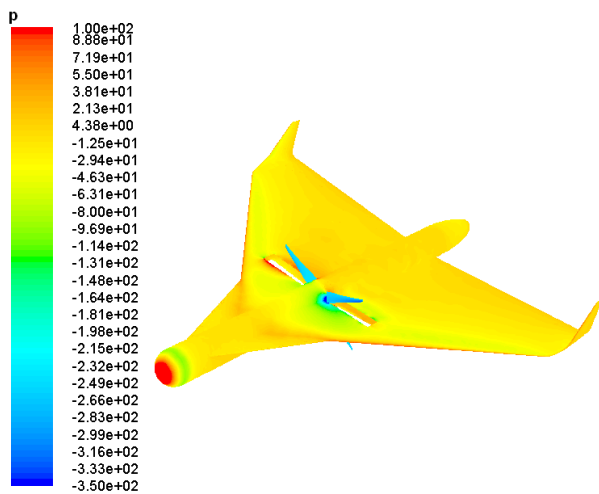


Fig.14 Example of numerical study result on propeller-aircraft interference

5 Plan for the near term future

Flight test campaign will start as soon as second prototype is built. It should provide the confirmation of the counter-rotating propeller quality. Moreover some experiments with flight dynamics are envisaged to provide information for autopilot selection. Wind tunnel tests are also considered to measure the effect of counter-rotating propeller on the MAV aerodynamics for various angles of attack and angles of sideslip. This will also provide an information necessary for autopilot integration.

In the same time 2D numerical experiment is envisaged to better understand propeller-slot interference, to optimize the shape of the slot. Results of this experiment will be used for 3D optimisation of the complete MAV. The goal of this job will be obtaining the MAV geometry combining best cruise performance with ability

to deal with gusts causing brief periods of flight on large angles of attack. The last feature should not be worse than presented by first prototype, as described in chapter 2.

All this effort is directed to obtain useful MAV, equipped with suitable autopilot, which could be a stable platform for reconnaissance equipment in the turbulent environment.

6 Conclusions

- Vortical lift can be generated by cranked delta wing at low Reynolds numbers, which allows to create MAV capable of flying at high angles of attack.
- Leading Edge Extensions can be successfully integrated with the propeller propulsion, generating a leading edge vortex in the neighborhood of the propeller stream. This conclusion is supported by flight testing
- Oversensitivity to the propeller torque is a problem if conventional propeller is considered. However, it should disappear if contra-rotating propeller is applied since the total torque of the contrarotating propeller is negligible.
- Contra-rotating propeller has greater efficiency than conventional one in the same, small size.

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