RESULTS OF THE GUST RESISTANT MAV PROGRAMME

Cezary Galinski, Jacek Mieloszyk
Warsaw University of Technology
cegal@meil.pw.edu.pl , jmieloszyk@meil.pw.edu.pl

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Abstract

Paper presents results of an investigation on unmanned, supermaneouvral, fixed wing, Micro Aerial Vehicle (MAV). In particular results of multidisciplinary optimization are discussed. They were validated both numerically and experimentally with application of the wind tunnel. Both steps of validation are presented. At the end, final flight test campaign and its results are described.

1 Introduction

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

Air turbulence is perceived as a major problem for MAV outdoor applications. According to the literature [1] 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 negotiate turbulence.

Delta wing is known to have excellent performance at large angles of attack [2, 3]. Generation of the leading edge vortex allows reattaching the flow and improving stall qualities. Therefore delta wing was considered as a candidate for MAV design. However, quantitative data about leading edge vortex effectiveness at low Reynolds numbers were not available, so wind tunnel experiment was undertaken in order measure them [4]. Generally, the effect appeared to be similar to this obtained for large, manned aeroplanes. Additional application of Leading Edge Extensions (LEX) appeared effective too.

Design of the delta wing MAV with LEX was not trivial. Propeller propulsion seems to be the most reasonable for MAV. Propeller at the very front of the vehicle would strongly interfere with leading edge vortex, and possibly vanish all its advantages. On the other hand pusher configuration could be dangerous in the case of hand launching. Therefore an aircraft configuration was developed with propeller located inside the wing contour. To prove the value of the concept wind tunnel experiment was undertaken again [5]. Results seemed to be better than expected. Stall angle appeared to be greater than 30°. No disadvantageous effects were detected. Therefore flying prototype was designed, build and flight tested [6].

Fig.1 First flying prototype of the MAV

Fig. 3 The MAV “Cobra” maneuver.

Once again positive result was achieved. The prototype demonstrated ability to fly controllably at extremely high angles of attack. It was possible to perform maneuvers like “cobra” and recover without altitude loss. Load factors achievable during this maneuver appeared to be greater than calculated from wind tunnel tests. On the other hand almost vertical safe landings in deep stall were also possible. These results were good enough to prove the ability of the airplane to deal with very rapid angle of attack changes. However a few disadvantages were also noticed. For example the prototype was very sensitive to the motor settings. Every rpm change required immediate airplane trimming to maintain straight line flight. To solve this problem contra rotating propeller was applied in the second prototype.

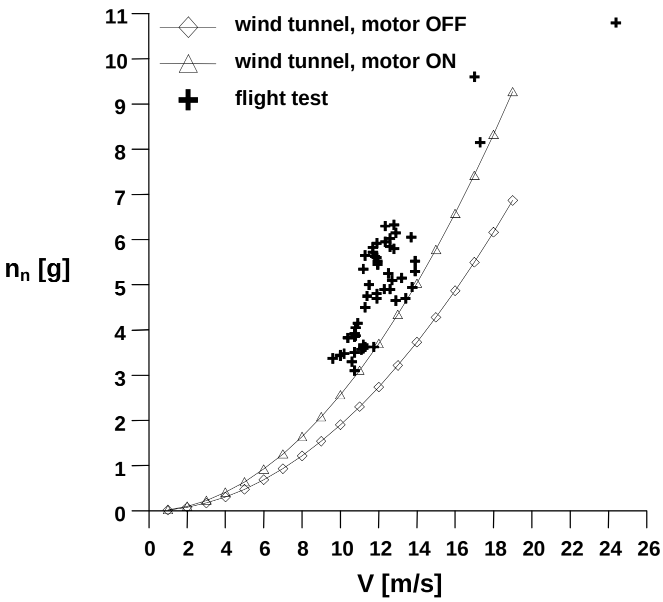

Fig. 2 Load factor acting on the MAV.

2 Design of the contra rotating propeller

One of authors developed computer code “DualProp” [7] for the design of the counter-rotating propeller according to Theodorsen theory published in [8-13]. Application of computer power helped to enhance calculations, which were conducted iteratively.

The propellers design was validated in a wind tunnel. Propellers were made out of carbon fiber-epoxy composite. Commercial coupled counter-rotating brushless motor [14] was used to drive the propeller. Conventional motor with a gearbox was considered first. However currently available coupled counter-rotating motors, are more promising for the MAV's propulsion. Their weight is almost two times lower than estimated mass of motor with a gearbox. Coupled motors are also more reliable, because of their simplicity. Therefore it was selected, as the final choice. Fig. 4 shows counter-rotating electric motor with propeller ready for testing.

Fig. 4 Set of counter rotating motor with the designed propellers.

Finally second prototype of MAV was equipped with this propulsion system and flight tested. It flies reliably in the design range of velocities, with minimum power consumption. Problem of the asymmetric rolling moment was successfully solved.

3 General MAV characteristics

Concept of micro delta wing with propeller working in a slot was new. Authors decided to make aerodynamic numerical simulation in Fluent [15] including high angles of attack to gain some knowledge concerning this novel configuration. At this point geometry used for analysis was not optimized and was estimated upon engineering assumptions, driven from previous flying platforms. This geometry already included some improvements based on previous experience, for example bigger fuselage volume necessary to contain equipment. Fig. 5 shows screen taken during analysis.

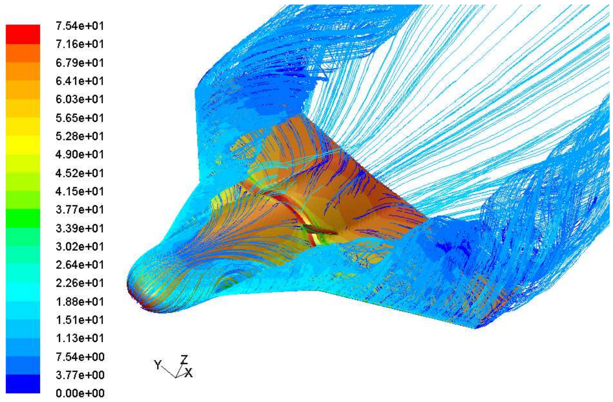

Fig. 5 Example from initial MAV's numerical analysis

During the analysis, mesh with moving propeller was considered and values of aerodynamic coefficients were averaged over significant number of time steps. Three cases were compared: aircraft with slot and rotating propeller in it, aircraft with slot but without propeller, and clean wing configuration without slot. Thanks to this approach it was possible to answer how big is the influence of the slot and working propeller on the global aerodynamic characteristics. Fig. 6 shows obtained results, which contain characteristics of lift and drag coefficients as a function of angle of attack. For small and medium angles of attack characteristics doesn't differ very much. Influence of the slot on the wing becomes visible for angles of attack above 20deg. Lift coefficient rises significantly. The greatest difference of 0.1 occurs for angle of attack equal to 34deg. The difference in lift coefficient drops and disappears after maximum lift coefficient is reached. Presence of the slot causes also some additional drag.

The last configuration, with slot and working propeller, is the closest to the reality. This configuration is represented by two curves on the chart, one representing characteristics with additional forces resulting from the thrust vector and second without it, to see also the influence of the thrust vector on forces. Presence of the propeller significantly strengthened aerodynamic mechanism of the slot. As a consequence both lift coefficient and drag coefficient were raised. Lift coefficient of the clean configuration is smaller by 0.3 than lift coefficient of the configuration with slot and propeller. 0.1 of this difference results from the thrust vector. Simultaneously drag coefficient of complete configuration is greater by 0.2 for the highest computed angle of attack. After summing drag and thrust vector components together the aircraft forces were balanced along X axis for angle of attack of about 6deg, which represents MAV's cruise conditions and corresponds with available flight data.

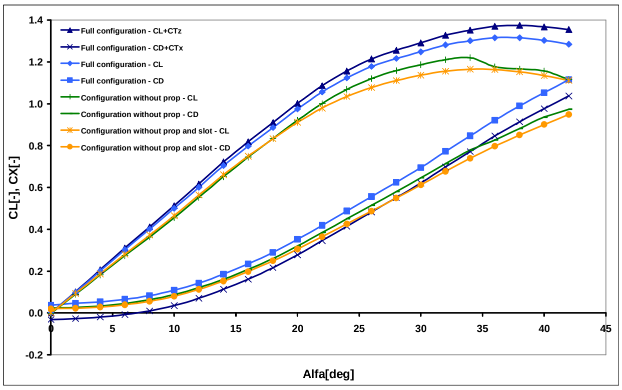

Fig. 6 MAV aerodynamic characteristics.

Unfortunately, this investigation showed that applied software was not useful for optimization of the whole airplane in existing conditions because calculations were too time-consuming. Therefore it was decided to split the whole process into two separate tasks [16]. 2D optimization of the slot was performed first with the Fluent and then the whole airplane without slot was optimized with less demanding software [17, 18].

4 2D analysis of the slot

Aerodynamic flow is very complicated in the area of the slot, where strong interaction is present between the counter rotating propeller and the wing. This paragraph discuses quantification of generated drag and its initial reduction, by testing different types of slot edges. 2D numerical simulation with application of Fluent software was done and compared with simulation of clean airfoil, which shows how big is the drag penalty because of the slot and what is the most desirable edges geometry. Example of the investigated geometry can be seen in Fig 7.

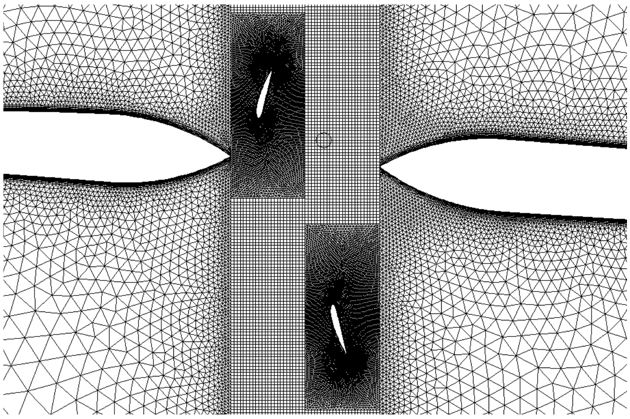

Fig. 7 Example of mesh used for 2D analysis and optimization.

Many different types of the edges were tested: sharp edge in the middle of the airfoil, in the upper part of the airfoil, in the lower part of the airfoil, rounded edges, ellipsoidal edges with varying axis lengths. The results were compared with the clean airfoil without propeller and with isolated propeller. The following parameters were obtained: wing's lift coefficient, drag coefficient, aerodynamic efficiency, longitudinal moment coefficient and propeller's thrust and drag coefficient. Values of these parameters were normalized. Every value was divided by arithmetic mean for easy comparison. Fig.8 shows results for the finally chosen edge geometry, with ellipse axis proportions 1:2 and the clean configuration.

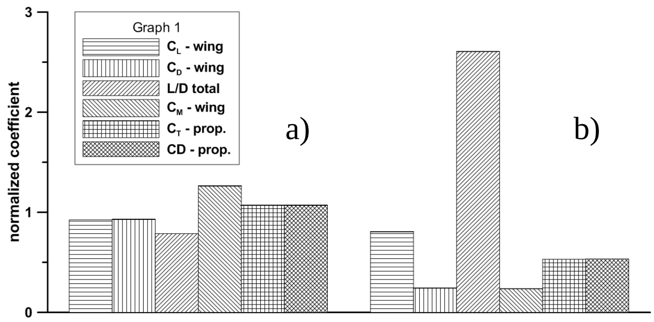

Fig. 8 Normalized coefficients for: a) airfoil with slot and propeller, b) clean airfoil.

Comparing configurations with each other indicates that thrust coefficient and drag coefficient of the isolated propeller are both two times lower than in the configuration with the slot. What is interesting, the ratio of the thrust coefficient to drag coefficient of the propeller doesn't change. It means that the propeller's aerodynamic efficiency is insensitive for a presence of the slot in the wing. In almost every investigated configuration, with slot present, lift coefficient of the wing is higher than for configuration without the slot, but in consequence drag and pitching moment values also increase. High pitching moment, which in the used coordinate system moves nose of the aircraft down, has negative effect, because it increases trim drag of the MAV. It has to be compensated by elevons to attain appropriate balance.

It is important to reach MAV's high aerodynamic efficiency for the investigated cruise conditions, on small angles of attack, because it has direct impact on the flight range. From Fig. 6 one can see that the aerodynamic efficiency is approximately 2.5 times higher for clean configuration. This is a price paid for excellent maneuvering capabilities. Without propeller working in the slot the MAV couldn't have such a good characteristics as presented in Fig 2, 3.

Influence of the propeller blades on the front and rear part of the airfoil was also checked. The drag coefficient is always higher on the rear part of the wing with slot and propeller in comparison to the clean configuration. Therefore shape of rear edge of the slot has crucial meaning for the drag reduction.

5 3D optimization of the airplane

The optimization was preceded by careful mass distribution analysis and electric wires layout planning. This part of the design was crucial because of very limited space in the airplane. Moreover different configurations of vertical stabilizers were investigated in the course of flight tests of both first and second MAV prototypes. It greatly reduced complexity of the optimization process since geometry of the vertical stabilizers became fixed. Uncertain points of the design were identified and optimization task of reasonable complexity was defined. The first optimization attempt was conducted with an inviscid solver PANUKL [17] with some simplifications imposed. Neglecting viscosity for the moment greatly reduced time of computations and allowed making tests with different solvers and different solvers' settings. The additional simplifications were: coarse grid, no vertical stabilizers, no propeller and slot in the wing, no vortex lift, and small angles of attack only. The last assumption was reasonable since drag reduction for cruise conditions was an objective of the optimization. The following parameters were used as design variables: angle of attack, length of the wing tip chord, wing sweep, position of center of gravity and parameters controlling polynomial defining nonlinear wing twist distribution.

Constrains enforcing balance of vertical forces and longitudinal static stability were set using penalty function method to obtain realistic solutions. This method of setting constrains is sufficient for gradient [19] as well as for genetic algorithms [20], which were used in this work.

Genetic and gradient algorithms were used for optimization, both giving corresponding results. Genetic algorithm was very robust, always delivering solutions. Contrary to that experience gradient algorithm needed a lot of time to set starting conditions allowing for solution convergence, but after they were set, solution converged much faster than in the case of genetic algorithm. Interestingly genetic algorithm, which can theoretically lead to random solutions, showed that two competitive solutions, with completely different geometry Fig. 9, are possible for the current optimization task definition. Wing sweep was a major difference between them. Dynamic stability analysis allowed defining correct wing sweep angle.

New conclusions were drown after obtaining first results from the optimization, with application of viscous solver VSAero [18]. This time vertical stabilizers were already present and the propeller was simulated by a disc with pressure jump (see Fig. 10). Analyses made during optimization showed areas of unfavorable pressure gradients, which couldn't be controlled by any defined optimization variable. Four additional variables were added, which modified wing tips and added filet in the center part of the wing.

The optimized MAV meets all optimization constrains and fulfills requirements for bigger internal volume for equipment components. Shape of the MAV became smoother and is more practical for maintenance and manufacturing in composite technologies. Fig. 11 shows the final optimized geometry.

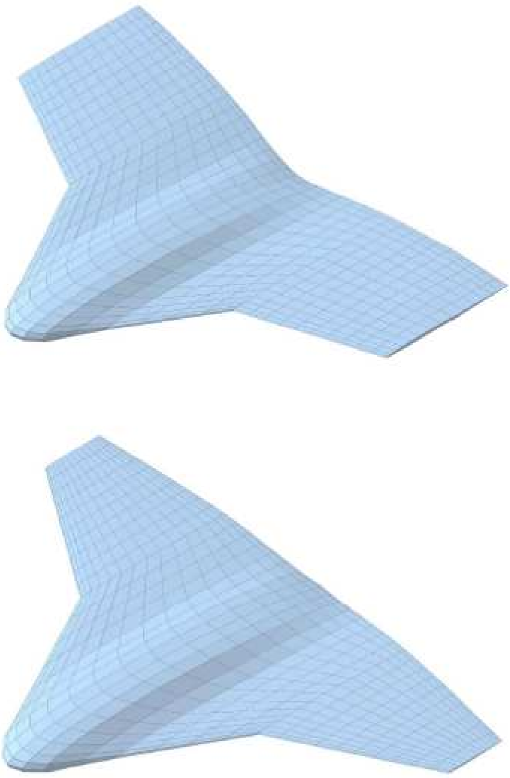

Fig. 9 Competitive solutions from genetic optimization method with inviscid solver.

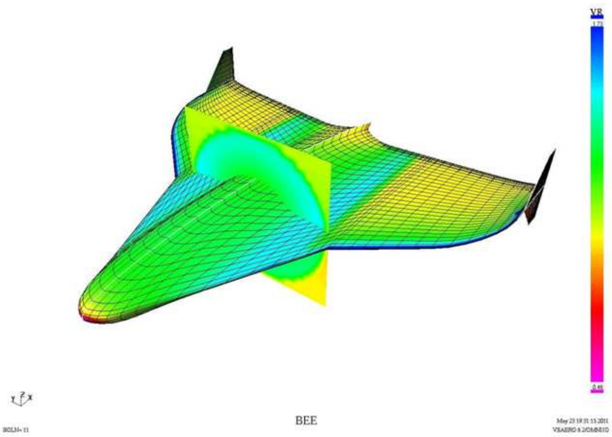

Fig. 10 Model used for optimization with viscous solver.

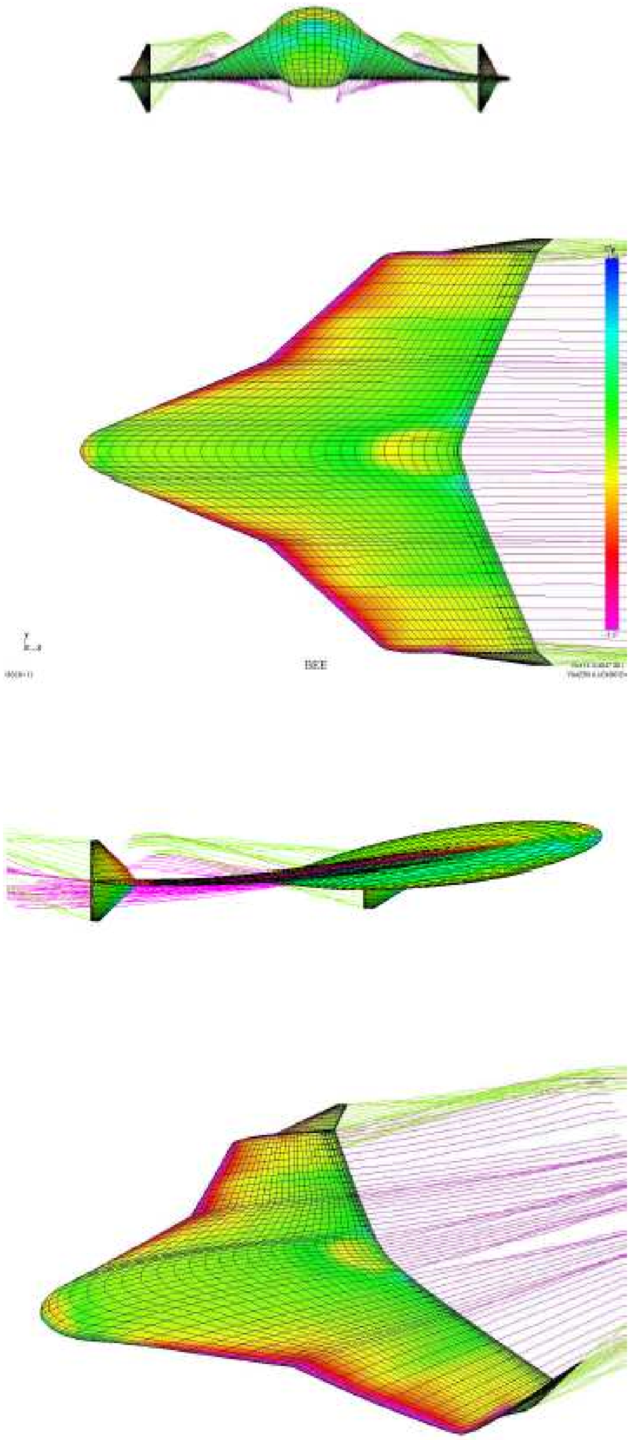

Fig. 11 The optimized MAV.

6 Numerical and experimental validation

Model applied for optimization had several simplifications; therefore results of final geometry aerodynamic analysis had to be validated. Validation was both numerical and experimental. Numerical part of this process was performed with Fluent whereas experimental results were obtained from wind tunnel. Experiment consisted of two major parts: static stability investigation and flight performance investigation.

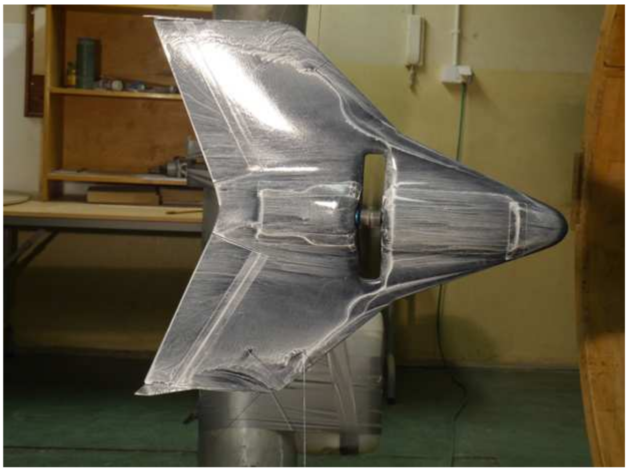

Fig. 12 MAV in a wind tunnel.

6.1 Static stability investigation

Derivative of pitching moment coefficient from lift coefficient was investigated. This parameter is very important, since it provides inevitable amount of aircraft longitudinal static stability. Pitching moment was measured for several origins to find center of gravity position providing correct pitching moment coefficient from lift coefficient slope Fig. 13. Position of origin, over which moments were measured, is presented in accordance to aircraft nose in mm units.

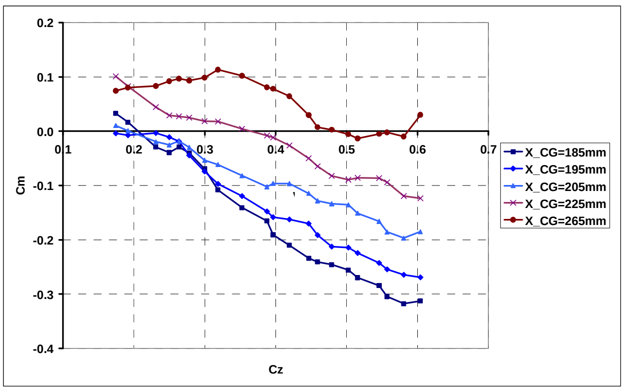

Fig. 13 Longitudinal moment coefficient from lift coefficient.

Neutral point position does not change since aircraft geometry was fixed. With position of origin shifted to the nose of the aircraft, distance between the origin and neutral point increased the slope of the pitching moment coefficient resulting in more stable aircraft. Origin located 265mm from the nose was very close to neutral point, which resulted in somehow erratic longitudinal moment coefficient value, far from being linear.

Finally position of center of gravity was set to X_CG=225mm for flying aircraft. This center of gravity position provided pitching moment equal to zero with undeflected elevons for lift coefficient equal to 0.4 corresponding to flight airspeed of 15m/s, which was assumed as a design point for the optimization. This result proves that wing twist was defined correctly in the course of optimization

6.2 MAV flight performance

Polar curve of lift and drag coefficient of the aircraft are shown in Fig. 14 and aerodynamic efficiency from lift coefficient in Fig. 15. The polar curve is very smooth. Minimum drag coefficient is equal Cx_0 = 0.06. Looking at Fig. 15 maximum aerodynamic efficiency point is between lift coefficient of 0.3 – 0.6. The aircraft design point is for lift coefficient equal to 0.4, what is in the middle of the optimum lift coefficient section. Conducted optimization enabled to achieve the best possible configuration and fulfill all stated constrains with very good final result.

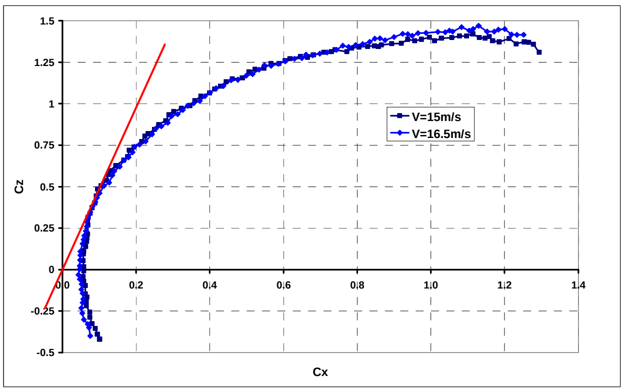

Fig. 14 MAV's polar curve.

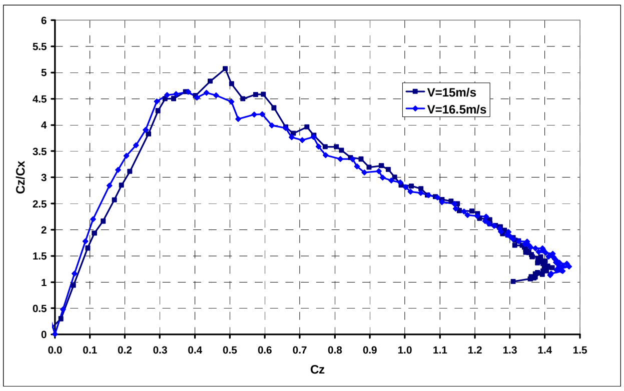

Fig. 15 MAV's aerodynamic efficiency from lift coefficient.

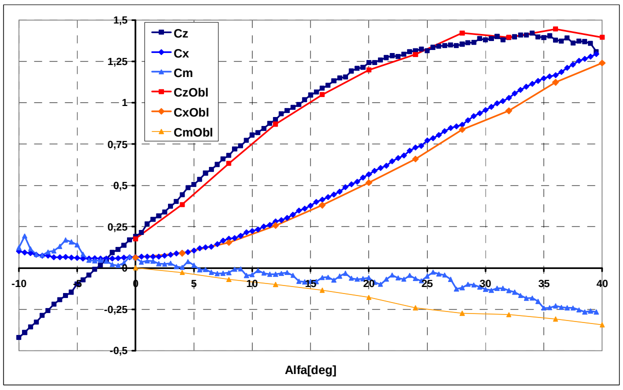

Fig. 17 Comparison of characteristics computed and measured in wind tunnel.

6.3 Numerical simulation validation

A number of simulations were performed to gain more detailed knowledge about aircraft aerodynamic characteristics. These simulations were performed with Fluent. Fig. 16 shows a mesh that was used for these calculations.

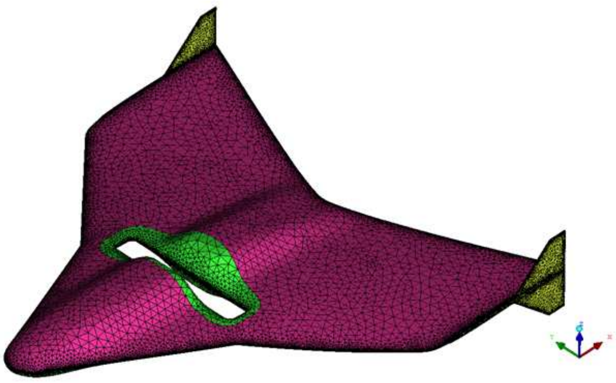

Fig. 16 Mesh applied for simulations with Fluent.

Fig. 17 shows comparison of aerodynamic characteristics of lift coefficient, drag coefficient and moment coefficient obtained in numerical simulation and during wind tunnel tests. Curves of lift coefficient and drag coefficient fit to each other very well, especially for low angles of attack. Moment coefficient has bigger error of correlation, but for low angles of attack, where trimming of aircraft is of most importance, they also correspond with satisfactory accuracy. This means that simulation gives valid results, and can be used for further detailed analysis of the flow.

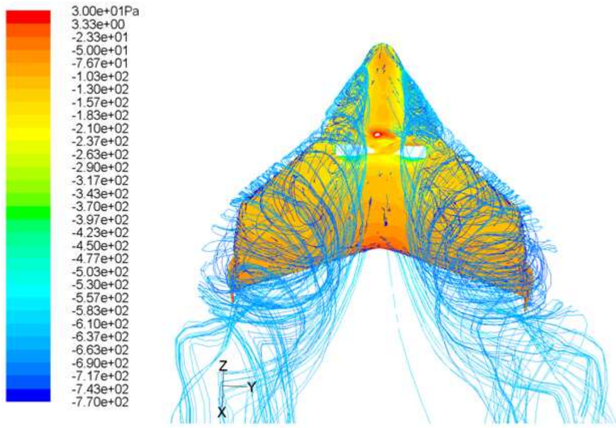

Fig. 18 Vortex flow visualization for the MAV with contra-rotating propeller running.

Some general conclusions about MAV performance can be also drawn from Fig. 17. Stall of the aircraft is very mild, with maximum lift coefficient achieved for 34deg angle of attack. Transition from small angles of attack to high angles of attack is also very mild without any characteristic lift coefficient curve slope change, which can be sometimes observed for wings equipped with LEX. Drag coefficient rises quickly for high angles of attack, having values of similar magnitude as lift coefficient for maximum angles of attack. Pitching moment coefficient is mostly linear with small kink with maximum for 26deg angle of attack.

7 Flight testing

Flight testing campaign of third, optimized prototype was undertaken at the end of the project.

Fig. 18 Third MAV prototype just after takeoff.

Fig. 19 Third MAV prototype in cruise.

Fig. 20 Third MAV prototype just before landing in bad weather conditions.

MAV was integrated with autopilot MP2128 [21] which allowed for autonomous flights along predefined paths. Flights were performed in various weather conditions ranging from calm and sunny weather up to windy and heavy rain. No obvious sensitivity for weather conditions was detected. Small dutch roll instability appeared to be much greater problem. It seems like increase of vertical stabilizers area would be helpful and/or application of rudders on them.

8 Conclusion

MAV was designed for gust resistance. It was assumed that application of aerodynamic configuration with wide range of useful angles of attack combined with high quality autopilot can help to negotiate turbulent weather conditions. Vortex flow generated by the delta wing with Leading Edge Extensions (LEX) was used to achieve angles of attack as high as 34 degrees. Unusual propulsion configuration was used with contra-rotating propeller in the slot of the wing to combine proper LEX operations with hand launch requirement. Application of this concept decreased aerodynamic efficiency of the MAV in the cruise conditions, therefore optimization was undertaken to improve airplane performance. This allowed designing quite successful MAV which flies well in various weather conditions, however, some improvements still can be done.

9 Acknowledgements

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