PERFORMANCE OF A MICRO-UAV LIFTING SYSTEM BUILT WITH THE USAGE OF RAPID PROTOTYPING METHODS

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Abstract. This article presents results of the aerodynamic testing of a micro unmanned aerial vehicle rotor efficiency. The rotors were prepared as a set of two rotors in a counter-rotating ducted drive. Prototypes of the drives were made using two rapid prototyping techniques - FDM – fused deposition modelling method and SLS - selective laser sintering. Rotors were made then treated by introducing additional finishing cyanoacrylate coating and abrasive processing. Main differences between those models were observed in fan shape, porosity, surface roughness and mechanical properties – stiffness. An influence of these factors was observed on an aerodynamic efficiency. For the obtained prototypes both simulations and experimental testing were conducted with thrust, power, torque measurements, as well as the measurement of velocity and pressure distribution at the outlet of the duct. The results show the possibility of using rapid prototyping techniques to produce prototypes of drives operating in the low and medium Reynolds numbers (6000-60000), and the aerodynamic shape relevant factors affecting the preparation and performance of such drives. In addition, simulation studies were performed using the Fluent environment where experimental results were confronted with the results of simulation studies.

1. Introduction

A growing scope of applications for MAV’s encourages further development in low and ultra-low Reynolds number aerodynamics [1], [2] and [3]. This field may be characterized by very low lift-to-drag ratio (15-35 for Re in the range from 5000 to 40000). Presented work relates to low Reynolds number drive manufactured by means of rapid prototyping methods designed for rough terrain purpose. The idea for a ducted counter-rotating drive came as an idea for the most ergonomic drive for the purpose to which the designed mechanism is addressed, namely autonomous flight in a rough terrain (shrubs, trees etc.). On the same basis requirements for dimensions were defined as a compromise between weight and performance. Taking these aspects into account, basic assumptions were fulfilled by the construction presented below.

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2. Design

The system was designed with the usage of software based on calculations according to Blade Element Method developed by Glauert [4], and further adopted to VTOL flight by McCormick [5] and profile characteristics estimated in Xfoil. Primary design was later verified by Fluent modelling taking into account effect of a duct. Samples were then produced using two rapid prototyping methods – FDM (fused deposition modelling) and SLS (selective laser sintering). Rough samples were then tested and after the test finished using hand abrasive polishing. Samples were then tested again. Different designs were tested according to this manner. This study was performed to find the best design out of the tested concepts.

A basic NACA 3404 with extended trailing edge gap was adopted for blade geometry (figure 1). Pitch angle and chord distribution along the radial coordinate are presented in figure 2 and 3. Duct and hub geometry is sketched in figure 4.

![Figure 1. Naca 3404 with a broader trailing edge gap (1% c).](image1)

![Figure 2. Pitch angle distribution along the span.](image2)

![Figure 3. Chord length distribution along the span.](image3)

![Figure 4. Duct and hub geometry.](image4)
3. Production process output

Manufactured samples are presented in figure 5 (rough samples) and figure 6 (comparisons before and after finishing). Rough samples produced by SLS method (Polyamide material was used) characterize good consistency, material is rough with low porosity. Blades are not very stiff and during testing flutter occurs for significant range of RPMs. FDM made rough samples (base material ABS) picture clear artefacts of manufacturing process – single fibres are clearly seen, for thin parts of blade single layer of fibres gives significant transparency. Samples are quite stiff and do not suffer from aeroelastic problems.

![Figure 5. FDM (ABS) rotor, right and SLS (PA) rotor, left after manufacturing.](image)

To increase aerodynamic performance samples were finished with the usage of: firstly cyanoacrylic coating, secondly abrasive treatment of the coating. Both processes were hand-made. Significance of the second phase is vital for the final effect. For SLS samples low abrasive properties of polyamide were very useful because rough sample was a very good base for the process and the surplus coating was eliminated without significant destruction of base material, therefore the intended shape was not significantly corrupted. In the FDM samples, on the other hand, base material (ABS) was vulnerable to abrasive treatment, therefore final geometry depends very much on worker skills and the recurrence properties of each blade may be questioned. SLS properties were finally improved also because of improved stiffness of the blade, therefore aeroelastic behaviour of the blades was insignificant for the results of the test. Final mass of FDM rotor after finishing was 1.45g, and SLS 1.15 gram.

![Figure 6. Raw samples roughness and porosity (SLS on the left and FDM on the right).](image)

Effects of surface treatment can be observed in following pictures (figures 7 to 12). Figure 7 presents roughness of rough SLS sample, figures 8 and 9 present roughness of respectively treated upper and lower surface of the blade. Shape of first diagram reflects non-structured composition of the rough sample reflecting grains of sintered base material. The following two pictures show small scale
roughness of the surfaces after treatment. No significant differences between upper and lower surface are observed.

Figure 7. Raw samples roughness (SLS).

Figure 8. SLS surface-treated samples roughness (upper surface).

Figure 9. SLS surface-treated samples roughness (lower surface).

Effects of surface treatment of the FDM samples can be observed in figures 10 to 12. Figure 10 presents roughness of rough FDM sample – fibres are clearly seen, figures 11 and 12 present roughness of respectively treated upper and lower surface of the blade. Important increase of lower blade surface roughness is caused by deep crevasses – artefacts of initial structure.
Roughness results were summed up in table 1. Surface treatment decreased roughness by two orders from approximately 35 \( \mu m \) (Ra) to 0.5 \( \mu m \) (Ra). It is likely that further decrement of roughness may further influence the result but in this course of investigation resulting performance was satisfactory. Further investigation will also cover further improvement of surface quality, although rather decrement of aerodynamic performance may be expected due to increased likelihood of laminar separation occurrence.
Table 1. Roughness measurements results.

| Sample               | Ra (µm)               |
|----------------------|-----------------------|
| SLS rough            | 16.53 (+8.93/-4.78)   |
| SLS finished upper/lower | 0.39 (+0.04/-0.06) |
| FDM rough            | 35.73 (+3.67/-4.55)   |
| FDM finished upper   | 0.55 (+0.03/-0.03)    |
| FDM finished lower   | 3.01 (+0.4/-0.4)      |

4. Simulations

After the design stage, Fluent simulations were performed as well as corrections to the preliminary design were implemented. Pressure-based Navier-Stokes model with transient SST turbulence modelling, on transient solver with rotating parts was used.

Figure 13. Meshed duct and the domain.

Figure 14. Meshed blade and the domain.

Figure 15. Pressure contours in passing-by configuration of blades (19 kRPM).
Fluent results at this stage were performed on a mesh with approximately 1.6 mln nodes. Although layered mesh was generated around the blades to solve boundary layer more accurately, it needs further improvement of quality. A special mesh treatment is planned for further investigation. Some properties of rough and smooth profiles may be controlled by transition properties, and to some extent by shape deformation (3404ZZ profile) in Xfoil [6] (figure 16 and 17), although it is a problematic issue and significant shape deformation (such as in rough FDM samples) should be further investigated.

Figure 16. Xfoil – generated polars graphs for different transition scenarios. 

Figure 17. Xfoil – generated CL(α) graphs for different transition scenarios.

5. Testing

Tests were performed on a dedicated test stand presented in figure 18. During the course of design process many configurations were tested (rotors, motors and regulators). Results presented in table 2 were obtained for final set of motor, regulator and rotors.

Figure 18. Test stand arrangement.
6. Results and discussion

Final tests were presented in table 2. Rough samples present significantly lower thrust and definitely lower thrust@power-supplied performance. Two reasons seem to be of greatest significance – overall and surface shape and porosity. FDM samples’ results, where porosity is clearly visible, are lower comparing to SLS samples’ results (although roughness is similar). Finished samples results are significantly better (over 50% increase in thrust, similar power consumption), where SLS samples are slightly better than FDM samples. This effect is most probably because surface geometry was less rough and overall geometry reproduction was better because of low-abrasive properties of polyamide.

|          | 19 kRPM | 21 KRPM | 22.5 kRPM |
|----------|---------|---------|-----------|
| SLS rough| 28 (@ 12W) | 36 (@ 14.7W) | 40.7 (@ 16.9W) |
| SLS finished| 42 (@ 13.2W) | 53 (@ 15.5W) | 60.5 (@ 17.6W) |
| FDM rough| 23 (@ 13.6W) | 32 (@ 15.2W) | 37 (@ 17.4W) |
| FDM finished| 41 (@ 13.6W) | 51 (@ 16.8W) | 58 (@ 18.9W) |
| BEM      | 40.5 (@ 13.5W) | 49.5 (@ 18.2W) | 56.9 (@ 22.4W) |
| Fluent   | 44 (@ 16W) | -       | 68 (@ 24W) |

Presented study showed the need for further investigation for dependency between roughness and performance, taking into account transition control and detailed study of shape reproduction.

7. References

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Acknowledgements

This work was supported by The National Center for Research and Development in course of a Lider Program. Grant no. LIDER/04/143/L-3/11/NCBR/2012.