THE PROPELLER DESIGN FOR MINI UAV VUT – 700 SPECTO

Ivan Dofek
Faculty of Mechanical Engineering Brno University of Technology
Technická 2896/2
616 69 Brno
ydofek00@stud.fme.vutbr.cz

Abstract. The article deals with design of advanced composite propeller for Mini UAV VUT - 700 SPECTO. The design process is naturally divided into three main parts - theoretical design of optimal blade shape, CAD design and production. The last part of this article concerns CFD analysis of propeller and basic overview of propeller test stand for practical propeller ground test.

Keywords : airfoil, blade, CFD, efficiency, optimization , power, propeller, thrust, torque, validation, vortex theory

1 Nomenclature

c_d	blade section drag coefficient
c_l	blade section lift coefficient
d	propeller hub diameter
D	propeller tip diameter
Q	nondimensional propeller tip radius
N	power
$\overline{N}$	nondimensional power
T	thrust
$\overline{T}$	nondimensional thrust
μ	drag-to-lift ratio
t	blade section thickness
$\overline{\Gamma}$	nondimensional circulation
$\overline{b}$	nondimensional blade section chord
λ	variation problem constant
V_∞	freestream velocity
n	propeller rpm
k	number of blades
J	advance ratio
nr	number of cross setions

2 Introduction

The aim of this article is to summarize the important facts of propeller design for MINI UAV VUT – 700 SPECTO, basic view on CFD analysis this propeller and propeller test stand. The motivation for making of new propeller was that there are a lot of model airplane propellers on the market but they are without propeller characteristics, airfoil and other informations. The propeller design is divided into three main parts : theoretical design of optimal blade shape, CAD design and production. The theoretical design of optimal blade shape describes an optimization technique with the constrains by solving variation problem. The CAD design is focused on creating of design documentation. The production, the last part of propeller design, describes the process of manufacture of propeller blade. Furthermore, the CFD analysis is focused on numerical solution of propeller flow by CFD software Fluent, its validation and comparison of analytical and numerical solution. The purpose and the function of propeller test stand are briefly discussed.

3 Propeller design

3.1 The theoretical design of optimal blade shape

There are a lot of approaches in literature which are focused on propeller design procedure, analysis of arbitrary design of propeller. These approaches differ mainly in accuracy of the gained distribution of the aerodynamics loads along the propeller blades and the blade section chord, the complexity of numerical solution and computing time. One of the approaches are analytical processes. They have good accuracy, low computing time and their complexity of numerical solution is not problematic. It is only possible to gain distribution of the aerodynamics loads along the propeller blades. The applications of the analytical processes can be found in Čenský [1], Adkins [2] and Gur [3]. Next approaches are the vortex lattice methods and CFD methods. These are more detailed in solution of aerodynamics loads but they are generally more complicated than the analytical methods. The application of vortex lattice method, especially for UAV, is described in Burger [4]. The analyze of fluid flow by CFD method is presented in Caridi [5] and Koch [6].

Joukovsky's vortex theory of propeller (under mentioned vortex theory) is one of the analytical processes. Design procedure and analysis of arbitrary design of propeller by vortex theory are presented in Alexandrov [7], Švéda [8], Čenksý [1] and are lectured in the Aeroplane propeller classes at Aircraft department of Brno UT. In the vortex theory, there is not possible to obtain an optimal design of propeller blade, but only informations about propeller thrust and power can be received. This vortex theory was extended to include optimal design procedure on Aeroplane propeller lectures by solving variation problem with constrains. This optimal design procedure and vortex theory were used for the theoretical design of optimal blade shape.

3.1.1 Formulation of problem

The task is to design the adjustable blade propeller. The shape of propeller blade is designed to have the best efficiency for one flight regime. The efficiency is defined by formula: $\eta = \frac{V_{oo} \cdot T}{N}$

3.1.2 Airfoil

There are a lot of airfoils, which are used for propeller design. The Clark Y is frequently used as the section of propeller blade for very light aircrafts. In Koch [6], the airfoil Eppler 387 was chosen as the propeller blade section for very high altitude flight. The airfoil NACA 44XX was selected for the section propeller blade in this work. There are several reasons for selection of the airfoil NACA44XX:

- available generator of airfoil NACA 44XX shape
- small influence of airfoil thickness on change of lift curve in linear region
- these series of airfoils were tested many times for different Reynolds and Mach numbers in wind tunnel (e.g.NACA reports)
- in wind tunnel low sensitivity for contamination and roughness of surface

3.1.3 Variation problem

For to find a solution of the isoperimetric problem, the task can be simply formulated as follows: find a closed flat curve of a given perimeter which encloses the largest area. The next formulation is used in application for optimization process : There are two given functions $F(x,y,y')$ and $\Phi(x,y,y')$ and task is : find a flat curve for which functional $G=\int_a^b \Phi(x,y,y')dx$ gets value of constant G and at the same time it leads to extreme of functional $I=\int_a^b F(x,y,y')dx$. The problem can be reduced in $H=\int_a^b [F(x,y,y')+\lambda\Phi(x,y,y')]dx$. The solution of functional corresponds with Euler differential equation $F'_y-\frac{d}{dx}F'_{y'}=0$.

The function F can be thrust $\bar{T}(\bar{r},\bar{\Gamma},\bar{\Gamma}')$ or $\bar{N}(\bar{r},\bar{\Gamma},\bar{\Gamma}')$ in the same way like the function Φ can be thrust or power. These functions represent distribution of thrust coefficient or power coefficient along the propeller blade.

3.1.4 Solution of isoperimetric problem and its application for optimal blade shape

The process of the solving isoperimetric problem and its application for optimal blade shape is explained on figure 1. and this process can be used as iteration process by changing input parameters. There are three main parts: input, solution of isoperimetric problem and output. These individual parts form optimization process and are described next:

Input

One flight regime is selected and there are input informations about free stream velocity, airfoil characteristics, width distribution along the propeller blade, tip and hub diameter, rotation speed, number of blades and flight level. The power or the thrust are the last input informations and create two different constrains and solutions. If the power (thrust) is a constrain, the maximal (minimal) value of thrust (power) is found. The input informations could be divided as follows :

- aerodynamics input informations : free stream velocity, airfoil characteristics and flight level
- design information : tip and hub diameter, width information along and number of blades
- engine informations, constrains and numerical informations : power, thrust, rotation speed number of cross sections

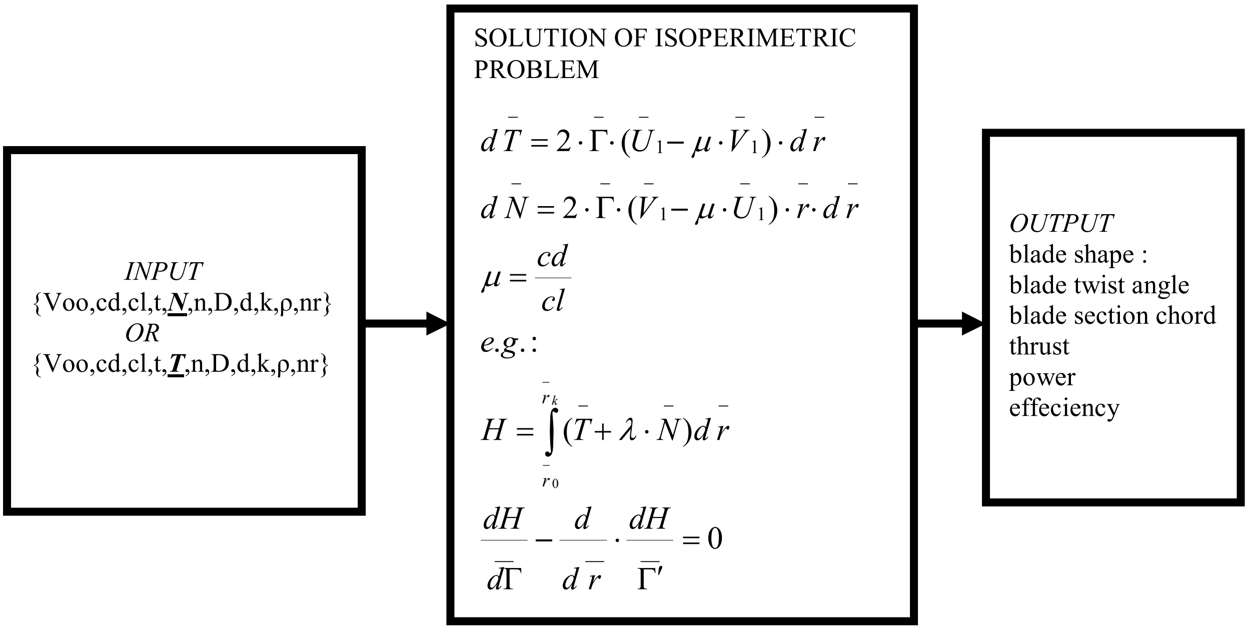


Figure 1: The flow chart Solution of Isoperimetric Problem.

Solution of isoperimetric problem

There is found the optimal distribution of non-dimensional circulation along the propeller blade with constrains by solving Euler differential equation. The drag-to-lift ratio is selected for every cross section and this is set up at minimal value.

Output

The blade shape and value of delivered propeller or thrust are the output informations. The blade shape is described by distribution of blade twist angle and section chord. The value of propeller efficiency is important information. This says whether efficiency needs to be improved or not. If there is a request for better value of efficiency than input values can be changed and process will be repeated until this is accomplished.

3.1.5 Practical examples of propeller for Mini UAV VUT – 700 SPECTO

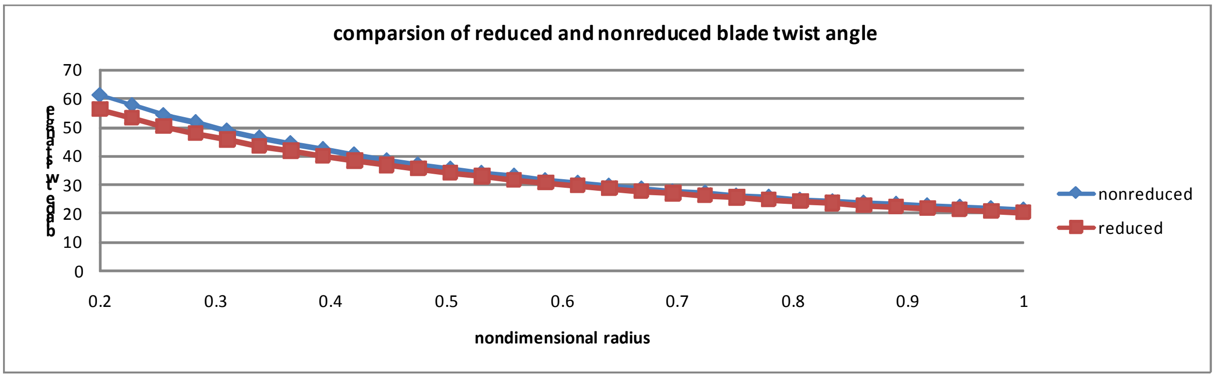
There is described practical application of propeller design process for one flight regime.

Input information

free stream speed Voo = 160 km/h
rotation speed n = 6000 rpm
engine delivered power N = 2.8 kW
hub and tip diameter d = 0.05 m, D = 0.5 m
number of blades k = 2
flight level 0 m International Standard Atmosphere, $\rho = 1.225\ kg/m^3$
airfoil characteristics for NACA 44XX
drag-to-lift ratio is set at minimal value, about $\mu = 0.023$
linear distribution of thickness along the propeller blade, hub diameter t = 30%, tip diameter t = 10%

Output information

The results : Thrust T = 54.96 N, Power N = 2.8 kW, efficiency $\eta = 87.2\%$.
The propeller blade shape is presented in figure 2 as non-reduced.



a) comparison of reduced and non-reduced blade twist angle
b) comparison of reduced and non-reduced blade section chord

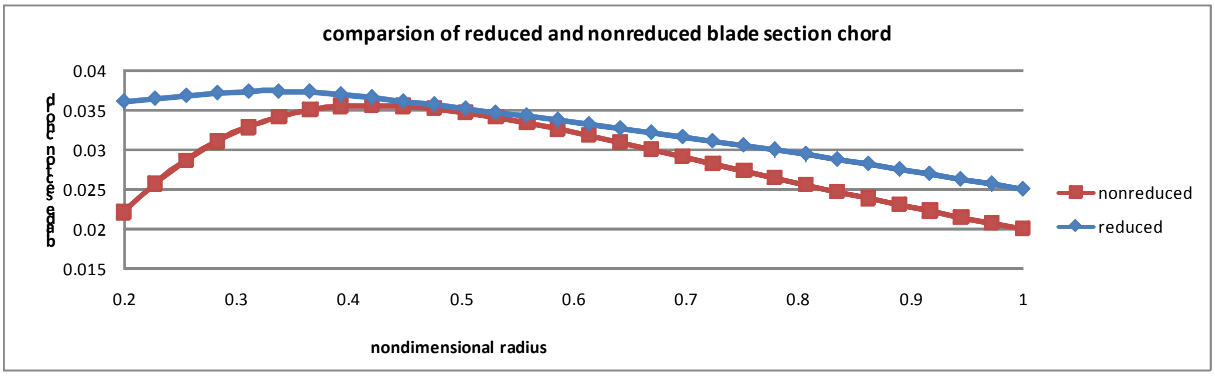
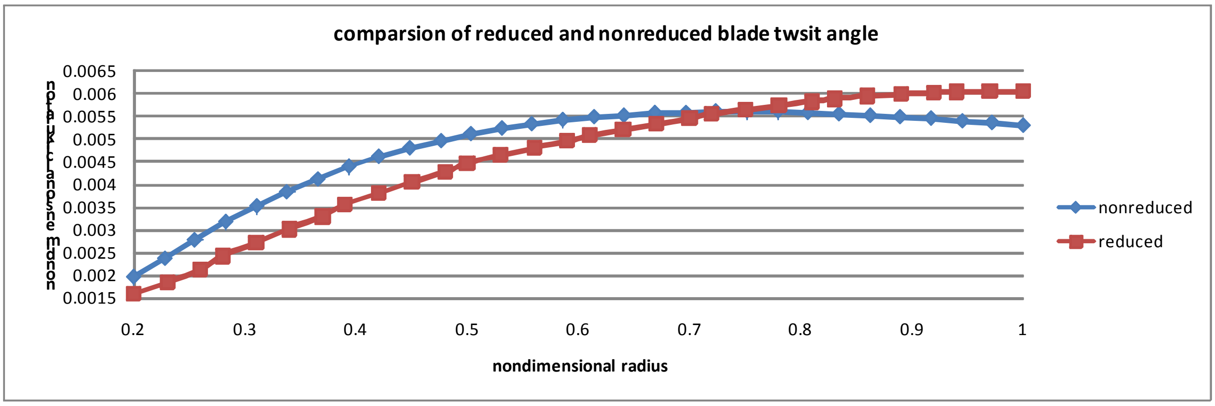


Figure 2: The Graph of propeller blade shape a), b), c)

c) Comparison of reduced and non-reduced blade twist angle



The process has additional part because of structural constrains. The output blade section chord distribution along propeller blade does not need to accomplish structural constrains. Therefore it must be reduced by solving equation $\bar{\Gamma} = \frac{1}{2} \cdot c_L \cdot \bar{b} \cdot \overline{W_1}$. Where $\bar{b}$ is prescribed non-dimensional blade section chord along the propeller blade. There is subsequently changed distribution of lift coefficient and output values thrust, power and efficiency must be maintained. The comparison of non-reduced and reduced values blade twist angle, blade section chord and non-dimensional circulation is in the figure 2. as reduced.

Here are values of thrust, power and efficiency before and after reduction.
non-reduced Thrust T = 54.96 N, Power N = 2.8 kW, efficiency η = 87.2%
reduced Thrust T = 54.38 N, Power N = 2.79 kW, efficiency η = 86.5%.

The maximal percentage difference between reduced and non-reduced values of thrust, power and efficiency is about 1%.

3.2 Parametric shape generator and CAD model

There was need to have CAD model of propeller blade. For this purpose, it was necessary to create blade shape generator. It uses output shape informations, b-spline and NACA 44XX generator for generating main part of propeller blade which is in figure 4. The part is composed by several sections. Each of this section is function of distribution of blade section chord, blade twist angle and local thickness. Thereafter, the main part of the propeller blade is exported into CAD software CATIA V5, where the propeller blade tip and hub are added. The cad model is in figure 3.

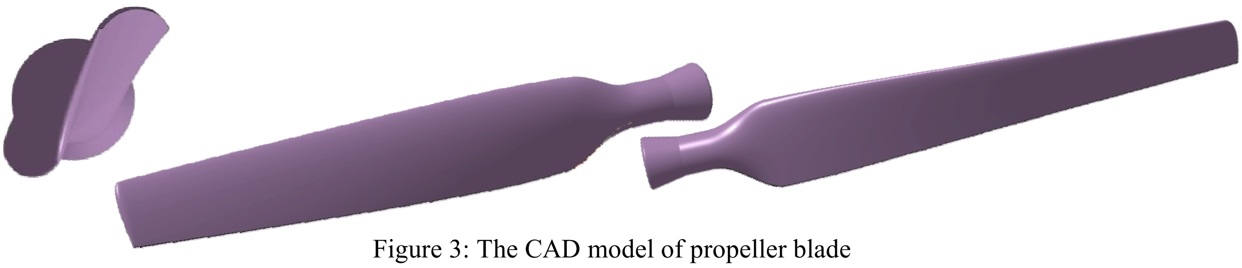


Figure 3: The CAD model of propeller blade

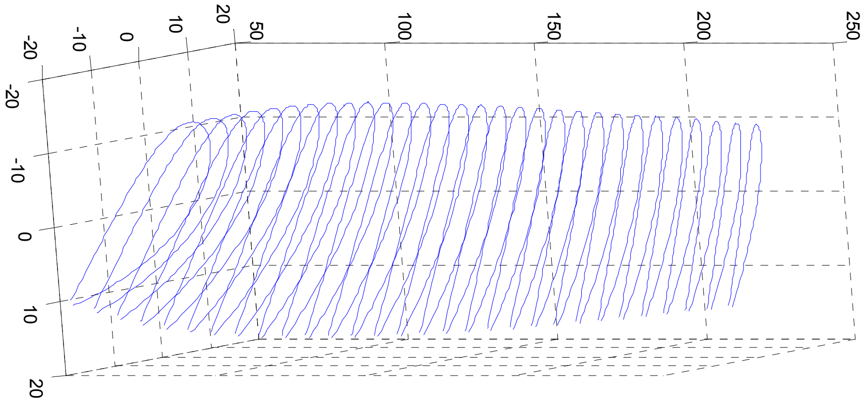
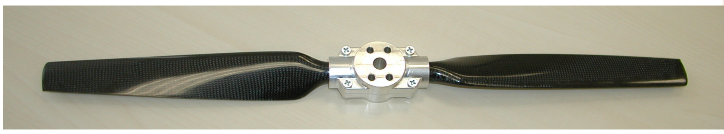


Figure 4: Shape of propeller blade

3.3 Production of propeller

The propeller consists of propeller hub and two composite propeller blades. Propeller hub was made by CNC mill from dural. The production process of the composite propeller blade is briefly presented in figure 5. There was used 3D printing technology for making of solid body of propeller blade. The solid body was used as a positive form and afterwards it was used for creating of negative form.



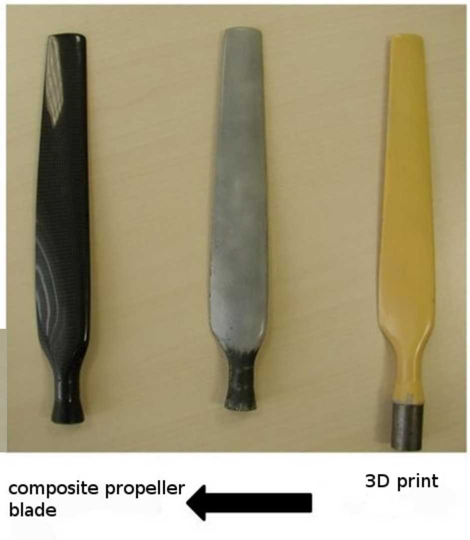


Figure 5: Process of production, complete propeller

4 CFD simulation

The propeller CFD simulation is divided into two parts. The first part is focused on comparison of CFD simulation results with wind tunnel test data and the second is focused on simulation of designed propeller and comparison with analytical solutions.

The main settings for all CFD simulations :

- The fluid flow was stationary, compressible and viscous
- Software : Fluent 6.3.26 and ANSYS Release Version 12.1
- Density Based Solver, Steady, Implicit Formulation
- Turbulence model : Spallart Almaras •
- The first cell height of the prism layer was set that Y+ values were below 1
- Green-Gauss Cell Based gradient discretization
- Discretization scheme : Third-Order MUSCL
- MRF model

4.1 CFD validation

The combined wind tunnel tests of force and wake survey NACA[9] were preceeded with three-blade propeller. There were seven propellers tested. They are labeled with numbers from 1 to 7. The propeller numbers from 1 to 6 have NACA 16 – series airfoil section along the propeller blade, united thickness and twist distribution and different blade section chord distribution. The forms of first six propellers are presented in figure 6. The propeller number 3 was selected as a CFD testing case because of shape similarity with designed propeller. MATLAB script was programmed for generation and export geometry data. The propeller geometry was made in CAD software CATIA V5 (figure 6.).

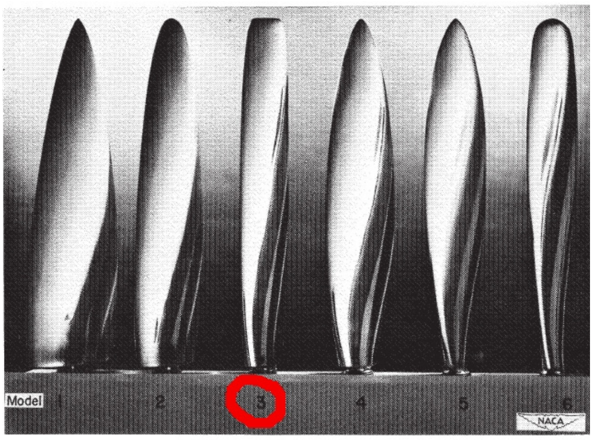


Figure 1.- Forms of model blades tested.

a)

b)

Figure 6: a) Form of 6 propeller [8], b)CAD model of propeller number 3.

The hybrid mesh was created in ANSYS ICEM CFD 12.1 software. There was used periodic boundary condition. Hybrid mesh has about 2.2E6 elements and 20 prismatics layers. The periodic computation domain is in figure 7.

Test case properties

propeller blade was set at β75 = 12 deg

rotation speed = 2100 rpm

advance ratios = 0.182, 0.248, 0.282, 0.319, 0.361, 0.401, 0.437, 0.482, 0.520, 0.560, 0.597

each values of advance ratio have ordinal number from 1 to 11 (e.g. J = 0.182 ... 1, J = 0.248 ... 2,...)

free stream velocity V_∞ was computed from $J = \frac{V_\infty}{n \cdot D}$, where n is rotation speed in rps and D propeller diameter in m.

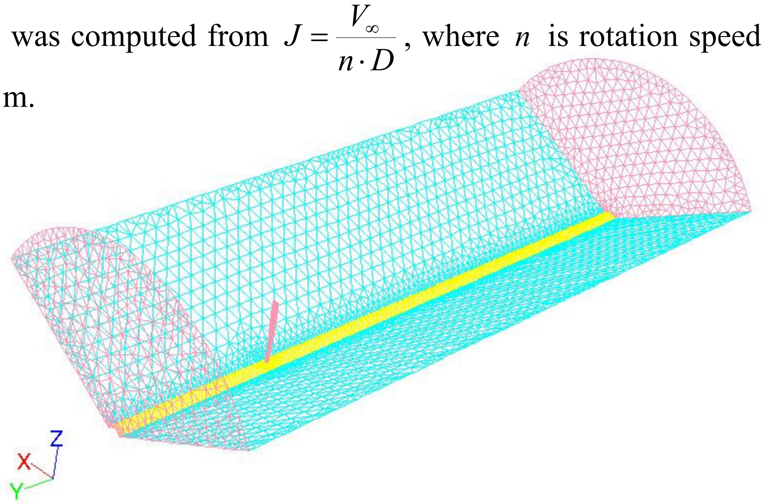


Figure 7: The periodic computation domain

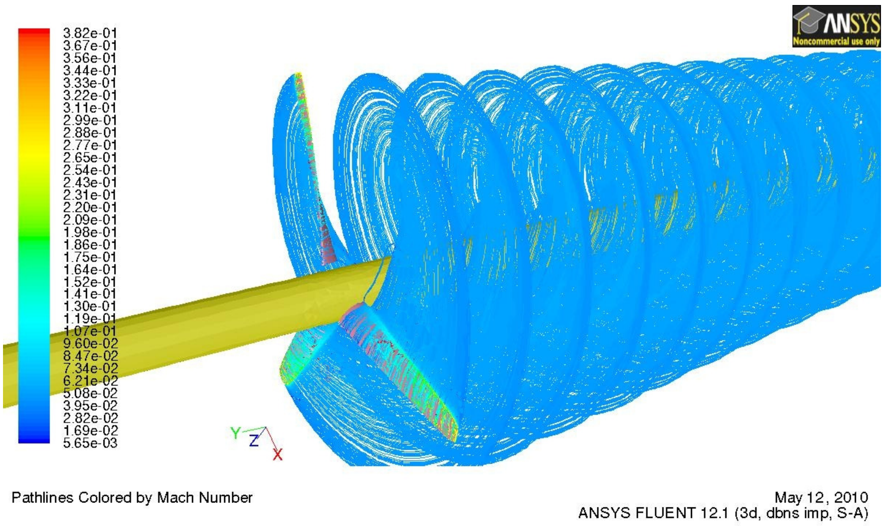
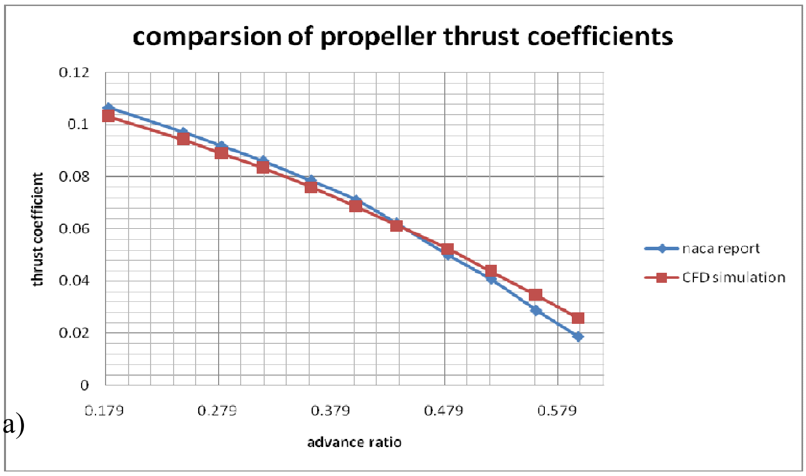


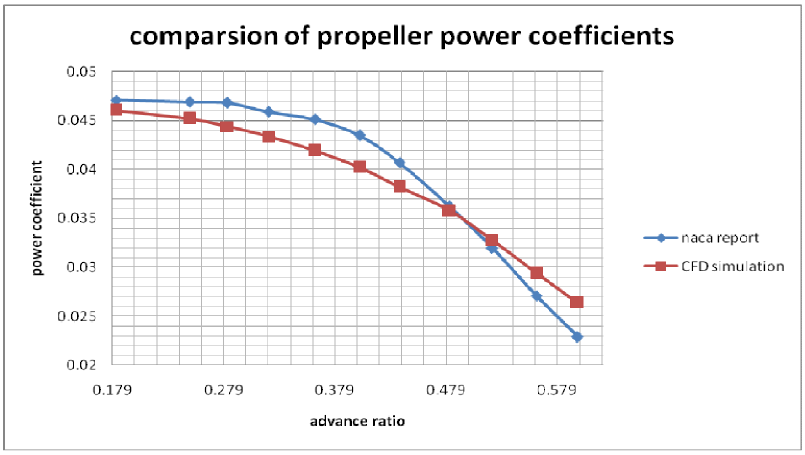
Figure 8: Pathlines of propeller 3

In figure 9., there can be seen good agreement of experimental data and CFD simulation. The maximal percentage difference for thrust and power coefficients is about 7.5% in test number from 1 to 9 but for test numbers 10-11 is ct% = 20%,38% and cp% = 8.5%,15%. The high percentage difference in test numbers 10-11 can be caused by flow separation on propeller blade.



a)

b)



c)

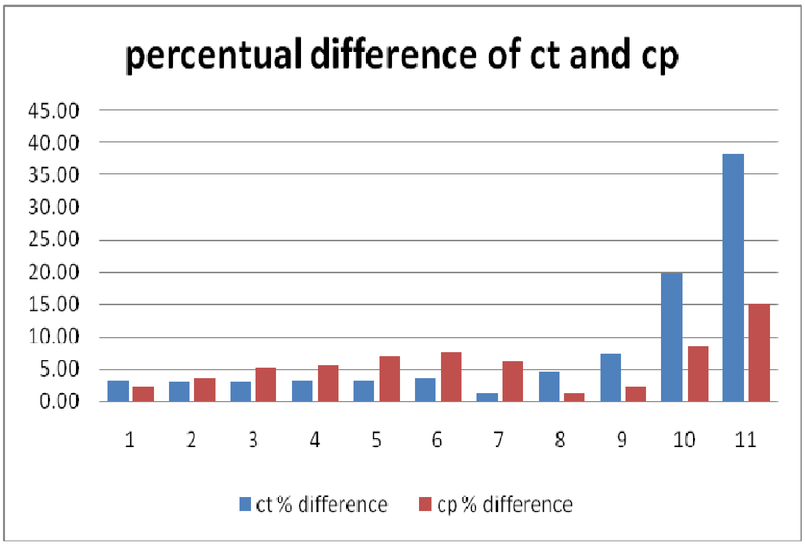


Figure 9: The comparsion of wind tunnel test with CFD simulation

4.2 CFD simulation of designed propeller

There were performed two CFD simulations of two propellers. First simulation is focused on CFD analysis of designed propeller and comparison with analytical solutions. The second simulation was focused on CFD analysis of designed propeller with non-reduced shape propeller. In the end the results of the simulations of these two propellers were compared. The non-reduced propeller has different thickness distribution along the propeller blade and so it would be used for arbitrary design in the future. The distribution of thickness along the propeller blade of non-reduced shape propeller is linear, at the hub t = 12% and at tip t = 10%.

The hybrid mesh was created in ANSYS ICEM CFD 12.1 software. There were used two different types of computation domains. For the first CFD simulation cylindrical computation domain was created. For the second one there was created computation domain with periodic boundary condition. The mesh for the first simulation has about 1.1E6 elements and the second about 1.2E6. Both have 20 prismatic layers.

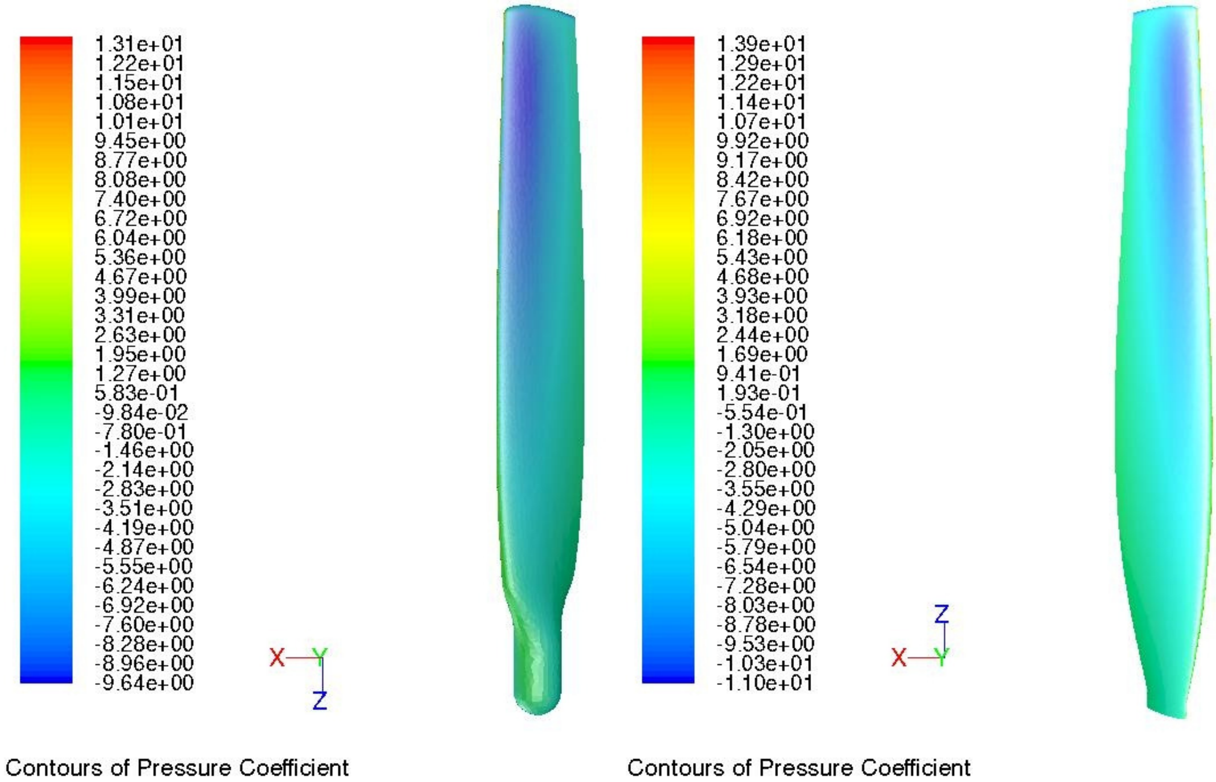


Figure 10: The Contours of Pressure Coefficient of non-reduced and reduced propeller blade shape

Test case properties
rotation speed = 6000 rpm
free stream velocity = 160 km/h

The comparison of CFD simulations with the analytical solutions

the analytical solution
reduced T = 54.38 N, Q = 4.45 Nm

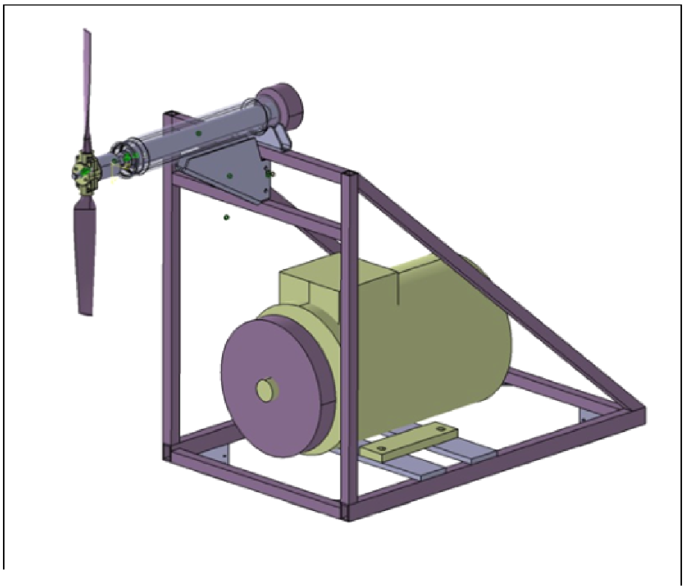
the CFD simulations
reduced T = 51.74 N, Q = 4.30 Nm
non-reduced T = 49.20 N, Q = 4.19 Nm

percentual difference
CFD reduced and analytical reduced T% = 5%, Q% = 3%
CFD reduced and non-reduced T% = 5%, Q% = 3%

5 Propeller test stand

The stand has two different objects. The first is measurement of propellers, particularly measurement of propeller static thrust and engine power. The second object is over torque to prove strength and reliability of propellers. The stand image is based on lever principle (figure 11c.). The rotation axis will be near the centre of gravity to eliminate electromotor weight. Propeller is driven by 7.5 kW Siemens electromotor with frequency convertor to change the rotation speed. The propeller drives belt with gear ratio 1:3. The maximal rotation speed is going to be approximately 9000 rpm. The propeller test stand is still in progress. It will be finished in two months.

a)



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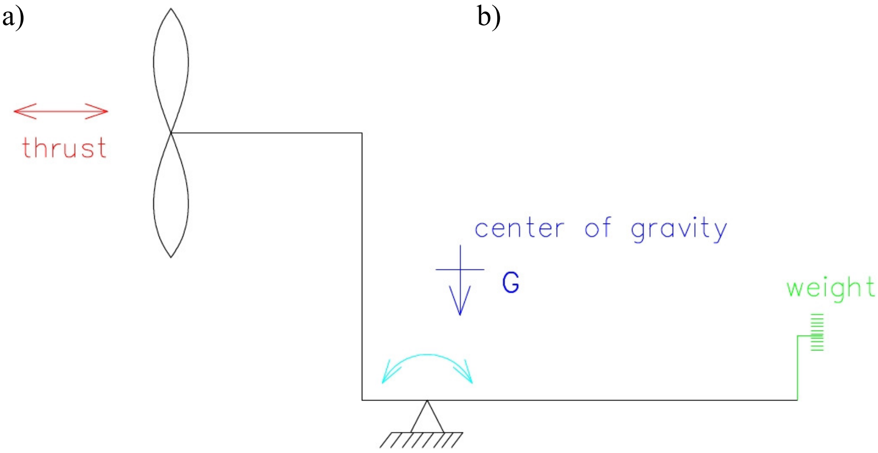

c)

Figure 11: a) the part of test stand, b) the CAD model of test stand, c) the lever principle

6 Mini UAV VUT – 700 Specto

Specification
Wing span: 4.2 m
Max. take off weight: 20 kg
Max. design speed: 150 (160) km/h
Structure: composite
Engine: MVVS 45 ccm, 3.8 kW (2.8 kW)

Figure 12: Mini UAV VUT – 700 Specto

For more detail information about Mini UAV VUT – 700 Specto, see the web http://lu.fme.vutbr.cz/ .

7 Conclusion

The paper presents design of optimum propeller. This design process includes three parts: theoretical design of optimal blade shape, CAD design and production. All these three parts lead to composite adjustable propeller.
The CFD simulation is important part of presented paper. This simulation was validated with wind tunnel test data and the results have good agreement. The thrust and torque values of theoretical propeller design were compared with values from CFD simulation and the difference between these values is small.
The used analytical approaches for propeller design do not include condition of zero value of circulation at the hub and at the tip of the propeller blade. The nonzero value of circulation can be a cause why the thrust value of analytical solution is higher than the thrust value of CFD simulation. An interaction between the fuselage and the propeller is not considered. The CFD simulation is only performed with one turbulence model.
The more detailed approaches for propeller design, aeroacoustics and optimization methods are the next aims of future work. Vortex lattice methods or Momentum/Blade element model with genetic algorithms are often used for Multidisciplinary Design Optimization. The CFD simulation will be performed with other turbulence models.

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