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DESIGN, ADDITIVE MANUFACTURING AND EXPERIMENTAL STUDY ON SMALL SCALE WIND ROTORS

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Abstract: Development of energetically effective technological solutions and parallel cost effective manufacturing technologies brings up the idea of micro–scale wind generators. Large scale wind power plants are widely used and studied. Small sized wind generators may have advantage of mobility and ability of utilizing intensive air flow in a relatively small space. In this paper we present development of a series of rotors and experimental investigation of their efficiency. In this study we designed a series of small size, multiblade rotors and fabricated them by additive manufacturing. Wind tunnel experiments were performed and rotors compared with the same type but larger sized rotors in efficiency. Body models were used in two way. After exporting those into STL file format those were imported in an additive manufacturing system which printed out real specimen. On the other hand CAD models of rotors were utilized for building up a model for numerical simulation.
Keywords: additive manufacturing, wind power plants, micro–scale wind generators, small scale wind rotors, multiblade rotors, efficiency, experimental investigation

INTRODUCTION

Streaming fluids carries kinetic energy. On Earth we have significant amount of flows like wind and different form of water motion (e.g. rivers or undulation), which can be utilized as sources of so–called renewable energy. Expression „renewable" refers to the fact that energy of them finally comes from the Sun, which of course contains not infinite amount of energy, but from „terrestrial" point for view it can be considered as an inexhaustible source of power [2,3].

Nowadays science, technology and application of wind power plants accumulated a large amount of knowledge and experience. Size, construction, buildup, shape, working speed are some of important parameters which influence efficiency and economy of a wind power plant [4,5,6].

Figure 1 points to one of most interesting feature of different types of wind rotors that is how their efficiency varies by tip speed ratio. One cannot state which the best is. Indeed an appropriate solution can be selected for special circumstances.

Tip speed ratio (λ),

$$\lambda = \frac{\text{rotor tip speed}}{\text{wind velocity}}$$

shows the ratio between wind velocity and the speed of the end point of a blade of a rotor. It depends on the radius of the rotor and its angular velocity. Consequently the same tip speed ratio with the same wind velocity can be reached with a larger rotor by smaller angular velocity.

There is a complex comprehension between tip speed ratio, wind velocity, aerodynamically force on the blade and the diameter of the rotor. Tip speed ratio also depends on control system of a wind generator while larger power gain from the rotor results in a smaller angular velocity, so a smaller tip speed ratio. This is a critical point of wind generator control to obtain energy from a rotor so that it works with a tip speed ratio value close to optimal, in other words not to slow down it too much, and not to allow to rotate too fast.

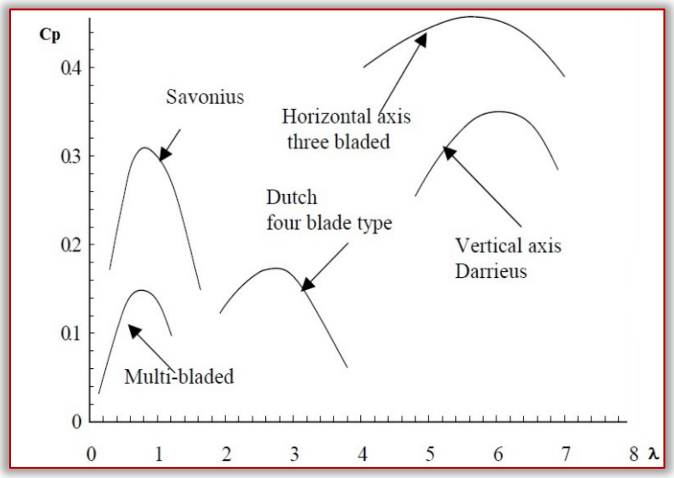


Figure 1. Efficiency can be characterized by power coefficient (C_P) as function of tip speed ratio (λ) for different types of wind rotors. In our work curve for multi–bladed rotors is relevant. Source: Matthew S: Wind energy … p 22 [9]

Power coefficient (C_P) of a rotor vary with tip speed ratio. Albert Betz derived from the axial momentum theory of rotors a theoretical maximum value of power coefficient

$$C_P = \frac{16}{27} \approx 0.593 = 59.3\%$$

This value called as Betz–limit. In practice most wind generators fall far behind this theoretical limit. As Figure 1 shows horizontal axis three bladed rotors come near to this value, that's why this is the most frequently applied form. [9]

When large amount of energy has to be gained for supply for example a city, industrial factories, or a whole country best solutions for wind power plants are large scale generators usually installed in clusters forming wind farms or wind parks. However medium and small size wind generators used standalone for domestic or small scale industrial applications [1].

Development of energetically effective technological solutions and parallel cost effective manufacturing technologies brings up the idea of micro–scale wind generators.

In this paper we present development of a series of rotors and experimental investigation of their efficiency.

DESIGN

In our experiments we investigated rotors designed by ourselves. Without going into details of calculation we refer to textbook [9]. Now we describe only main design parameters and give an example of results.

As first step we selected NACA4412 blade profile, which is widely used for airfoils and wind turbines. We choose 12 degrees for angle of attack (α), because for this profile lift force coefficient (C_L) has maximum at this angle. It can be read from C_L–α diagram that C_L=1.4 at this angle. The radius of the rotor (R) was set to 115 mm. As we designed 3 different rotors with different number of blades, values of this were 3, 5 and 7. Tip speed ratio at the design point (λ_D) was chosen to 2.

With these parameters design of cross sections were performed according to [9]. As an example we demonstrate results for 3 bladed rotor in Table 1.

Calculations were performed for cases of 3, 5 and 7 bladed rotors. From these results orientation and scale parameter of standard NACA4412 cross section are given for each selected radius (r) values. By these data a series of closed curves were generated in a CAD software. Body model of a single blade was generated by lofting. Then whole body model of rotors were generated. It is important to note that cross sections and shape of blades are different for the three different cases in spite of many design parameters of them are identical. This is because number of blades is also a variable factor in formulas applied for calculations.

Body models were used in two way. After exporting them into STL file format those were imported in an additive manufacturing system which printed out real specimen. On the other hand CAD models of rotors were utilized for building up a model for numerical simulation. Figure 3 illustrates the process of design, fabrication and simulation model building.

Table 1. Results of design calculations for cross sections of 3 bladed rotor (r: radius, distance from the axis of rotor, λ_r : speed ratio at radius r, φ: β: blade setting angle, C: chord length)

r [m]	λ_r	β [°]	C [m]
0,01	0,173913043	41,42279537	0,024180963
0,02	0,347826087	35,21399465	0,038385826
0,03	0,52173913	29,63145895	0,045340643
0,04	0,695652174	24,7836739	0,047655979
0,05	0,869565217	20,66060873	0,047308794
0,06	1,043478261	17,18741651	0,045587489
0,07	1,217391304	14,26710711	0,043253177
0,08	1,391304348	11,80446093	0,040725455
0,09	1,565217391	9,71603809	0,038222033
0,1	1,739130435	7,932601226	0,035847487
0,11	1,913043478	6,398197246	0,033645238
0,115	2	5,710034118	0,03261305

FABRICATION

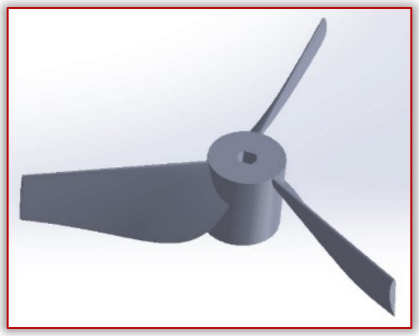
3D body models of rotors converted to STL (standard triangulation language) models and were exported into STL files. An STL model approximates surfaces of a body by plane triangles, like a „tessellation".

From an original CAD model it is possible several different STL model depending on what accuracy is required. Quality of STL model is controlled by STL parameters. Deviation tolerance and angle tolerance are two most important STL parameters. Deviation tolerance is a parameter which controls how far nodes positioned from the original surface. Angle deviation parameter controls the fine structure of triangles like following curved details of a surface so influencing shape accuracy. In both case smaller value means higher accuracy. We applied highest accuracy in our work.

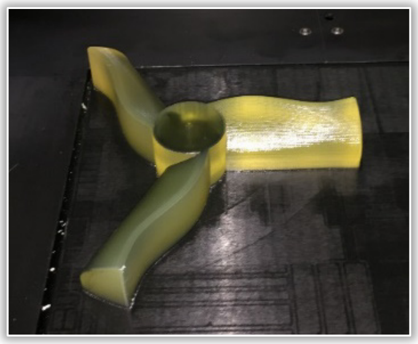
Digital model of rotors were imported into the preprocessing software. Orientation of the model was set to horizontal so that curved surfaces of wings could be built up more accurately in vertical direction. Surface quality was set to mate, because with this option more support material is added to the surroundings of the model, what ensures higher size and shape accuracy.

Rotors were fabricated in the Additive Manufacturing laboratory at University of Nyíregyháza. We applied an OBJET Eden 350V additive manufacturing machine. It works with photopolymer resins, we used FullCure 720 material [10]. This machine applies a certain type of so–called material jetting additive manufacturing technologies, PolyJet. Generally material jetting methods build models by hetting material in liquid for onto the surface of the tray of build surface where they cure so the model builds up layer by layer. This kind of methods have the advantage of high surface quality and high resolution. In the machine applied in this work photopolymer resin is stored and pumped as a liquid before manufacturing process.

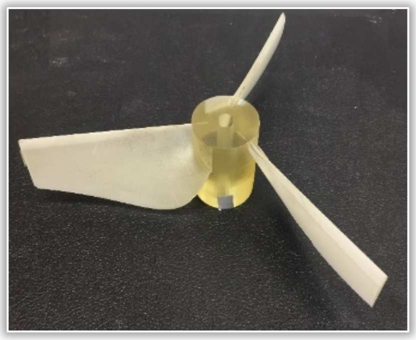
Printing unit involves 8 printing head with several holes 5 micrometers in diameter. Piezoelectric crystals are responsible for ejecting the material in the appropriate time instant while the unit performs alternating movement. It is controlled by an inner auxiliary computer of the 3D printing machine. Material droplets fly onto the upper surface of the model, and a strong ultraviolet lamp irradiates the layer, so resin cures and turns into solid state material.



(a) Model of 3 bladed rotor



(b) 3 bladed rotor before cleaning



(c) 3 bladed rotor made by AM

Figure 2. Main steps of production of rotors: electronic STL body models of rotors, a shot when it was printed out but before cleaning (removal of support material), and experimental workpiece made by additive manufacturing (AM)

This AM machine builds models with support material in order to ensure good size and shape accuracy. It can be shown out that this technology has orientation dependent error in size less than 0.1 mm with small standard deviation [7]. At the end of printing process support material must be removed by mechanical and chemical treatment.

Figure 2 demonstrates manufacturing process from digital body model to real part. Definite advantage of additive manufacturing at this size is promptness and moderate cost.

Aerodynamical flow significantly depends on not only the mere geometry of a body, but the surface quality. That's why additively manufactured surfaces were also polished after cleaning, because this kind of surface is comparable with surface quality of molded plastic or fine machined metal parts.

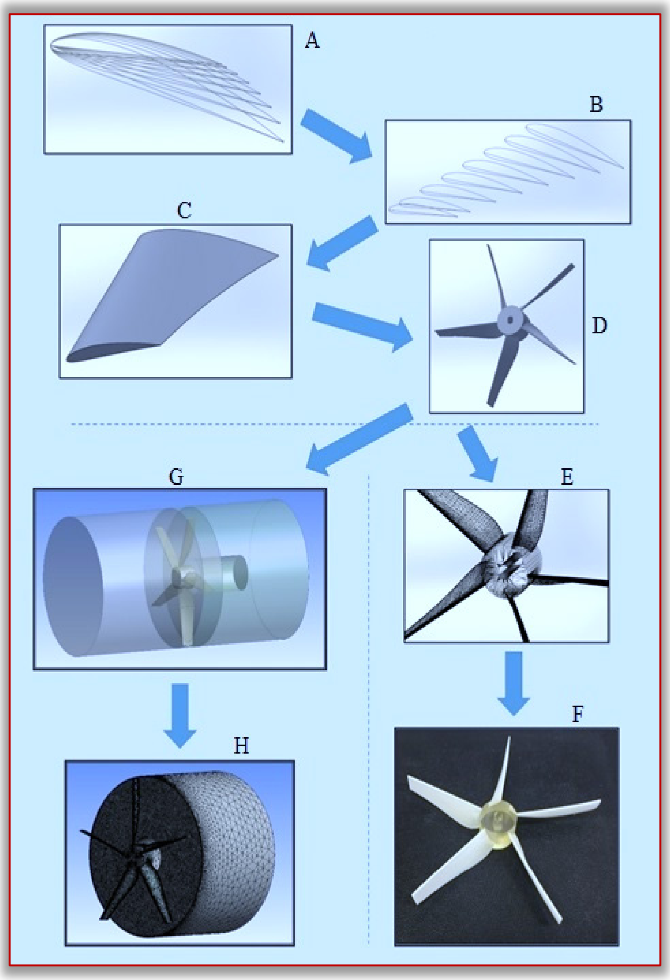


Figure 3. Main steps of design, manufacturing, preprocessing of simulation and their connection during the research process, labels A … H are explained in the text

- A – cross sections calculated by given parameters,
- B – importing cross section into a CAD software (SolidWorks),
- C – one blade created by lofting the cross sections,
- D – copies of the blade arranged and the body model of the rotor built up,

≡ E – an STL file generated from the body model for the additive manufacturing system,
≡ F – experimental workpiece fabricated by additive manufacturing (AM),
≡ G – body model imported into a FEM software (Ansys) for preprocessing,
≡ H – finite element mesh generated from the geometry.

Main advantage of this process is that common body model was used for both additive manufacturing and simulation so geometries investigated by different ways were identical within accuracy of manufacturing. It was important because air flow is highly sensitive for geometry, that's why not too large differences in the shape might have led to significant artificial errors between results of simulation and experiments.

EXPERIMENTS

Objective of our experiments was to investigate efficiency of rotors designed by ourselves and compare them with literature data.

We applied a wind tunnel for generating air flow. Rotors were installed on an electric generator. Wind tunnel does not simulate a freestanding wind generator, indeed a kind of that what has some cover, or works is a narrow place. Really small scale wind generators may be positioned in such a way utilizing intensive airflow in a small spatial area.

Principle of measurement is determining the difference in electric energy demand of the rotor at a certain angular velocity without airflow and with airflow. Measured quantities were the followings:

≡ angular velocity of the rotor in stationary state (ω),
≡ mechanical power gained by the rotor from air flow (P).

We performed two series of measurement with two different velocity (v) of air (wind) 6.7 m/s and 8 m/s.

Tip speed ratio (λ) was calculated from angular velocity and wind velocity:

$$\lambda = \frac{R\omega}{v},$$

where R stands for radius of the rotor.

Efficiency coefficient (C_P) results from the following formula:

$$C_P = \frac{P}{\frac{1}{2}\rho A_d v^3},$$

where ρ means mass density of air, A_d area of cross section of the rotor, v velocity of the air.

RESULTS

Efficiency coefficients and tip speed ratios were calculated from experimental data and demonstrated on diagrams Figure 4 and Figure 5. Each figure shows 3 diagrams simultaneously in order to support comparison of them. One diagram contains data belonging to the same wind velocity experiments, and consecutively to 3, 5 and 7 bladed rotors.

Results at lower wind velocity are more disturbed by errors than results at higher wind velocity.

It can be stated that each diagram shows maximum at least in trend. On Figure 5 it is more obvious. This feature stand sin accordance with what we can expect by literature. On Figure 1 curve for multi–bladed rotors has a maximum at $0.7 < \lambda < 0.8$ with value $1.4 < C_P < 1.5$. In our experiments for our rotors in case of v = 6.7 m/s the maximum is at $\lambda \approx 0.54$ and $C_P \approx 0.75$ (except when number of blades is 3). In case of v = 8 m/s the maximum is at $\lambda \approx 0.6$ and $C_P \approx 0.75$.

We may account it as a qualitative accordance. Of course since rotors and constructions are different, and performance of wind generators highly depends on those, we cannot expect exact coincidence with data of literature. Difference may arise also from the fact that literature reports freestanding wind generators, but our experiments were performed in a wind tunnel.

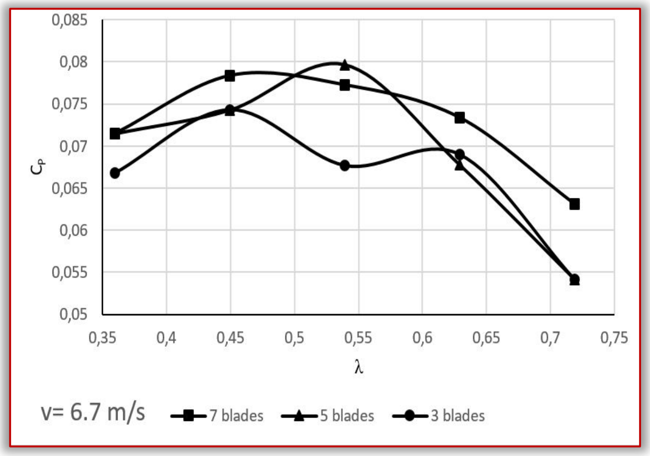


Figure 4. Efficiency result of experiments at v=6.7 m/s wind velocity

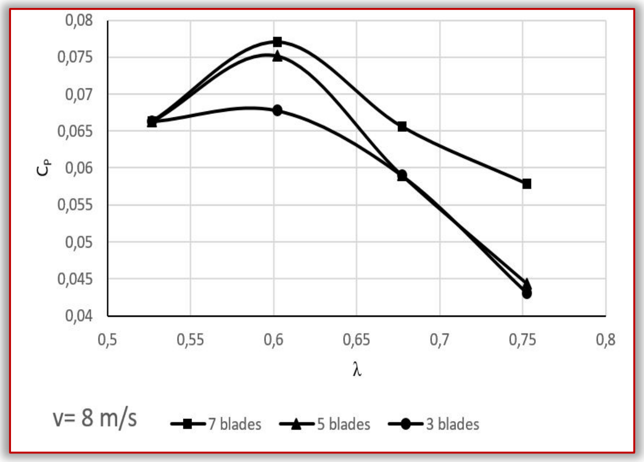


Figure 5. Efficiency result of experiments at v=8 m/s wind velocity

CONCLUSIONS

Rotors with 3, 5 and 7 blades were designed with NACA4412 airfoil cross section. Body models were applied for additive manufacturing of rotors. Wind tunnel experiment was built up and two series of measurements were performed at 6.7 m/s and 8 m/s. Power coefficient by tip speed ratio diagrams were derived from measured data.

Shape of diagrams at v=8 m/s are in qualitative agreement with data of literature. It has maximum, and value of maximum is higher and higher as number of blades increases. Diagrams at v=6.7 m/s shows not so clear maxima, but tendency is similar. Wind speed in this case probably is too low and errors of measurements makes evaluation more difficult.

Such kind of experiments may bring more knowledge about features of rotor sin a wind tunnel which is able to provide higher wind velocity.

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