Design and Manufacturing Method of GFRP Blades for Vertical Axis Wind Turbine

Paul Bere 1, Radu Ciobanu 2, Oleg Ciobanu 2, Marin Gutu 2

1 Technical University of Cluj-Napoca, Bd. Muncii 103-105, Cod 400641, Cluj-Napoca, Românía
2 Technical University of Moldova, Bd. Ştefan cel Mare, 168, MD-2004, Chişinău, Republica Moldova

marin.gutu@pmai.utm.md

Abstract. Today, environmental protection and the rational use of natural resources have become growing challenges. One of these aspects is energy producing with less impact on the environment. For some applications the small wind turbines can be a solution. In this paper are presented some aspects regarding the design and manufacturing technology of 500 W vertical axis wind turbine blades. The turbine will be installed in the urban environment so that requirements regarding rotor aesthetics and noise level will be considered. The optimal geometric parameters of the turbine rotor were determined by specialized MathCAD and elaborated in 3D modelling software. For the blades the NACA 0018 airfoil was used with the chord length of 110 mm and is constant throughout the length of the blade. The blades are helical and are 1800 mm long. To estimate the aerodynamic performance of the turbine rotor, a computational fluid dynamics model was developed using ANSYS CFX finite element analysis software. The authors proposed a new method for rapid prototyping of blades using fused deposition modelling procedure. In order to increase the mechanical properties, the blades were covered with several layers of glass-fibres reinforced polymer. Estimation the blade strength to operating loads was performed using Ansys Workbench software. The modelling of the composite material architecture on the blade surface was performed using the special ANSYS Composite PrepPost module. Several simulations were performed with different number of layers and stacking sequences. In order to prevent rotor over engineering the maximum rotation speed of 400 min⁻¹ was accepted (equivalent to ~12 m/s wind speed). Simulation of the blade strength to operating loads indicate values of around 40 MPa for shear stress (50% less than failure shear stress) and around 80 MPa principal stress (60% less than failure tensile stress). The maximum blade deformations of 3 – 4 mm shows that the blade is stiff enough at imposed operation conditions. For the blade manufacturing, based on the numerical analysis results, the configuration of the strength structure composed of 5 layers of GFRP was selected, which forms a total blade weight of 1895g.
1. Introduction

Environment protection is one of the most important factors of sustainable development. Energy production without harming the environment is an ongoing concern of research centers. The wind turbine in last period has a very impressive development. Different authors traded in papers research regarding the evolution, design or behavior of wind turbine generators. Using different airfoils the positioning of attack angle of the blades were obtained different performance and efficiency. Numerical modeling and simulation of blades rotation are a challenge and different authors proposed some solutions in order to obtain the best blades geometry, airfoils, curved-bladed and helically twisted configuration [1, 2]. In [2] the authors presented analysis for H-rotor Darrieus turbine as a low speed wind energy converter. The numerical analyze presented in [3] can be adapted like solution in order to simulate the blades motion. The vertical axis of wind turbine generators are studied in [3-4] from numerical analyses point of view. In this paper are presented aspects regarding the design, Computational Fluid Dynamics (CFD) analysis, blade strength structure evaluation, and manufacturing method for vertical axis wind turbine blades. To obtain the blade prototype an additive manufacturing methodology was used [7-10]. Using a Fused Deposition Modeling (FDM) solution a plastic prototype from ABS was manufactured. The prototype of the blade was covered by Glass Fiber reinforced Polymer (GFRP) in order to improve the mechanical properties of the blades.

2. Design and manufacturing

2.1. Design of vertical axis wind turbine rotor

The parameters required to develop the wind turbine rotor with aerodynamic blades are the following: the airfoil, airfoil chord (which defines the rotor solidity), aspect ratio, rotor diameter and its height. For this rotor the symmetrical NACA 0018 airfoil was chosen which is among the most used one for VAWTs. The airfoil selected is good one for low values of Reynolds numbers (Re < 200 000) and show reasonably constant performance, in terms of lift and drag coefficients Cl/Cd ratio, for a large range variation of the angle of attack and unsteady wind conditions, according to airfoiltools publicly available database. The VAWT’s solidity is the ratio between the blade’s area and turbine’s swept area. The blade’s area is considered the area of one side of it. For a straight bladed VAWT, the blade’s area is calculated as chord’s length and blade’s height, thus the solidity σ is:

\[ \sigma = \frac{(N \cdot c \cdot L)}{A} = \frac{(N \cdot c)}{D} \]  

(1)

Where: N – the number of blades; c – the chord length; L – blade’s length; D – turbine’s diameter.

Solidity directly influences the turbine’s performance depicted by the power coefficient as well as tip speed ratio TSR. The TSR is the ratio between the blade’s tangential speed and unperturbed wind speed. The optimal length of the airfoil chord was determined with the special applet QBlade. Several rotor simulations were performed for decent wind speed - 7 m/s (Re <100,000). At this speed the rotor should generate about 30% of its rated power. The results are presented in the diagram of the dependence of the power coefficient and the tip speed ratio, figure 1. From the diagram 1 we can observe that high solidity rotors have an improved self-starting ability, but their tip speed ratio (TSR) is lower compared to those with a low solidity. The rotor diameter and its height were determined approximately from the power calculation relation. The power output \( P \) of a wind turbine is directly proportional to its swept area:

\[ P = \frac{1}{2} \cdot Cp \cdot \rho \cdot A \cdot U^3 \]  

(2)

Where: \( \rho \) – air density; \( U \) – wind speed, \( A \) – the swept area of the rotor; \( Cp \) – the power coefficient which in efficiency terms can takes values ranging from 0 to 0,593 (Betz limit).
Figure 1. Power coefficient vs TSR dependence on chord length for Re < 100000.

To determinate the nominal power of a wind rotor, the wind speed equal to 11 m/s was accepted. This value fits in the range of wind speeds between 10 – 12 m/s used by most manufacturers of wind turbines. According to the parameters of the vertical axis wind turbines with aerodynamic blades existing on the market, the power coefficient does not exceed the value of 0.3. In our case, in order to select the power coefficient close to the real one, several works were analyzed, of which the most relevant was considered [1]. According to this paper the power coefficient was accepted equal to 0.22. All the calculations were performed in MathCAD software. For the rotor design the aspect ratio between height and diameter was accepted close to 1. Since the rotor is an experimental prototype, determining the optimal aspect ratio will be achieved under real test conditions. So, the rotor diameter was obtained 1600 mm and its height - 1800 mm. From the graph presented in figure 1 the airfoil chord length of 110 mm was accepted. The rotor designed in SolidWorks is presented in figure 2.

Figure 2. Wind turbine rotor geometry

The blade is designed in a helical shape according to recommendations in [2] and it is twisted to 60°.

2.1.1. CFD analysis of the rotor model. In order to verify the rotor conversion efficiency or the power coefficient a CFD model was developed using finite element analysis software ANSYS CFX. The rotor geometry, designed using SolidWorks, was then imported into the ANSYS Design Modeler software. In order to reduce the time and computing resources, only blades geometry was considered. The dimensions of the computational fluid domain were chosen taking into account the recommendations of the authors [3] so that the boundaries of the field do not influence the free flow of the air. The simulated fluid
domain was divided into two subdomains: the Stator (static) subdomain and the Rotor subdomain inside of it (of cylindrical form, which rotates around its axis).

![Computational model](image)

**Figure 3.** Computational model: (a) computational fluid domain; (b) mesh details around the blade.

After uploading the geometric model the following regions were defined: (Inlet – the face with black arrows on the perimeter), (Outlet – the opposed face of the Inlet), (Openings – the four side faces), and the common regions between Fluid_stator and Rotor (Fluid-Fluid). Figure 3 (a) illustrates the considered fluid domains. The mesh used for finite element analysis of the rotor was generated using the ANSYS Meshing Workbench. In order to capture the effects of the boundary layer on the surface of the blades it was fine meshed in 9 layers using the function inflation. The transition from the fine-meshed areas to the gross meshed ones was done by specifying the Growth Rate = 1.1 expansion factor, figure 3 (b). The maximum variation of the characteristic dimensions of two adjacent elements is not bigger than 5%. The entire domain was meshed into approx. 5,000,000 finite elements.

In order to perform CFD simulation of the rotor the following input parameters are necessary: wind speed and rotation speed. Optimal rotor speed depends on suitable tip speed ratio. These aspects were well analyzed in the paper [1], on the basis of which the tip speed ratio value equal to 3 was accepted. Several simulations were performed according input parameters indicated in table 1.

| Wind speed, m/s | 4  | 6  | 7  | 8  | 10 | 12 | 14 |
|----------------|----|----|----|----|----|----|----|
| Rotational speed, min⁻¹ | 142 | 213 | 263 | 283 | 354 | 425 | 496 |

Using ANSYS CFX Expression Language (CEL) the following output parameters were defined: the torque appearing on the rotor shaft \((M_z = \text{torque}_z()@\text{Rotor})\) and the power \((P = M_z \times \pi \times n / 30)\). These parameters are necessary to draw preliminary rotor power curve.

### 2.1.2. Wind turbine rotor blade strength structure design and analysis.

Because of blades complex geometry and relatively low dimensions their support structure will be made of plastic ABS by 3D printing technology then covered by several layers of Glass Fiber Reinforced Polymer (GFRP). Thus, these materials were analysed for modelling the strength structure of the blade. Blade support structure was modeled in SolidWorks from ABS giving suitable wall thickness in order to achieve a mass of maximum 1 kg. The thickness of 2.4 mm ABS wall was accepted for the equivalent mass of approximately 0.94 kg. Modeling the stacking sequence of the composite material of the blade structure was performed using the ANSYS Composite PrepPost (ACP) application. An orthotropic elastic material model was used to model 0.3 mm - 280 g/m² and 0.16 mm - 160 g/m² 2×2 Twill, E-glass woven fabric composite material while the ABS was modeled as an isotropic elastic material. The section of the
A meshed blade with 400,000 elements is presented in Figure 4. For the preparation of the blade analysis model some recommendations for boundary conditions settings presented in the paper [5] were used. Blade model boundary conditions are depicted in Figure 5. Several simulations were performed according the input parameters presented in Table 2. During operation, the wind turbine rotor is charged at variable wind speeds causing aerodynamic and centrifugal forces in the blades leading to cyclic deformations and fatigue. For centrifugal load evaluation, in order to prevent rotor over engineering, the maximum rotation speed of 400 min⁻¹ was accepted (equivalent to ≈12 m/s wind speed).

### Table 2. Input parameters for strength structure simulation.

| Number of layers | GFRP stacking sequence | GFRP thickness, mm | Total mass, kg | Centrifugal force, kN |
|------------------|------------------------|--------------------|----------------|----------------------|
| [2]+1ᵇ           | [0/90/±45]            | 0.76               | 1.40           | 1.97                 |
| [3]+1ᵇ           | [0/90/±45/0/90]        | 1.06               | 1.64           | 2.3                  |
| [4]+1ᵇ           | [0/90/±45/0/90]        | 1.36               | 1.88           | 2.64                 |
| [5]+1ᵇ           | [0/90/±45/0/90/±45/0/90] | 1.66               | 2.12           | 2.97                 |
| [6]+1ᵇ           | [0/90/±45]            | 1.964              | 2.36           | 3.3                  |

ᵇComposite layup of 280 g/m² Twill fabric (1 layer mass - approx. 240 g);  
²+1 is the final layer of Twill fabric 163 g/m².

All the values of centrifugal forces were calculated using 400 min⁻¹ rotation speed. Therefore, the following constraints were imposed for the preliminary design of the blade strength structure: the total mass of the blade must not exceed 2 kg; maximum shear stresses [σ] = 40 MPa (shear failure stresses are around 80 MPa). Shear stresses are critical for composite materials because they cause resin degradation and delamination of the layers. The value of the allowable shear stresses was accepted based on the own research presented in the paper [6].

### 3. Manufacturing of the blades

#### 3.1. Rapid prototyping of the blades

After the complex blades geometry analysis was decided to use an additive manufacturing procedure. A FDM method was used to obtain a plastic prototype. The blades length was 1800 mm. Because of limited working volume of the printer, the blades were sectioned in 8 segments and assembled finally in one piece. The FDM procedure greatly reduces manufacturing time and ensures good accuracy. The parts surface obtained have certain roughness. That is proper to create a good adhesion of the glass fiber reinforced polymer layers and the plastic prototype. For this, an ABS thermoplastic material was chosen to be used in order to make the blades prototype. The FDM printer used in this case is type LeapFrog, the Creart HS XL model, its print size is 280x270x590. Close manufacturing conditions were used in [7].
The authors used the same printer in the previous work. They used the different material (PLA) like master model and different parameters of the printer. To create the G slicing code used to make the blade prototype Ultimaker software Cura 4.0 was used. The used material was ABS LEAPFROG MAXX Essentials by the printer provider. The printing temperature was 245 °C for the material. The printer heated plate temperature was 80°C. The used filament thickness is 1.75 mm, and extruder head nozzle diameter 0.4 mm. The layer thickness was 0.2 mm, and as the internal structure of the piece we have: wall thickness - 1 layer; for the exterior blade infill (filling) - 85%; structure of infill "grid". The printing speed was 60 mm/s. For the exterior shell printing, a lower speed of 40 mm/s was adapted in order to achieve better dimensional accuracy and roughness. Considering the weight evaluation of the blade segments finally the grid internal structure was chosen. The segments were assembled by bonding using a structural adhesive type Scotch-Weld™ Epoxy Adhesive from 3M Company. In order to have a good connection and centering of the ABS segments plastic joints were designed on each of face where the segments were assembled by bonding.

3.2. Reinforcement of the blades with composite materials
In order to increase the mechanical properties of the blades the ABS obtained prototype were covered by GFRP composite [7, 8]. Before prototyping the blade geometry was reduced by 1 mm in order to compensate the GFRP coating. For the reinforced materials were used 5 layers glass fiber type Twill with follow stacking sequence:
- [0/90/±45], 4 layers, 2X2 Twill, E-glass Woven Fabric, 280 g/m².
- [0/90] 1 layer, 2X2 Twill, E-glass Woven Fabric, 163 g/m².

The matrix used was epoxy type Epiphen RE/DE 4020 (France). The mixing ratio resin/hardener was 100:30 according to provider data sheet. Hand lay-up technology was used to applying the composite layers on plastic prototype. The last layer applied on the composite was Peel-ply by 163 g/m². by Nylon textile (figure 6).

![Figure 6. GFRP layers applied on the blade plastic prototype.](image)

The curing time were done 24 hours at 22°C and 8 hours at 75°C in the oven. At the final the peel-ply were rejected from the blade and the end border was cut at final dimension. The exterior surface was traded with sprayed filler and at the final the surfaces were covered by epoxy gel coat.

4. Results and discussions
4.1. Blade design results
The authors decided this design due to the following advantages: - a section of the rotor blade is always positioned optimally in relation to the wind direction, this allows obtaining a power coefficient relatively uniform, thus reducing fatigue loads; - the rotor is quieter and it has an aesthetic appearance. The rotor was designed with the possibility of easy disassembly of the blades in order to facilitate the change of blades with different geometry. For each wind speed was obtained a diagram as presented in figure 8 (a). The power diagram is variable because of variable torque appearing on the rotor shaft. For power curve construction, the average power values from each simulation were considered. In order to check flow field around the rotor, the velocity distribution was analyzed. Velocity contour section for 7 m/s wind speed is depicted in the figure 7 (b).
Figure 7. CFX simulation results at 7 m/s wind speed: (a) generated power diagram, (b) velocity contour.

As was mentioned above the power curve was created using simulation obtained values and for comparison, another one was drawn based on the calculations in the Mathcad application using the power coefficient \( C_p = 0.22 \). The results are synthetized in the figure 8. It can be noticed from the figure that the power estimated by ANSYS CFX is lower because of 3D aerodynamic effects. The blades experiences turbulences that are formed at the trailing edge and at the tips. The last ones have the most negative impact on the performance of the blade. The simplest method for diminishing the effect of the vortexes at the tips on the performance is endowing the blades with endplates.

Figure 8. Wind turbine rotor power curve

Validation of the CFD model will be performed after manufacturing the experimental prototype of the rotor and testing it in real operating conditions. The results regarding blade strength structure analysis are the following. The main output parameter was considered the Shear stress. The value obtained is around the maximum allowed value and was obtained because, for reasons of the blade geometry simplification, only the elements on the blade surface were constrained, figure 9. In fact, the real blade will be fixed with metal elements and bolts. If we check the principal stresses, they have values around 85 MPa. All results are presented in the table 3.

Table 3. Simulation results according input data.

|                  |      |      |      |      |      |
|------------------|------|------|------|------|------|
| Total blade mass, kg | 1.40 | 1.64 | 1.88 | 2.12 | 2.36 |
| Centrifugal force, kN | 1.97 | 2.30 | 2.64 | 2.97 | 3.30 |
| Shear stress, MPa  | 36   | 39   | 41   | 42   | 43   |
| Normal stress, MPa | 43   | 46   | 50   | 52   | 53   |
| Principal stress, MPa | 73   | 78   | 82   | 85   | 86   |
| Total deformation, mm | 3.55 | 3.44 | 3.5  | 3.6  | 3.7  |
Figure 9. Blade simulation results: shear stress and deformation

Tensile stresses for the weakest bidirectional fiberglass composite materials are over 200 MPa. Total deformation of the blade indicates that it is robust enough for the imposed conditions.

4.2. Blade manufacturing results

The FDM process is very suitable to obtain the complex prototype. The obtained segments of the blades prototype using ABS material have a good surface. The surface roughness Ra of the blade segments measured by a Namicon TR-220 device was 21±5μm. Very close results are obtained and mentioned by the authors in [9] using FDM 3D Printer. The ABS material was a good option for manufacturing a prototype support of the blades. This material is sensitive to solvents from epoxy resin and makes very good coupling between these two materials. In this case the GFRP applied on the ABS prototype create a good adhesion between composite layers and Plastic porotype. Different solution was applied by the authors in [7] which used a PLA prototype. Manufacturing of the parts from PLA using FDM method is more easily and the obtained prototype is more accurate but in this case the epoxy resin does not adhere so well to the surface of the PLA material. In this case delamination layers can happen. In Fig. 10 is presented the obtained segments from ABS prototype. In figure 10 (c). the ABS master model of the blade is covered by GFRP layers.

Figure 10. ABS segments of the blades obtained by FDM method. a. Connection points area of the blade. b. Three segments assembled at the end of the blade. c. The blade prototype covered by GFRP

The weight of the plastic ABS prototype was 910 g. The cost of plastic ABS filament is 11 €/100 g.
In our case this represented around 100 euros/blade. The obtained weight fraction ratio for GFRP material was 50%. The final weight of the blade was 1895 g. A tolerance of maximum 12 g main value was found between the blades. To balance the weight blades the supplementary plumb piece were applied to lighter blades to have the same weight. Obtained blade is presented in figure 11.

Figure 11. Obtained blade obtained from ABS and GFRP 1800 mm length.

This solution to reinforce the plastic prototype by GFRP is suitable to obtaining the master models for the blades. This can be a cheap option in order to obtain a functional prototype. In order to produce many parts for GFRP material the indicate solution is to manufacture a mold. The composite parts are obtaining into the mold and we can use couple manufacturing solution. In the prototyping phase in order to eliminate costs and manufacturing time of the molds this adopted solution can be used.

5. Conclusions
At the design stage, the aim was to develop an experimental prototype of the vertical axis wind turbine rotor to serve as a pilot station for testing blades with different geometry. As the wind turbine will be installed in the urban environment, the requirements regarding the aesthetics of the rotor and the noise level were considered.

The estimated power of the rotor is obtained at a number of rotations compatible with those of the available electric generators in this range (200 - 400 min⁻¹). Analyzing the comparative wind turbine rotor power curves it can be concluded the following. At the wind speed of 11 m/s for determination of the nominal power of the wind rotor, a difference of 10% was obtained between the values of the power calculated in the application MathCAD and the one obtained in ANSYS CFX. Therefore the value of the $C_p$ for the simulated rotor model is 10% lower than the $C_p$ value accepted in the initial calculations. This result can be considered as a partial validation of the computing model.

Simulation of the blade strength to operating loads indicate values of around 40 MPa for shear stress (50% less than failure shear stresses) and around 80 MPa principal stress (60% less than failure tensile stress). The maximum blade deformations of 3 – 4 mm shows that the blade is stiff enough at imposed operation conditions.

The manufacturing complexity of the blades was solved by using FDM method. The solution to use a plastic prototype from ABS covered with GFRP payers eliminate the mold of the blades. The FDM technology has a lot of benefices and can be mentioned: plastic material pieces can be produced in a short time, the internal structure of the blades can be designed in initial stage and manufactured according to the design, for the bigger piece that can be obtained by small sections and assembled, the cost production are low, reduced manufacturing time. If consider that the mold of the blades at this dimension (1800 mm) obtained by CNC milling machine from epoxy block, can be around 5000 euros we can observe a large cost reduction for the manufacture of a blade. The cost/one blade is around 150 euros. This is for functional prototype and the mold is not included. For production blades is useful to use a mold and a GFRP sandwich material can be solution for the blades. In this case the cost production of the blades can be reduced by 3 times.

The mechanical resistance of the blades increases by GFRP composite cover. In the same time the stiffness of the blades are bigger. Using the GFRP and plastic materials the blades can be lighter like traditional material (wood or aluminum). It can be obtained some specific internal structure design which it was impossible to obtain by classic technology or materials.
Acknowledgment

The authors are grateful for the opportunity to conduct this research within the State Program Project „Study of wind and solar energy potential of the Republic of Moldova and development of conversion systems for dispersed consumers”, cipher 20.80009.7007.10, funded by the Ministry of Education, Culture and Research of the Republic of Moldova.

References

[1] D. Hilewit, E. A. Matida, A. Fereidooni, H. Abo el Ella, F. Nitzsche. "Power coefficient measurements of a novel vertical axis wind turbine", Energy Science & Engineering Vol. 7/6 p. 2373-2382, 2019.

[2] F. Scheurich, T. M. Fletcher, „The influence of blade curvature and helical blade twist on the performance of a vertical-axis wind turbine”, American Institute of Aeronautics and Astronautics. Meeting AIAA, eISBN: 978-1-60086-959-4, 2010 DOI:10.2514/6.2010-1579

[3] A. Alaimo, A. Esposito, A. Messineo, C. Orlando, D. Tumino, „3D CFD Analysis of a Vertical Axis Wind Turbine”. Energies. 8(4); p. 3013-3033, 2015.

[4] P. Sabaeifard, H. Razzaghi, A. Forouzandeh, Determination of vertical Axis wind turbines optimal configuration through CFD simulations, International Conference on Future Environment and Energy, Singapore, p. 109-113, 2012

[5] K. A. Brown & R. Brooks, „Design and analysis of vertical axis thermoplastic composite wind turbine blade”, Plastics, Rubber and Composites, 39:3-5, p. 111-121, 2010.

[6] M. Guțu, „Correlation of composite material test results with finite element analysis” IOP Conference Series: Materials Science and Engineering, Volume 147, 7th International Conference on Advanced Concepts in Mechanical Engineering, 2016, Iasi, Romania 147(1):012004, DOI: 10.1088/1757-899X/147/1/012004.

[7] A. P. Chiriță, P. Bere, et al., „Aspects regarding the use of 3D printing technology and composite materials for testing and manufacturing vertical axis wind turbines”, Mat. Plast. 56, no. 4, pp. 910-917. 2019

[8] M. Bordoni, A. Boschetto, Thickening of surfaces for direct additive manufacturing fabrication, Rapid Prototyping Journal, 18, 4, p. 308–317, 2012

[9] G. Kroczyk, P. Raos, S. Legutko, “Experimental analysis of surface roughness and surface texture of machinedand fused deposition modelled parts”. Teh. Vjesn., 21, pp. 217–221, 2014

[10] R. Roșcuțel, C. Fetecău,”Techniques for rapid prototyping of scale models of blades for wind turbines”, Journal of Engineering Sciences and Innovation, Vol. 3, Issue 1/, pp. 15-24, 2018