Strength Analysis of an Archimedes Wind Turbine Model Designed for Additive Manufacturing

Ivan Mihálik[1*]; Marián Lázár[2]; Natália Jasminská[3]; Tomáš Brestovič[4]; Peter Čurma[5]; Lukáš Simočko[6]

Department of Energy Engineering, Faculty of Mechanical Engineering, Technical University of Košice, 042 00 Košice, Slovakia
*Corresponding Author

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Abstract— *The article examines the Archimedes wind turbine model with a diameter of 1,500 mm in terms of the strength of its construction. It describes in detail the material properties of the turbine produced by means of alternative methods, specifically by means of the Selective Laser Sintering additive technology. By combining CFD simulation and strength analysis, the article solves the influence of the pressure force of the wind and the speed of the turbine on the tension and deformations in its construction. The results are compared with commercially available turbines made of composite materials.*

Keywords— Wind Energy, Wind Turbine, Strength Analysis, Computational Fluid Dynamics.

I. INTRODUCTION

Research and development of new special types of wind turbines makes it possible to use the huge potential of wind energy in the world in areas where the application of conventional wind turbines is not suitable. One of the many types of wind turbines is the so-called Archimedes wind turbine, the development of which has been ongoing since the beginning of the 21st century. The design of the turbine minimizes the negative aesthetic impact on the surroundings. At the same time, the essence of the design forces the turbine to rotate automatically in the direction of the wind, which results in less demanding operation. From this point of view, the device is suitable, for example, for use for private purposes in densely populated areas. Therefore, increased safety requirements are placed on its operation, and it is necessary to know the strength limits of the device, so that during its operation there is no damage to it and subsequent damage to health and property.

II. PARAMETERS OF THE INVESTIGATED TURBINE

A 3-bladed Archimedes turbine with a diameter of 1,500 mm was subjected to strength analysis in order to test the mechanical strength of the turbine. A detailed view of the geometry of the individual stages of blades with an inclination of 60/50/65° is shown in Fig. 1:

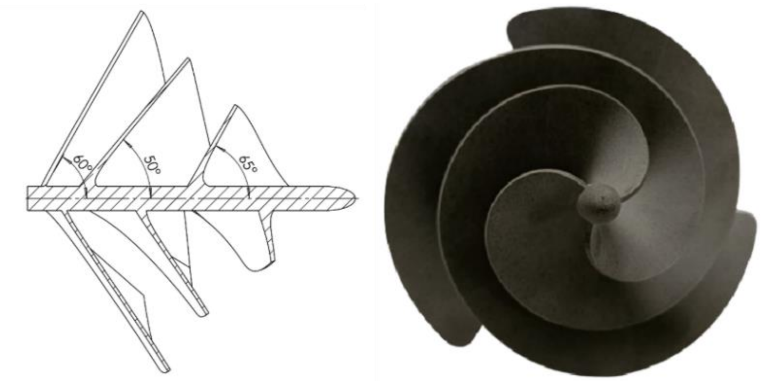

FIGURE 1: Geometry of the Archimedes turbine model

The material from which the Archimedes turbine is to be made is Nylon PA12 in powder form, while production is being considered through the SLS (Selective Laser Sintering) additive method. It is a 3D printing method that uses a high-powered laser to fuse together small particles of plastic, metal, glass, or ceramic powder into a solid object. Among the various additive manufacturing methods, this is the most suitable method for the production of functional prototypes in terms of their strength. At the same time, compared to other types of 3D printing, this method enables the production of larger parts, moreover, in a shorter period of time. The material properties of Nylon PA12 are listed in Tab. 1:

TABLE 1
PROPERTIES OF NYLON PA12

Density	1,010 $kg \cdot m^{-3}$
Molar mass	226.3 $g \cdot mol^{-1}$
Young's modulus	$1.8 \cdot 10^9$ Pa
Poisson's ratio	0.39
Yield strength	$4.8 \cdot 10^7$ Pa

When the turbine rotates, two main force components act on it. The first component is the wind force, represented by the pressure gradient on the surface of the turbine. The second component is the centrifugal force, which is a function of the angular velocity and diameter of the turbine. The design maximum of similar turbines made of composite materials applied in practice corresponds to a wind speed of 35 $m \cdot s^{-1}$. This data was used as the starting value of the wind speed together with the turbine speed of 10 $rev \cdot s^{-1}$. The monitored parameters were the tension and deformation of the turbine.

III. PARAMETERS OF STRENGTH ANALYSIS

The analysis also investigated the effect of wind pressure on the overall stress of the turbine. For this reason, two simulations were carried out, the first with the effect of wind and the second with only centrifugal force. The strength analysis was performed in the ANSYS software through the Static structural module. This is a module that works on the basis of numerical simulations using the finite element method. Since the wind pressure gradient also plays role in the strength analysis, it is necessary to link the CFD simulation performed using the "ANSYS CFX" module with the "Static structural" module. The ANSYS CFX module works on the principle of the finite volume method and is a powerful tool designed for simulations of fluid flow and thermal processes.

First, the CFD simulation settings were defined, while the Tetrahedrons method with a basic element size of 24 mm was used to create the network. The tetrahedral structure is suitable because it can define the complex shapes of turbine blades. In places where a steady state of pressures and velocities is expected, such as on the peripheral parts of the air tunnel model, it is advisable to choose a larger element size. Based on knowledge of hydrodynamics, it is necessary to take into account that even during turbulent events, such as when air flows around the turbine, a thin layer of air is created near the surface of the turbine, which has a laminar character. Neglecting the laminar layer would affect the accuracy of the calculation, so it is necessary to modify the network so that the elements in close proximity to the turbine form continuous surrounding layers. Type k-ε was chosen as the turbulence model. The turbine body was assigned a material with material properties defined from Tab. 1. Subsequently, a CFD simulation of air flow with a speed of 35 $m \cdot s^{-1}$ at 10 $rev \cdot s^{-1}$ was started.

After completing the CFD simulation, the parameters of the Static Structural simulation were defined. In the Engineering Data tab, a turbine material with the same properties as in the previous simulation was created. In the Model tab in the Geometry item, all bodies representing air were suppressed. Similar to the previous simulation, the mesh was created using the Tetrahedrons method, while the size of the elements was defined as 12 mm.

Acting forces and boundary conditions were defined in the Static Structural GDS item. By inserting the Rotational velocity function, the angular velocity of the turbine was defined for the Y Component, as the turbine rotates around the Y axis. At 10 $rev \cdot s^{-1}$, its angular velocity is equal to 62.4 $rad \cdot s^{-1}$. The next step is to define the boundary conditions in order to remove the degrees of freedom of the turbine body. The Cylindrical support function was used to define the rotation and then the rotor surfaces were selected, thereby removing four degrees of freedom from the body. The last degree of freedom was removed through the Displacement function, where the Y Component was defined with a value of 0 mm, allowing the body to move in the Y axis by a zero value. For this reason, the turbine can only move by rotating around the Y axis.

The pressure gradient acting on the turbine was subsequently imported from the performed CFD simulation via the Imported load item. In the function Imported pressure, the surfaces of the turbine were set as the geometry, which defined the places of pressure action. As the last step, the total deformation of the body measurements and von-Mises equivalent stress measurements were defined in the Solution item. After finishing the preparation of the simulation model, the strength analysis itself was performed.

IV. RESULTS OF STRENGTH ANALYSIS

The turbine with a diameter of 1,500 mm was subjected to a maximum stress of 341 MPa at a wind speed of 35 $m \cdot s^{-1}$ and a speed of 10 $rev \cdot s^{-1}$. This stress exceeds the yield strength of the selected material seven times, which would cause complete destruction of the turbine at the specified wind parameters. To compare the effect of the pressure caused by the flowing wind, a simulation was performed with the same settings, but without the effect of the imported pressure. The results of both simulations and their comparison are shown in Tab. 2. From the results of the simulations, it is obvious that the stress difference between the two simulations is at a maximum of 1.54 MPa and at an average value of 0.06 MPa. Based on these findings, it can be concluded that the pressure effect of the wind can be neglected even in extreme weather conditions. However, it should be noted that it is possible to neglect only the pressure effect of the wind and not its high speeds, since high wind speeds directly cause the high revolutions of the turbine leading to its destruction.

TABLE 2
STRESS AND DEFORMATION AT A WIND SPEED OF 35 $m \cdot s^{-1}$ AND A TURBINE SPEED OF 10 $rev \cdot s^{-1}$

The effect of imported pressure	Stress (MPa)			Deformation (mm)		
	Min.	Med.	Max.	Min.	Med.	Max.
With pressure load	$4.51 \cdot 10^{-5}$	15.35	341.78	0	313.4	1885.3
Without pressure load	$5.89 \cdot 10^{-5}$	15.29	340.24	0	312.11	1878.5

Since the turbine was destroyed at a speed of 10 $m \cdot s^{-1}$, it was necessary to determine the maximum speed at which the stress on the turbine would not exceed the yield strength value. Stresses and deformations were analyzed by gradually adjusting the speed, and based on the previous simulations, the pressure effect of the wind was neglected. Fig. 2 shows the course of stress and deformation at different turbine speeds. At a value of 4 $rev \cdot s^{-1}$, the maximum stress was 53.6 MPa, which still exceeds the yield strength. When the speed was subsequently reduced to a value of 3.5 $rev \cdot s^{-1}$, the maximum stress was reduced to a value of 41 MPa, which is the permissible value of the turbine load. When the speed was reduced to 3 $rev \cdot s^{-1}$, the maximum stress was equal to 30.2 MPa with a maximum deformation of 227 mm at the tip of the blade. From the course of the graph, an exponential growth of both stress and deformation is visible with increasing revolutions.

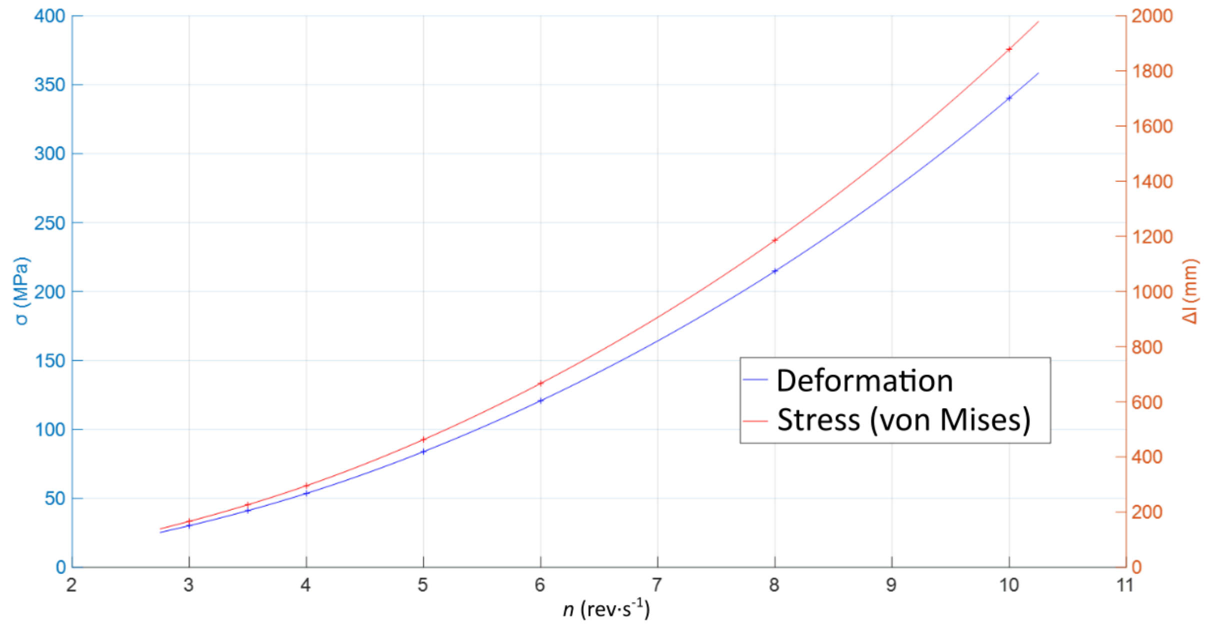

FIGURE 2: Dependence of stress and deformation on turbine speed

From the stress and deformation gradients, it is obvious that the rear part of the turbine is the most affected. The maximum stress occurs at the joint of the blades and the rotor, despite the roundness of the edge of the blades. When the yield point is exceeded, a crack will appear just at the back of the connection between the blade and the rotor. The first stage of the turbine blade is the most affected in terms of deformation. This is because the second and third stages are fixed to the shaft, while the first stage is not fixed by anything on the trailing edge of the blade. Areas of maximum stress are indicated by arrows in Fig. 3.

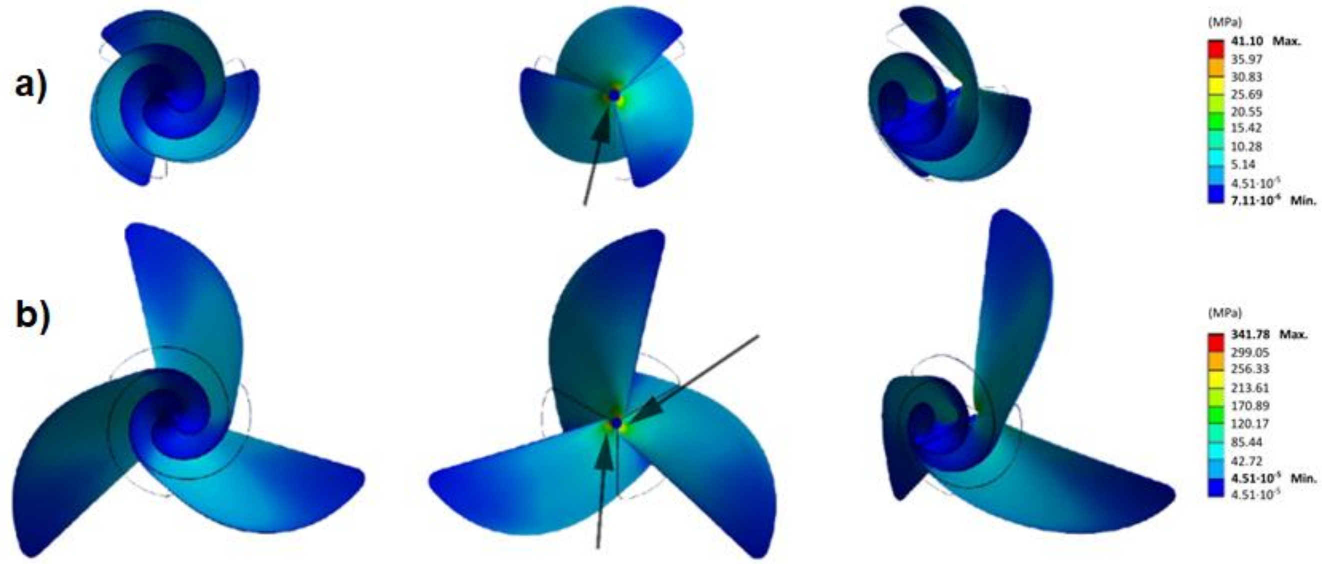

FIGURE 3: Von Mises stress: a) at 3.5 rev·s^{-1}; b) at 10 rev·s^{-1}

The deformation can be clearly observed by looking at Fig. 4, on which the original dimensions of the turbine are marked with black outlines. While the deformation of the turbine at 3.5 rev·s^{-1} is still acceptable due to the mechanical properties of the turbine, the deformation shown in Fig. 4b) is unattainable in practice due to several times exceeding the yield point at 10 rev·s^{-1}, since the turbine will be destroyed before such a level of deformation is reached.

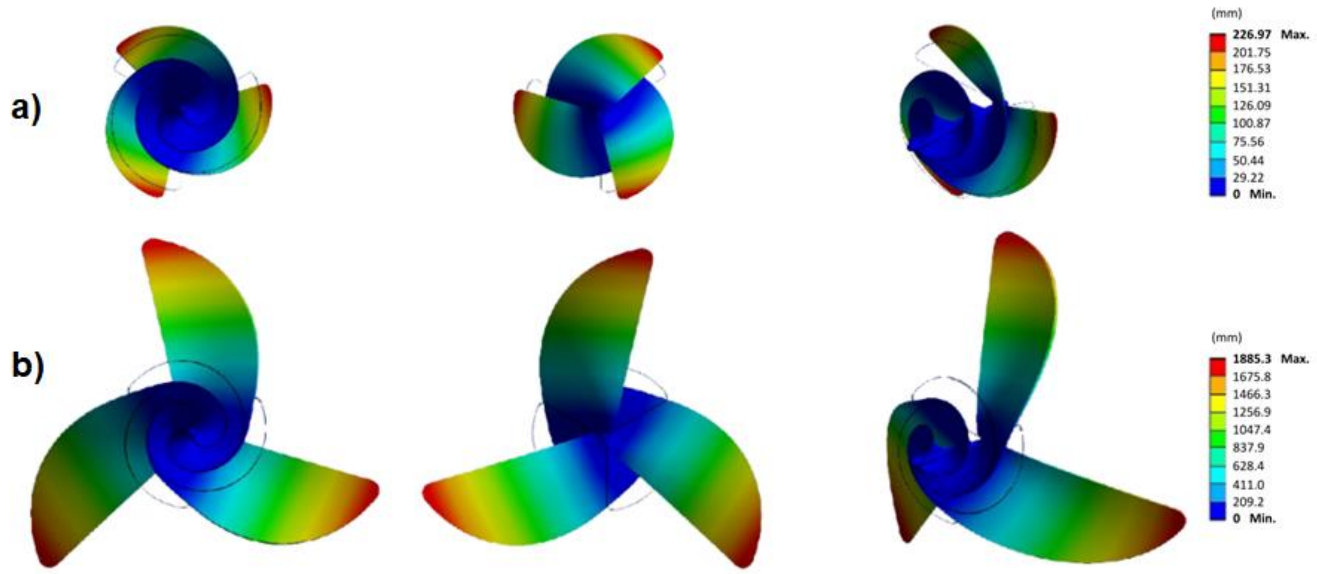

FIGURE 4: Turbine deformation: a) at 3.5 rev·s^{-1}; b) at 10 rev·s^{-1}

There are two options for increasing the mechanical strength of the turbine without significantly affecting its aerodynamics. The first solution is to use stronger and more rigid materials, ideally with a density similar to that of nylon PA12. The second solution is the use of reinforcements in the form of steel rods that connect the individual blades, which ensures higher turbine rigidity and lower applied stress.

V. CONCLUSION

Considering the development of events in the world in recent years, the Archimedes wind turbine can serve as one of the ways of diversifying energy sources for small companies and households, which could contribute to increasing their independence and stability. The production of electricity through wind power itself does not produce waste, does not pollute the air and does not have a negative impact on people's health. These are the most important reasons for the development of innovative equipment in the field of wind energy use. Commercially used Archimedes wind turbines are usually made from a single piece of composite material consisting of plastic and fiberglass. An alternative is the production of turbines through additive methods, which, however, results in a difference in the strength properties of the turbine. The maximum revolutions at which the examined turbine with a diameter of 1,500 mm, made by the additive method from the material Nylon PA12, is able to work without damage is 3.5 $rev \cdot s^{-1}$, at which it reaches a maximum stress of 41 MPa. Improving the durability of the turbine can be achieved without changing the material, for example by applying reinforcements in the space between the blades.

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REFERENCES

[1] H.S.A. Hameed et al., "Shape optimization of a shrouded Archimedean-spiral type wind turbine for small-scale applications," in Energy, January 2023, Vol. 263, Part B, 125809.

[2] K. CH. Kim et al., "Experimental and Numerical Study of the Aerodynamic Characteristics of an Archimedes Spiral Wind Turbine Blade," in Energies, November 2014, Vol. 7, No. 12, pp. 7893-7914.

[3] J. K. Kaldellis, D. P. Zafikaris, "Trends, Prospects, and R&D Directions in Wind Turbine Technology," in Comprehensive Renewable Energy, 2012, Vol. 2, pp. 671-724.

[4] M. A. A. Nawar et al., "Experimental and numerical investigations of the blade design effect on Archimedes Spiral Wind Turbine performance," in Energy, May 2021, Vol. 223, 120051.

[5] Y. Patil, "Design, Fabrication and Analysis of Fibonacci Spiral Horizontal Axis Wind Turbine," in International Journal of Aerospace and Mechanical Engineering, January 2018, Vol. 5, No. 1.

[6] T. Brestovič, N. Jasminská, Numerické metódy a modelovanie v energetike. 1st edition, 2015, Košice: Technical University of Košice, Faculty of Mechanical Engineering, 117 p., ISBN 978–80–553–0223–2.

[7] A. V. da Rosa, J. C. Ordóñez, "Chapter 15 - Wind Energy," in Fundamentals of Renewable Energy Processes, 4th edition, Academic Press, 2022, p. 721-794.