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# APPLICATION USE OF THE HP MULTIJET FUSION TECHNOLOGY IN THE RAPID PROTOTYPING OF WIND TURBINES WITH A VERTICAL AXIS OF ROTATION

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ABSTRACT

The article presents steps to be taken when designing a wind turbine with a vertical axis of rotation, based on the modification of the Savonius engine structure. The HP MultiJet Fusion additive manufacturing technology was used and discussed to generate experimental models. The results of numerical and experimental studies of the analyzed geometry of wind turbines, carried out at the Rapid Prototyping Laboratory and the Laboratory of Energy Machines, at the Department of Mechanics and Fundamentals of Machine Design, University of Warmia and Mazury in Olsztyn are presented.

## Introduction

Development of distributed wind energy is an important issue due to the need to search for and process common and available energy sources (Rea at al., 2018). Among renewable sources, wind energy has become a widely used source of renewable energy due to its technological features and low cost of useful energy produced (Akdağ and Güler, 2018). Wind turbines effectively convert the kinetic energy of the wind into usable energy, e.g., electrical or mechanical. Designs of wind turbines with a vertical axis of rotation have several advantages, such as insensitivity to changes in wind direction, silent operation, self-limiting of the maximum rotational speed of the wind turbine (Miąskowski et al., 2017).

The principle of operation of parts of wind turbines with a vertical axis of rotation consists in converting the force of the wind pressure on the surface of the blades into the rotor torque. Therefore, the effectiveness and efficiency of a wind turbine with a vertical axis of rotation depends on a greater air pressure force, but at the same time on low flow resistance at an unfavorable position of the blades relative to the wind direction (Marinić-Kragić et al., 2019).

The simplest construction of a wind turbine with a vertical axis of rotation is characterized by the Savonius design. It assumes the imposition of two shifted half-cylindrical blades (Al-Ghriybah et al., 2018). Attempts to modify such a profile often result in deterioration of some of the operating parameters of such engines, i.e., a decrease in torque, a decrease in rotational speed, an increase in the fluctuation of torque as a function of the angle of rotation, while improving the others, and increase the complexity of the simple shape of the turbine blades. The search for new geometries should also be conditioned by the technology of making such a structure in the target application (Zhang et al., 2017; Roy and Saha, 2013a, 2013b). The complexity of the shape of wind turbine blades carries the risk of creating a given profile and maintaining the basic operating parameters of the entire wind turbine. However, this should not limit research work related to the search for more and more effective geometries (Mahmoud et al., 2012; Worasinchai and Suwannakij, 2018).

Modern capabilities and technical facilities used in rapid prototyping allow the production of complex (compared to conventional manufacturing technologies) geometry in a relatively short time using, for example, additive technologies (Moczulak et al., 2017). Additive technologies are the most common method of production of elements in small-lot production and prototyping. Additive techniques were developed in the 1980s. Currently, additive technologies have a wide range of applications and can be seen e.g., in such fields as: medicine, construction, modeling, automotive, fashion, production of non-standard tools and many others (Kiński and Pietkiewicz, 2017). The most popular technology of additive manufacturing of FFF (FDM) consisting in the application of a hot-melt plastic has a number of advantages, i.e. a low cost of production of elements, low level of waste, quick implementation of the process of applying individual layers, or the use of materials (filaments) with a chemical composition that allows them to be used in printed objects, e.g. with exposure to various weather conditions and low weight of the resulting details. The use of materials that allow the functioning of manufactured objects in unfavorable environments is associated with ensuring, for example, stable thermal conditions during printing or the use of materials and support structures (depending on the complexity of the geometry). However, the main disadvantage of this technology is quite high anisotropy of the structure, which results in much lower strength in selected directions.

## MATERIALS AND METHODS

One of the recently intensively developed 3D printing techniques is the Multi Jet Fusion (MJF) technology. This technology was developed in 2016. The creators focused on speed and serial production, while maintaining relatively high accuracy of the manufactured parts. For better illustration, an example from the production of a specific order is given. The cost of production of an injection mold with a specific geometry is about PLN 40,000 and the cost of one piece using an injection molding machine is about PLN 1.50. The cost of production of 600 pieces of such a part with injection is PLN 40,900. The production time is about 5 weeks. Using the HP Multi Jet Fusion technology, the cost of production of one piece is PLN 14, which translates into PLN 8,400 for 600 pieces, with a delivery time of about 5 working days. Thus, in the context of the presented example, the customer saves about PLN 32,500 and 4 weeks (Cader and Kiński, 2020).

MJF technology is in a way a combination of previously known techniques - selective laser sintering (SLS) and PolyJet. The printing process of the Multi Jet Fusion technology consists in layer-by-layer fixation of plastic powders. The specially prepared and heated powder is applied with a roller. Then, the precision head applies two types of auxiliaries. The first one, the "fixing agent", is dosed in the areas of the model, and its properties increase the absorption of thermal radiation. A second agent, a detailing agent, is then applied to the outer contours of the components to help separate unfired powder and increase mapping accuracy. After applying both substances, the heating head passes over the material layer causing the model layer to melt and then the process is repeated for the next layer until the final geometry is obtained. In this technology, no additional support structure is used. After the printing process is completed, the chamber is cooled down, and then the element is transferred to the loose powder removal station (http://www.tth.com). Figure 1 shows the principle of operation of the printing operation in accordance with the assumptions of the MJF technology.

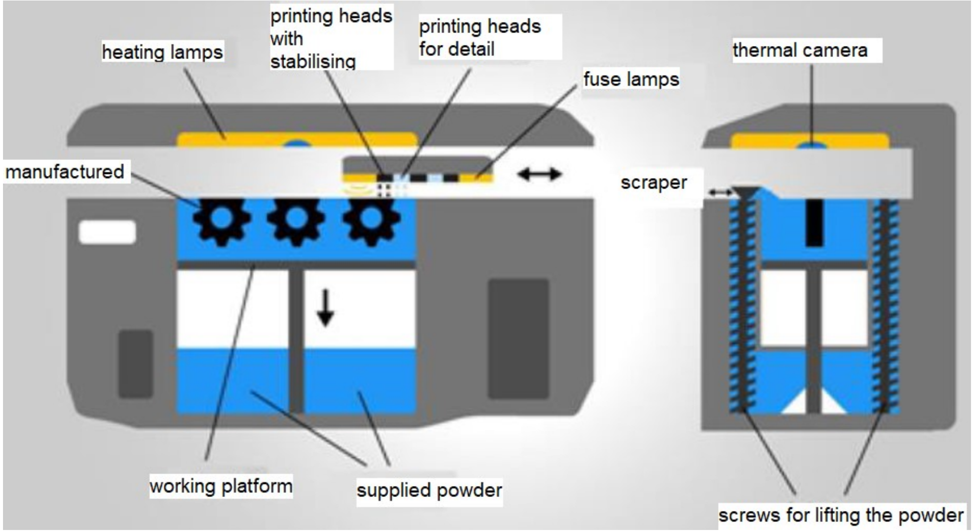

*Figure 1. The principle of operation of the MJF technology (http://www.hp3d.pl)*

HP MultiJet Fusion technology, used for additive manufacturing at CUBIC INCH, allowed the production of experimental models of wind turbines from PA12 material.

The authors, based on previous publications, e.g. (Moczulak et al., 2014; Miąskowski et al., 2016) and experience in the field of numerical analyzes and experimental models of wind turbines, decided to perform a quasi-static numerical analysis of the air flow and experimental verification of the model. The methodology used in this article concerning simulation and experimental tests in a wind tunnel is described in more detail, e.g., in (Moczulak et al., 2017; Moczulak et al., 2014; Miąskowski et al., 2016; Kosiewska et al., 2021)

According to the authors, the prepared geometry of the wind turbine is an example of the influence of the shape of the blades on, for example, the dynamic properties of the rotating engine and quite well illustrates the need to use additive manufacturing technology in the design of engineering applications. The outer outline of the blades is based on a semicircle. Figure 2 shows comparison of the simulation torque distribution as a function of the rotation angle of the proposed geometry with the geometry of the Savonius engine.

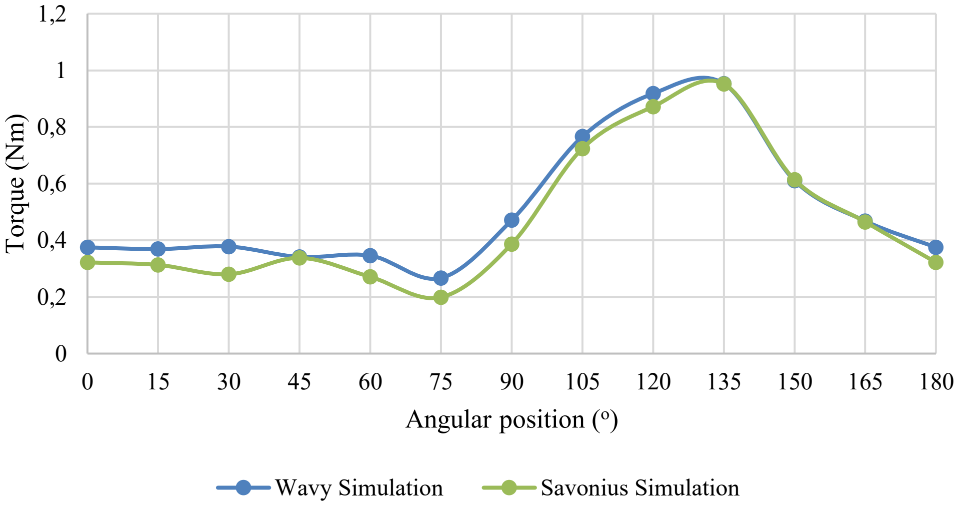

*Figure 2. Distribution of moments as a function of the angle of rotation (10 m·s$^{-1}$)*

Based on the simplified comparative analysis of the new geometry with the geometry of the Savonius engine (Worasinchai and Suwannakij, 2018) well described in the literature, it can be concluded that the predicted torque distribution for the selected wind speed (10 m·s$^{-1}$) as a function of the angle of rotation is comparable. This proves the correct proposal for the shape of the inner surface, no significant deterioration of the above-mentioned parameters and the need for further analyzes of the shape of the blade profiles.

Geometry as well as simplified simulation flow studies were performed in the SolidWorks environment using the FlowSimulation add-in. The dimensions of the model were dictated by the capabilities of the 3D printer's workspace. The outer diameter of the model was 373 mm and the height was 370 mm. The model and dimensions of the said turbine are shown in Figure 3.

The quasi-static numerical analysis was carried out for 13 angular positions, every 15 degrees, shown in Figure 4. The angular "zero" position was the position shown in Figure 3 and 5. The wind speed was set at 8, 10 and 12 m·s$^{-1}$.

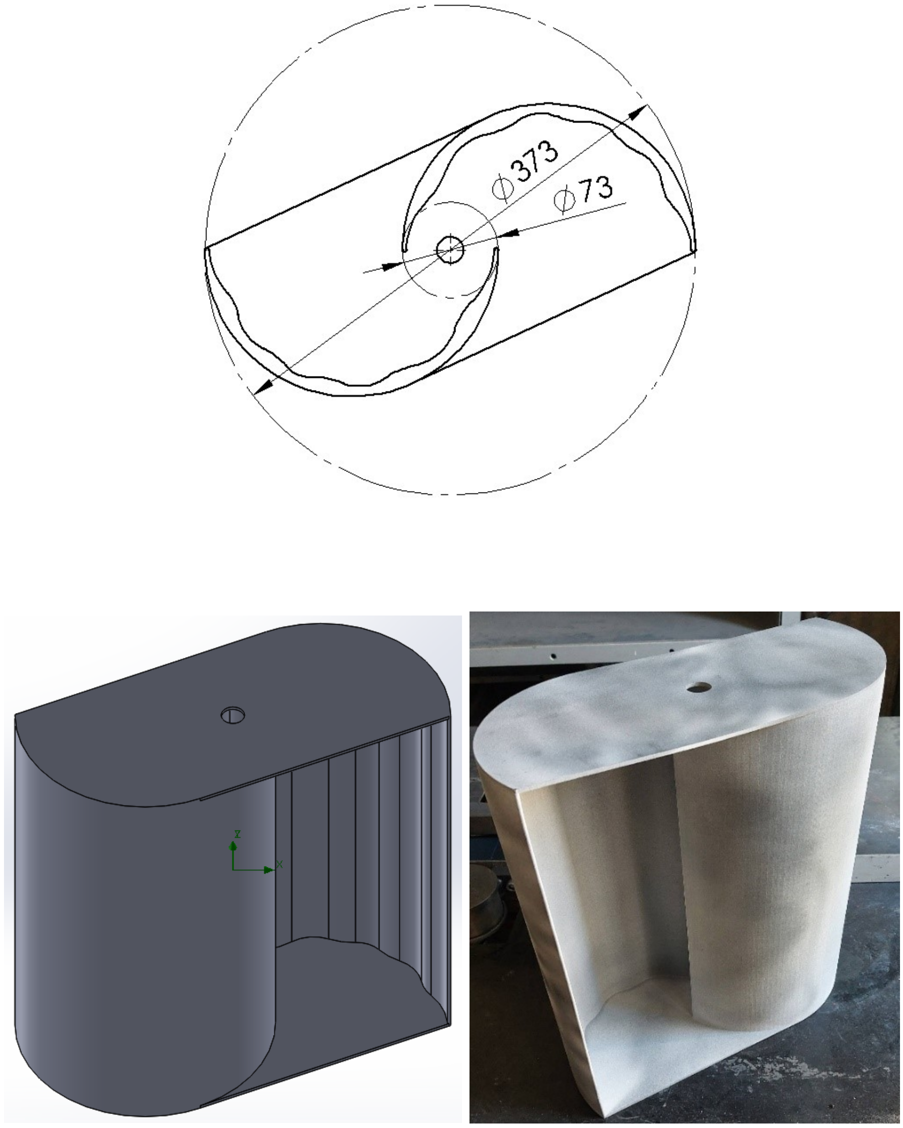

*Figure 3. Isometric view and cross-section of the profile used in the analysis (own elaboration)*

## RESULTS AND DISCUSSION

Analyzing the results presented below, it can be concluded that the use of two-blade straight-out wind turbines is subject to torque fluctuations as a function of the angle of rotation. It becomes reasonable to use several segments of given blades rotated relative to each other by an appropriate angle.

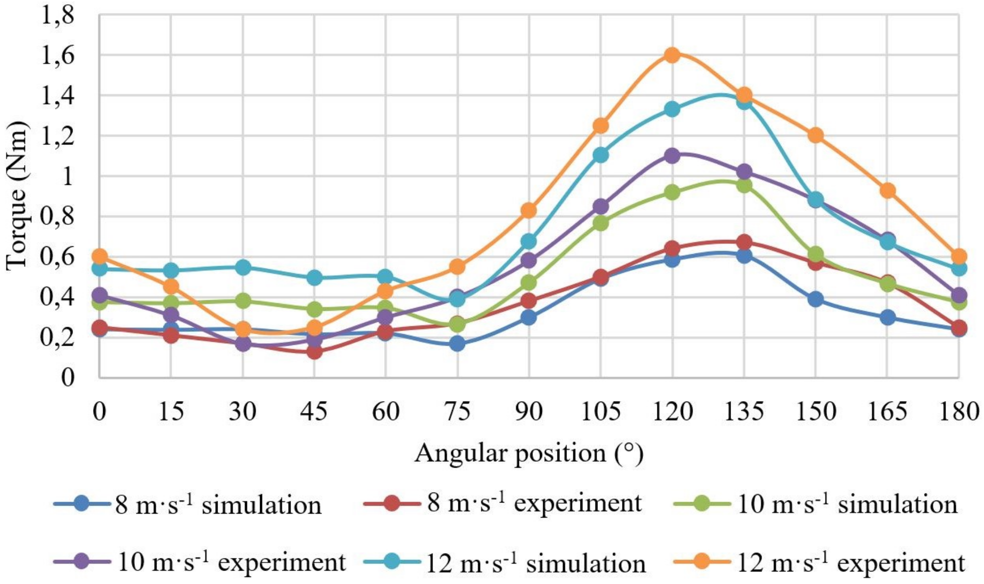

*Figure 4. Torque distribution for selected wind speeds as a function of the angle of rotation for the tested profile in numerical and experimental analysis (Torque = f (angular position))*

A simplified flow simulation illustrates how changing the internal geometry of the profile affects changes in the torque distribution.

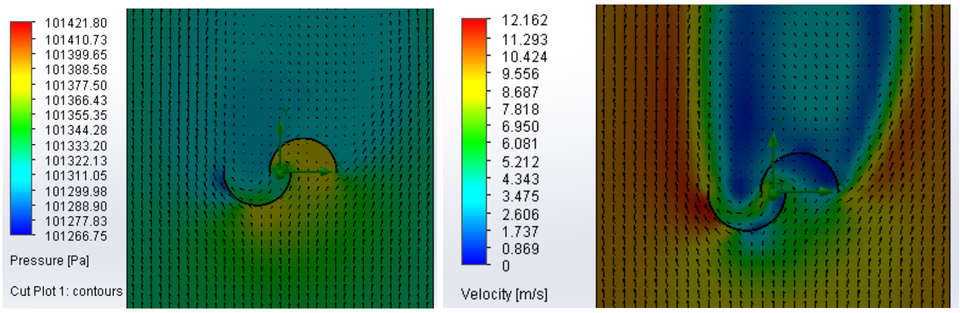

*Figure 5. Distribution of pressure and wind speed around the Savonius engine for a velocity of 10 m·s$^{-1}$ and an angular position 0$^o$*

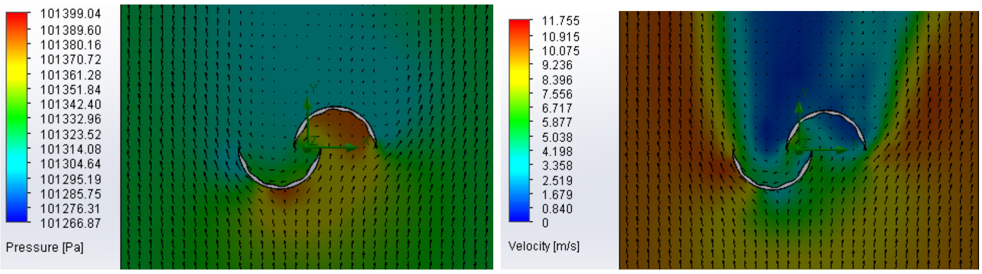

*Figure 6. Distribution of pressure and wind speed around the engine of the Savonius modification (with a corrugated profile) for the speed of 10 m·s$^{-1}$ and the angular position 0$^{o}$*

Figure 5 and 6 show the change in the distribution of pressure and wind speed on the internal surfaces of the models, which proves the significant influence of the shape of the profile on the value and nature of the wind flow. The results obtained from the numerical analysis were decided to be verified on a dedicated test stand.

The test stand shown in Figure 7 and described in a number of publications, e.g., in (Kosiewska et al., 2021), is used to determine the quasi-static and dynamic characteristics of wind turbines with horizontal and vertical axes of rotation. The presented braking system with a mounted torque meter allows to determine the characteristics for different wind speeds. The wind tunnel with the Witoszyński profile ensures a constant wind speed distribution at the exit of the tunnel.

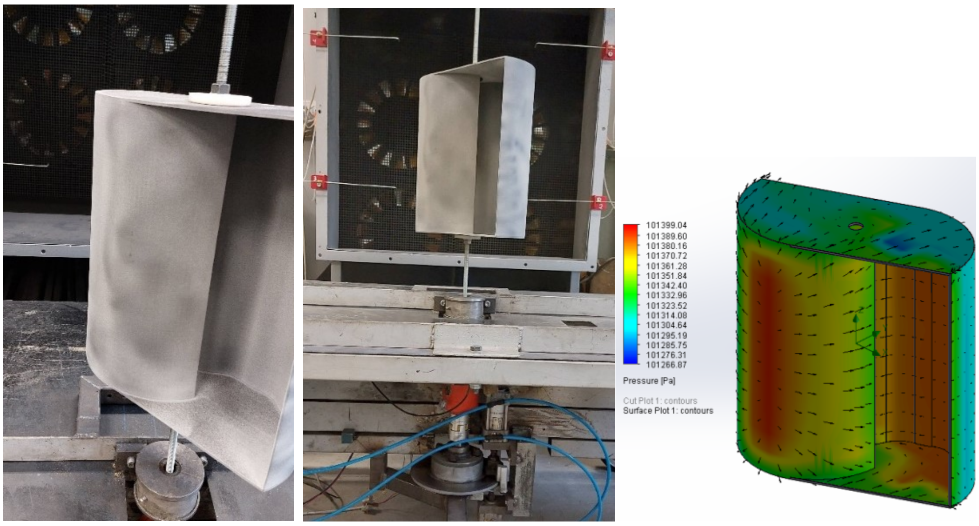

*Figure 7. View of the printed model on the test stand and isometric view of the pressure distribution on the blades of wind turbines at a wind speed of 10 m·s$^{-1}$.*

An undoubted advantage of the HP MultiJet Fusion technology is the use of a material resistant to the harmful effects of weather conditions. The possibility of shaping the geometry while maintaining the isotropic structure gives several additional benefits and the possibility of direct application of details to the final destination. The results regarding printouts in the above-mentioned technology presented in (Cader and Kiński, 2020) and the issues raised in (Kiński and Pietkiewicz 2017; Moczulak et. al., 2014) draw attention to quite important issues regarding the preparation of prototypes using additive manufacturing technology in research and the use of models for further experimental work, described, among others, in others in (Kosiewska et al., 2021).

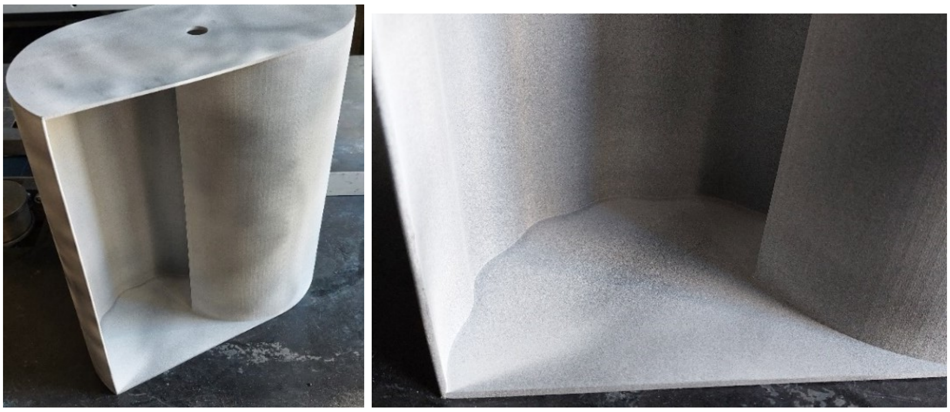

*Figure 8. View of the created 3D model of the selected wind turbine*

*Figure 9. View of the surface of the model produced in the HP MultiJet Fusion technology*

The use of the above-mentioned technology to create blades of a small wind power plant or a small water pump is a very developing issue of reducing the production cost of prototype components and checking their physical and/or functional properties in a dedicated application. The lower surface roughness visible in Figure 8 and Figure 9 does not provide an ideal smooth structure and flow in this case, but it approximately reflects possible surface contamination while maintaining quite good strength properties. The ability to carry out a long-term analysis of the created model and verify numerical research brings a lot of benefits for future implementation works. The possibility of shaping any geometries forces the need to look for solutions in the production of desired shapes in large-scale production.

Figure 10 shows an example of a wind turbine application, where assembly to the support column is carried out by a string solution, and the rotor is placed on a set of precision ball bearings.

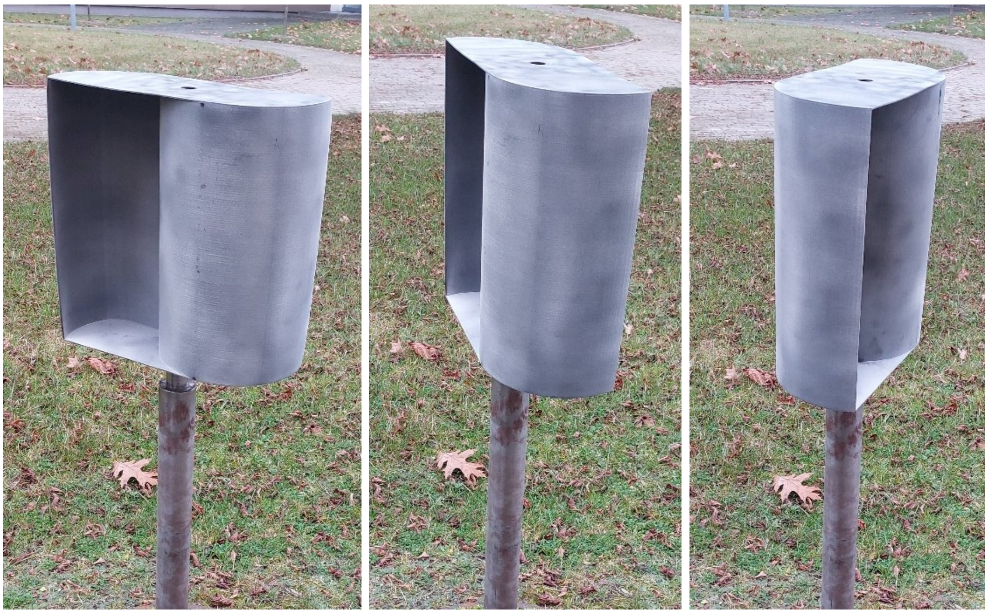

*Figure 10. An example of using the HP MultiJet Fusion technology in small-power wind turbines (view from several positions of the wind turbine during rotation)*

Accuracy of shape mapping for e.g., wind turbines and maintaining a homogeneous print structure and surface roughness allows for predictable effects of external forces on the model. The durability of the presented prototypes and the authors' experience after the research positively assess the usefulness of the described methodology in the search for new solutions, e.g. wind turbine engines and open up new possibilities and extensions of existing research in the field of numerical analysis and quasi-static and dynamic experimental research. The problem of geometry optimization described, among others, for example (Marinić-Kragić et. al., 2019; Zhang et. al., 2017; Roy et. al., 2013) is also an additional determinant of the conducted research and, according to the authors, is part of the use of additive technologies in research work as well as the application of the created prototypes.

## CONCLUSIONS

As part of the ongoing design work, when verifying the results of numerical analyzes or checking the functionality of the proposed solutions, the use of additive manufacturing technology brings a number of advantages. The use of HP MultiJet Fusion technology further extends the utilization of the models produced in a way that other technologies cannot always guarantee. Verification of the results of air flow analyses around the wind turbine clearly shows the need to use technologies that allow for precise and quick creation of a physical object. The direct use of a spatial object in the target application allows for a greater assessment of possible deficiencies or shortcomings during designing, and the increased durability of the material extends the time of exposition of the model to unfavorable working conditions.

The experimental tests of the torque distribution as a function of the rotation angle of the wind turbine in the wind tunnel, presented in Fig. 4, confirm the results obtained in the simulation, which proves the correct path of designing and setting the boundary conditions.

Presenting an objective assessment of model wear as a result of, for example, weather conditions, requires further work and comparison of additional parameters and taking into account new guidelines for its assessment. However, the benefits of using additive manufacturing technology in the search for new shapes of wind turbine blades open the way to faster comparison of results of numerical and experimental analyses.

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## APLIKACYJNE WYKORZYSTANIE TE`CHNOLOGII HP MULTIJET FUSION W SZYBKIM PROTOTYPOWANIU SILNIKÓW WIATROWYCH O PIONOWEJ OSI OBROTU

**Streszczenie.** W artykule przedstawiono etapy postępowania podczas projektowania silnika wiatrowego o pionowej osi obrotu, bazującego na modyfikacji konstrukcji silnika Savoniusa. Omówiono i zastosowano technologię przyrostowego wytwarzania HP MultiJet Fusion użytej do wytworzenia modeli doświadczalnych. Zaprezentowano wyniki badań numerycznych i doświadczalnych analizowanych geometrii silników wiatrowych, przeprowadzanych w Laboratorium Szybkiego Prototypowania oraz Laboratorium Maszyn Energetycznych, w Katedrze Mechaniki i Podstaw Konstrukcji Maszyn, Uniwersytetu Warmińsko-Mazurskiego w Olsztynie.

**Słowa kluczowe:** silnik wiatrowy, Savonius, numeryczna mechanika płynów, druk 3D, MultiJet Fusion