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Numerical Analysis of Deformation of a Wind Turbine Blade With Variable Geometry Controlled by Means of Centrifugal Force

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The efficiency of energy conversion from wind to mechanical energy of a rotating wind turbine rotor depends on the flow conditions of the medium and its impact on the rotor blade. Flow conditions change with change in wind speed and rotor rotational speed. Therefore, in order to increase the operating area of a wind turbine with good efficiency values, it is necessary to modify the turbine blade setting. Mechanical solutions for changing the pitch setting of turbine blades exist for large wind turbine rotors. For small wind turbines, such systems are not used due to the system's costs, which significantly increase the cost of a small turbine. Therefore, it is necessary to develop a solution that will be cheap to use and will ensure an improvement in the efficiency of a small wind turbine. The article discusses analysis of turbine blade deformation caused by centrifugal force. Deformation analyses of the blade with the proposed structure were carried out in numerical tests, and the results are presented in the article. The simulations and obtained results indicate the key role of turbine blade cross-section stiffness. Furthermore, they indicate the need for further work to investigate the relationship between blade stiffness, cross-section geometry, and blade wall thickness.

topics: wind turbine, analysis, deformations, small wind turbine blade

1. Introduction

The issue of achieving a wide operational characteristic range of a wind turbine is directly related to its efficiency in extracting energy from the wind. This depends on the flow conditions of the medium and its interaction with the rotor blade [1–8]. In wind turbine operation, the flow conditions vary with changes in wind speed and wind direction. These parameters and their values also serve as a determinant for obtaining the mechanical parameters of the turbine rotor, such as torque and rotational speed, which in turn translate into the amount of electrical energy generated by the generator [9–14]. Large-scale wind turbines have a wide operational range due to the blade pitch control mechanism [15, 16]. This is commonly applied in high-power three-bladed wind turbines (Fig. 1).

Thanks to the blade pitch control device, it is possible to shape the operational characteristic of the turbine to maintain a constant maximum power value obtained at a certain wind speed, known as the rated speed. For large wind turbines, this typically falls in the range of 11–16 m/s (40–56 km/h).

The operational characteristic of a turbine is limited by the critical wind speed value, which is about 23–27 m/s (82–100 km/h), and is determined by the mechanical strength of the turbine components. A large-scale wind power plant starts operating at wind speeds from 3 to 5 m/s (10–18 km/h). This is the cut-in wind speed, at which torque develops on the turbine shaft and the blades begin to rotate, driving the generator (Fig. 2).

Wind turbines are designed with the goal of generating electricity at the lowest possible wind speed. This assumption stems from the fact that strong winds are rare. Therefore, the rated wind speed

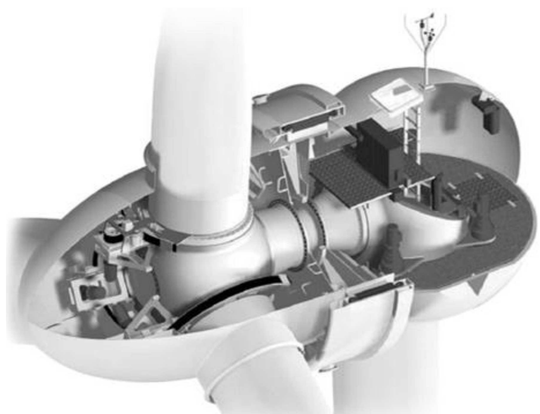

Fig. 1. Example of mechanical pitch adjustment of wind turbine blades [16].

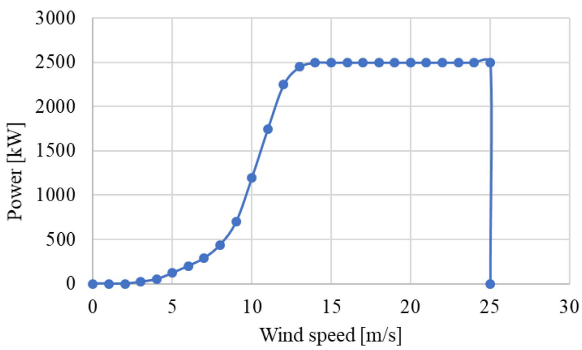

Fig. 2. Example operating characteristics of a 2.5 kW wind turbine [16].

for designed turbines is typically assumed to be around 15 m/s, at which the maximum generated power is achieved. As a result of this assumption, wind speeds higher than the rated speed are undesirable because they cause excessive loading of the wind turbine. For this reason, every wind turbine must be equipped with the capability to control its power [17–27].

There are several methods for controlling the operational parameters of a wind turbine:

- Pitch angle control — It requires advanced control systems to ensure that the blade pitch angle is precisely adjusted to the wind conditions. A dedicated algorithm continuously analyzes wind speed and turbine operational parameters to regulate the blades in order to achieve a specific power output.
- Passive stall control — In this case, the turbine blades are fixed to the hub at a defined pitch angle. The blade profile geometry is aerodynamically optimized for this setting. When the wind speed increases beyond the rated value, turbulence appears on the blade profile surface, disrupting the flow and reducing the lift force, which in turn decreases the rotor's driving torque. The advantage of this regulation method is the absence of a complex pitch control mechanism. However, this type of control requires extremely complex aerodynamic blade design.
- Active stall control — This method is similar to pitch angle control, but instead of optimizing lift, the pitch angle is adjusted to induce a controlled stall condition on the blade's aerodynamic profile. This approach provides higher precision and allows for a wider operational range of the wind turbine.
- Yaw control — It involves rotating the nacelle, and thus the rotor axis, relative to the incoming wind direction. This can be implemented actively or passively.

In this context, a wide range of research and development activities is being conducted to advance rotor design and increase the efficiency in mechanical energy generation. The application of small wind turbines is closely linked to distributed electricity production in urban areas. Therefore, the development of small wind turbine rotors is oriented toward incorporating additional design constraints arising from their operation in close proximity to humans, such as acoustic emissions and mechanical safety.

These factors impose new engineering challenges for small wind turbines. However, their operation within the built environment also offers benefits, including on-site consumption of generated energy and the spatial dispersion of energy sources over a wide area. Furthermore, the specific arrangement of buildings and their architectural features in urban zones may induce local flow acceleration, increasing wind speed and improving flow characteristics. This effect can be exploited through the proper selection of installation sites for small wind turbines.

Such locations include gaps between buildings, sloped rooftops, edges of flat-roofed structures, and street canyons aligned with prevailing wind directions. The large number of additional factors affecting the operational conditions of small wind turbines dedicated to urban environments necessitates the customization of turbine design to local site conditions. Such customization is feasible primarily for small wind turbines due to the relatively acceptable cost of adapting their structural configuration.

Therefore, to increase the operational range of a wind turbine while maintaining high efficiency, it is advantageous to enable modification of the turbine blade pitch setting. Mechanical pitch control solutions exist for large wind turbine rotors. However, such systems are not used in small wind turbines due to their cost, which significantly increases the overall price of the device. Hence, it is reasonable to develop a structural design solution for a wind turbine blade with the capability of self-regulating the pitch angle of its aerodynamic profile. In this context, the phenomenon of centrifugal force could be utilized.

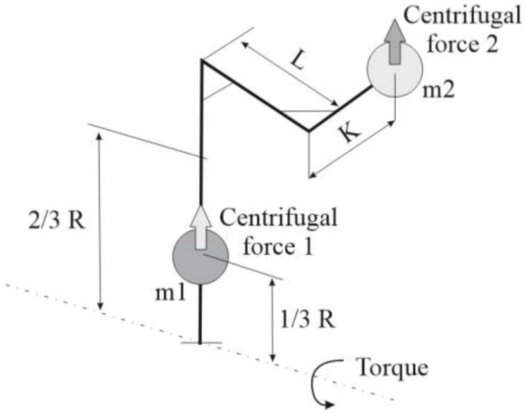

Fig. 3. Mass distribution diagram in a simplified physical model of a small wind turbine blade.

Therefore, the article assesses the possibility of twisting a small wind turbine rotor blade due to the centrifugal force generated by an additional mass placed on the offset part of the blade end.

2. Rotor blade twist via centrifugal force from tip mass

To conduct the structural analysis assessing the feasibility of wind turbine blade deformation, the operational assumptions of the turbine rotor were first defined. The following parameters were adopted: a rotor diameter of 0.6 m, a rated power of 2500 W, and a rotor rotational speed of 700 rpm. For these parameters, the torque on the wind turbine shaft equals 34 N m, with the rotor consisting of 7 blades. Consequently, the torque acting on a single blade amounts to 4.85 N m. The expected angular adjustment range, measured at the blade tip and resulting from the variation in the resultant velocity vector of the incoming airflow relative to the aerodynamic profile, was assumed to be 50°.

Based on the adopted operating conditions, a geometric blade profile was proposed and subjected to numerical investigations regarding its deformation under simulated load conditions. The simulated load of the turbine blade included the average force derived from the generated torque, applied at a distance of 2/3 of the blade radius from the axis of rotation, as well as the radial stretching force caused by centrifugal action of the mass accumulated at the blade tip.

For the purpose of the analysis, a simplified mass distribution model of the rotor blade was assumed. According to this concept, up to 2/3 of the blade radius contains ≈ 80% of the total blade mass. The resulting centrifugal force from this section acts radially and, under a simplifying assumption, may be considered to act at a distance of 1/3 of the blade radius. Therefore, to generate a torsional moment

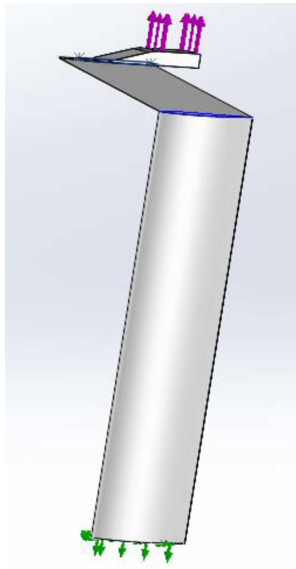

Fig. 4. Load conditions of turbine blade deformation.

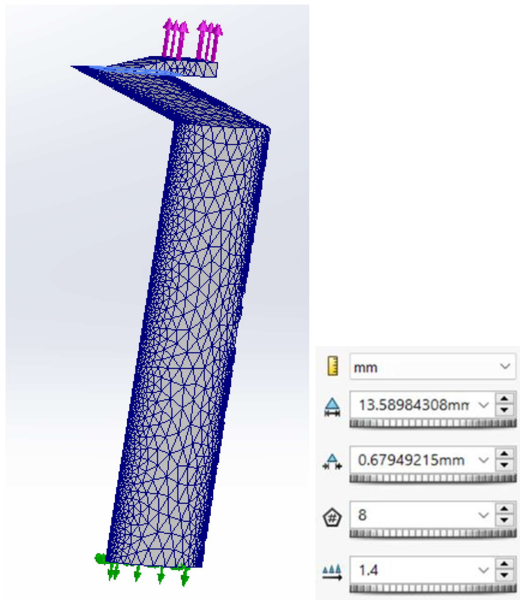

Fig. 5. Mesh view of turbine blade deformation. Mixed curvature mesh is shown with the presented parametric values.

on the blade, it is necessary to position an offset mass displaced laterally by a distance L from the longitudinal axis of the blade and by a parallel distance K relative to the longitudinal axis of the blade cross-section (Fig. 3).

A possible structural approach to implementing the proposed concept of mass distribution on a turbine rotor blade is the application of a blade extension in the form of a winglet with increased material density at its tip. To develop an initial geometry, it is first necessary to determine the required stiffness of the blade. This is a highly complex issue,

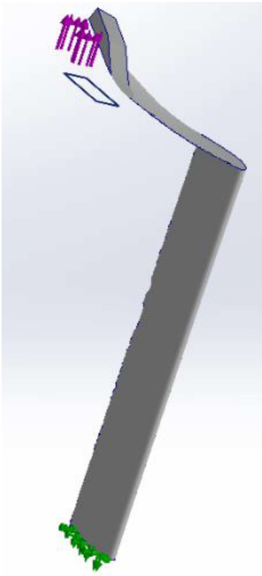

Fig. 6. Deformation of an illustrative element of a turbine blade.

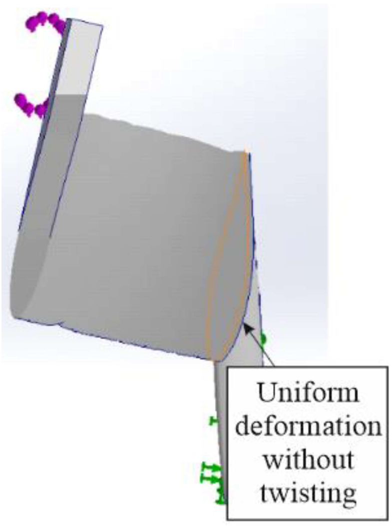

Fig. 7. Turbine blade displacement relative to the edge without load.

since stiffness depends both on the material properties and on the shape and surface area of the blade's cross-section. Therefore, certain simplifications were adopted for the analysis.

It was assumed that the blade profile would be represented by the aerodynamic cross-section NACA 63-415, with the wind turbine blade maintaining a constant cross-section along its entire length. The offset mass elements were modeled using simplified geometry. The offset distances L and K were set to 100 mm. The centrifugal force acting at the end of the K arm amounts to 160 N, which results from the rotor speed of 700 rpm and the mass located at the end of the K arm, being $m_K = 0.1$ kg (Figs. 4–7).

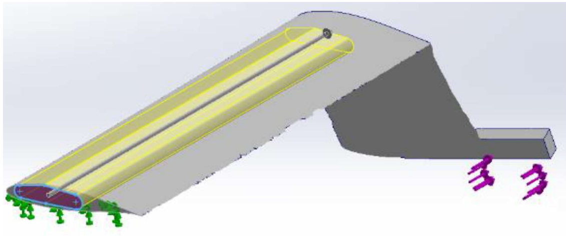

Fig. 8. Load conditions of deformation of a turbine blade with a longitudinal bore.

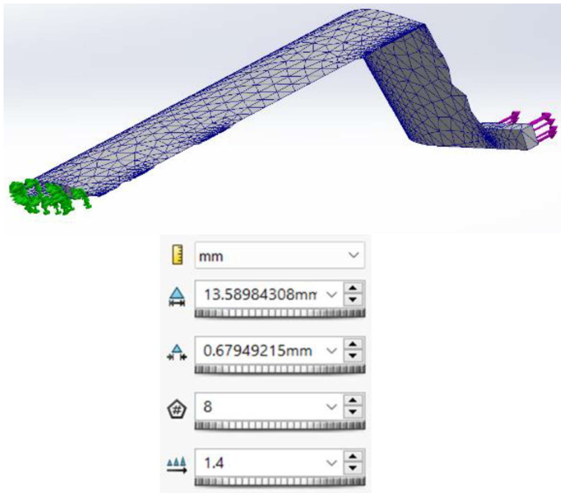

Fig. 9. Mesh view of deformation of a turbine blade with a longitudinal bore. Mixed curvature mesh is shown with the presented parametric.

As the structural material, polyester resin was selected, with the following characteristic parameters: an elastic modulus of 1.9×10^{10} Pa, a density of 1160 kg/m^3, a tensile strength of 190 MPa, and a compressive strength of 230 MPa. The deformation analysis of the element was conducted using numerical tools available in SolidWORKS 2024. For the purpose of the analysis, mesh discretization of the components was carried out using triangular elements based on equilateral triangles with mixed curvature, refined in areas of complex geometry. The side lengths of the mesh elements ranged from 0.674 to 13.482 mm.

The structural blade element was subjected to a static analysis by fixing the structure at the blade root and applying an inertial load corresponding to the mass m_K located on the designated surface of the K arm.

The analyses of wind turbine blade profile deformation, carried out under the assumed static load conditions corresponding to rotor operating parameters, indicate only minor deformation of the blade profile in its working section. This deformation exhibits the characteristics of linear bending while maintaining the parallelism of the cross-sectional axes. No significant torsional deformation along the

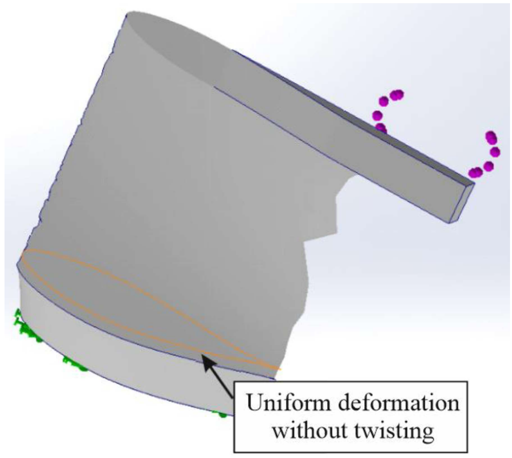

Fig. 10. Displacement of a turbine blade with a longitudinal bore relative to the edge without load.

blade length was observed. This outcome demonstrates the high stiffness of the blade cross-sectional profile. Subsequently, the prepared blade structure with an internal asymmetric cutout at a distance of 280 mm from the blade root was analyzed (Figs. 8–10). The numerical study was repeated under the same load parameters.

Analyses of the deformation of a wind turbine blade profile with an asymmetrically hollowed structure, conducted under the same static load conditions as in previous study, again indicate only minor deformation of the blade profile in its working section. This deformation is again characterized by linear bending while maintaining the parallelism of the cross-sectional axes. Similarly, no significant torsional deformation was observed along the blade length. The blade deflection of ≈ 1 mm for the tested blades does not affect the airfoil twist angle. This indicates that the centrifugal force at the blade tip offset element is too low and that the offset distance is too short. At the same time, it highlights the high stiffness of the NACA 63-415 airfoil and its resistance to blade twist.

3. Conclusions

Comparative analyses performed using numerical methods indicate that, under operating conditions of wind turbine blade, the relatively small load resulting from the centrifugal force of the mass placed at the end of the offset blade element does not significantly affect its deformation. The resulting deformation in the form of blade bending, illustrated by a displacement of the end of the main blade profile by 1 mm, is too small to produce a noticeable twist of the blade profile along its length. Consequently, it is necessary to apply modifications to the blade cross-sectional geometry, taking into account both aerodynamic factors and parametric factors arising from the properties of the composite material structure. After implementing such modifications, only minor changes in deformation can be expected; however, these changes may still be insufficient for optimizing the airflow dynamics around the rotor blades during operation. Much greater potential lies in the application of an active blade pitch control mechanism. Nevertheless, such a solution requires the development of a dedicated structural design that is economically feasible for small-scale wind turbine rotors.

Acknowledgments

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