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Modelica-based dynamic analysis and design of lift-generating disk-type wind blade using computational fluid dynamics and wind tunnel test data ☆

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A B S T R A C T

Wind power generation research and application technology have received much attention in the development of renewable energy. However, the traditional blade-rotating type wind power system has a number of drawbacks such as natural landscaping damage, flow-induced noise, and shadow flickering problems. In this paper, we propose a lift-generating disk-type blade power generation mechanism that can effectively generate wind power even with a simple structure considering the problems of the existing systems. Data on the lift force in relation to the shape of the designed blade were derived through a computational fluid dynamics simulation, and the Modelica language was used to model the integrated multi-physics wind power system. Then, a wind tunnel test was conducted using a small-scale model of the disk-type blade created to verify the simulation. The experimental results were in good agreement with the simulated results. Thus, we validated the modeling of the wind power system and applied the law of similarity to obtain the generator power output prediction results for the actual scale model.

1. Introduction

Wind power technology is one of the various methods used to obtain electricity from natural energy and has received much attention because it utilizes an infinite and free resource. In Europe, particularly in Germany, Denmark, and the Netherlands, there has been much research on wind power systems (WPSs) since the 1970s. As a result, several megawatt WPSs have recently been commercialized. Thus, wind energy is expected to play a decisive role in the future world energy supply [1–3]. To produce WPSs aligned with this purpose, efficient development is required to lower the development cost. With this objective, computer simulation technology is used in all development fields. Therefore, the simulation technique is a very important means for streamlining development work. When a WPS is being designed, numerous factors must be considered, including various physical phenomena such as the mechanical dynamics, electricity, control, and flow, along with a suitable program for the required integrated simulation of the system. The multi-physics system simulation has been typically integrated under different hardware/software platform environments. Consequently, it is easy for this design method to effectively cope with frequent design changes to the initial conceptual design, which results in reduction unnecessary work and increase efficiency. In the initial design phase, it is necessary to use integrated simulation software because it is important to communicate, coordinate, and cross check between concept verification and development personnel rather than conduct detailed analyses [4,5].

For this reason, the Modelica [6–9] language has been adopted for integrated simulation. Various WPS studies have been conducted using Modelica. Enge-Rosenblatt et al. [10] published a paper on the power energy results of varying the simulation configuration based on the way the WPS operates. Strobel et al. [11] proposed a Modelica library by designing an offshore WPS and verifying the simulation results. Petersson et al. [12] presented a mathematical model of a vertical axis WPS and presented simulation results for it. Eberhart et al. [13] constructed an open source library for the simulation of a horizontal axis WPS.

In this study, a new type of WPS utilizing Modelica was designed based on these studies. The conventional WPS is a horizontal-axis-type because the rotation axis of the blade is placed horizontally. These types of blades have suitable characteristics for high-speed rotation, but various problems are raised, such as noise generation due to the large scale wind power system (tip speed ratio, etc.) [14–16], changes in the landscape of the natural environment, and social pressure issues because of the shadows cast by the structures [17]. Therefore, the authors had the goal of designing a

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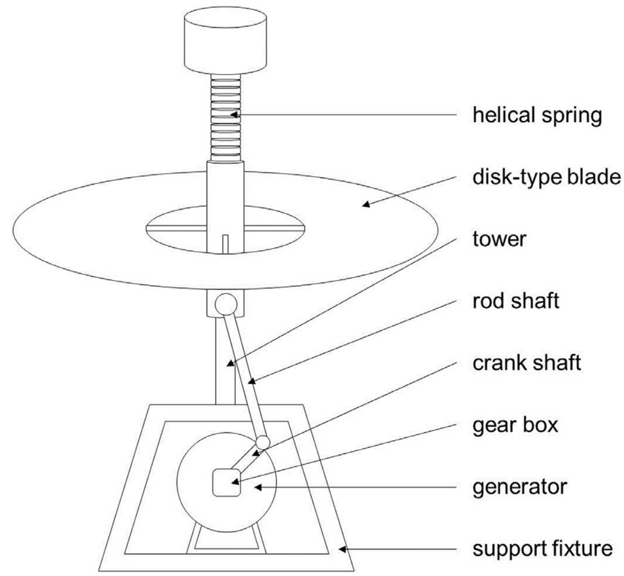

Fig. 1. Schematic diagram of the lift-generating disk-type WPS.

lift-generating disk-type WPS that could generate electricity in response to an omni-directional wind instead of a conventional WPS. The disk-type blades were first designed using computer-aided design (CAD). Then, they were modified based on the design parameters. We designed the WPS by applying the designed blade in a Modelica simulation. Wind tunnel tests were performed to verify the simulation, and the results were in good agreement.

2. Mechanism of wind power system

The lift-generating disk-type WPS is a system in which the blade is disk-shaped, and power is generated while it moves in a vertical direction. The basic principle of the system is that along the vertical axis of the supported tower, the disk-type blade is lifted up and down by the wind. This type of system generates electric energy through a power transmission system (PTS) that converts such motion into rotary motion, along with a power conversion system (PCS) such as a generator. This type of model is very different from the typical WPSs such as the conventional horizontal or vertical axis turbines. The proposed WPS is advantageous for areas in which flow-induced noise and blade flickering/shadows are critical. The small-scale WPS developed by the authors includes a disk-type blade, spring for managing the vibration generated by the vertical movement of the blade, crank-rod mechanism [18,19] for converting the vertical motion into rotational motion, and tower for installing the system. Thus, through the PTS, power is produced by the generator. The proposed WPS is shown in Fig. 1.

The proposed disk-type blade has some distinct characteristics. First, the disk can move up and down to generate a lift force that is converted into electrical energy. Second, because of its symmetrical shape, it is easily activated by the wind coming from any direction. The proposed WPS can generate the power from the arbitrarily directed wind. The additional conversion equipment is not necessary and the power generation is available with the inverter equipment only. Finally, the proposed model makes a relatively weak contribution to aerodynamic noise and shadow flickering because it does not feature a multi-blade rotation. In the conceptual design, the space required for realizing its motion could be comparatively small in the vertical direction.

3. System modeling

3.1. Shape design of disk-type blade

The shape of the blade was designed using CAD and is shown in Fig. 2. The material used for the blade is a polymer-type polycarbonate [20] with a density of 1.12e3 kg/m^3, Young's modulus of 2.3e9 Pa, and Poisson's ratio of 0.33. The blade configuration is assumed as follows: the disk-type blade is hollow, and its shell thickness is 10.3 mm. The shape and dimension were determined by blade loads and material costs. For instance, more lift can be generated with a longer airfoil chord length for the blade. However, such a longer length increases the weight of the product, resulting in a non-economical design. Considering these conditions, an analysis of the parameters that affected the shape design was carried out in order to create a lightweight blade with a minimal airfoil chord length. A sensitivity analysis was performed to derive the maximum lift generation shape parameters by varying the geometric shape of the blade. Additionally, the fixed variables and control variables to be changed were accordingly selected. As fixed variables, the radius of the center tower connected to the blade is 0.3 m, thickness is 0.05 m, and inner radius between the tower and disk-type blade is 0.55 m. For the aforementioned fixed parameters, a total of three disk-type blade parameters, including the airfoil chord length, angle of attack (AOA), and NACA series airfoil cross-sectional shape of the blade, were designated as design variables [21–23], as shown in Fig. 3 and listed in Table 1. For each parameter, the three values represent the three levels considered when varying the design of the experiment [24]. The chord lengths were 0.2 m, 0.45 m, and 0.7 m. The values of the AOA were 5°, 10°, and 15°. In the present study, most commonly used NACA series airfoils of NACA632615, NACA64A410, and NACA631412 were selected. In this study, we used a central composite design (CCD) table that allowed the