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Numerical study of the aerodynamic performance of a 500 W Darrieus-type vertical-axis wind turbine

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A B S T R A C T

This study characterizes the performance of a Darrieus-type vertical axis wind turbine (VAWT) with the National Advisory Committee for Aeronautics (NACA) airfoil blades. The performance of Darrieus-type VAWT can be characterized by torque and power. Various parameters affect this performance, such as chord length, helical angle, pitch angle, and rotor diameter. To estimate the optimum shape of the Darrieus-type wind turbine in accordance with various design parameters, we examined aerodynamic characteristics and the separated flow occurring in the vicinity of the blade, the interaction between the flow and the blade, and the torque and power characteristics derived from these characteristics. In flow analysis, flow variations were investigated based on the unsteady Reynolds-averaged Navier–Stokes equation. A sliding mesh algorithm was also employed to consider the rotational effect of the blades. To derive more realistic results, we coaxially conducted experimental and numerical calculations in a three-dimensional domain. Additionally, we focussed on the optimum design of the blade shape showing few disturbances and interactions with the ambient flow. In general, although the NACA airfoil made significant changes in the lift and drag force against the angle of attack, the use of the longer chord length and smaller main diameter (i.e., higher solidity) increased the power performance in the range of low tip-speed ratio (TSR). In contrast, in the high TSR range, the short chord and long-diameter rotors (i.e., lower solidity) performed better. In addition, when a pitch angle equals -2° with a helical angle of 0°, the Darrieus-type VAWT showed maximum power.

1. Introduction

In recent decades, fuel prices have rapidly increased and global warming has worsened owing to the reckless use of fossil fuels. Consequently, as an alternative to fossil fuels, attention and demand for new renewable energy has increased across the world. Among new renewable energy sources, wind power energy has gained the spotlight. (IEA, 2012) [1] Wind turbines can be divided into two groups: horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). HAWT has successfully evolved into a mature technology for converting wind energy into electricity. Presently, HAWT is applied to large-scale wind power plants. Although many studies on VAWT were conducted from the late 1970s to the early 1980s, the depth of recent works and studies on VAWT are not as profound as those examining HAWT, primarily because of the superior efficiency of HAWT. However, VAWT has also its own advantages. In particular, a yaw control device is not necessary in VAWT, because VAWT can produce power independently of the wind direction. Additionally, the levels of noise caused by VAWT are relatively low owing to its slower rotational speed than that of HAWT. Other advantages include its low production cost and affordable maintenance cost, because a VAWT blade consists of a consistently shaped airfoil, whereas a HAWT blade consists of a variety of airfoils whose shape changes along the radius direction.

There are two primary types of VAWT: drag-type (Savonius) and lift-type (Darrieus). A drag-type turbine performs better at the initial start-up wind speed. On the other hand, drag-type shows lower power generation efficiency than a lift-type turbine. This study examines a Darrieus-type wind turbine, which is more efficient than a Savonius-type VAWT, under the condition of wind speed exceeding a specific level. Among the experimental studies on Darrieus-type VAWT, one by Ref. [2] examined the performance characteristics of Darrieus VAWT in accordance with various design parameters (for example, number of blades, chord length,

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thickness, pitch angle, and rotor diameter) by extensively combining experimental studies published before 2009. [3] and [4] studied stall and pitch control for Darrieus-type blades.

Owing to the evolution of computer technology, three-dimensional computational fluid dynamics (CFD) have led to highly accurate models and calculation. Using these technologies, a wide variety of studies on blade-shape development are being actively conducted. Regarding numerical studies focusing on small-scale VAWT, [5] employed air as a fluid to present different detailed strategies for predicting the aerodynamic characteristics of a VAWT. [6] applied the sliding mesh strategy to two blade VAWTs using commercial software combined with the one-equation turbulence model, Spalart-Allmaras. [7] performed an extensive numerical study examining the hydrodynamic performance of a three-bladed tidal current turbine introduced in a duct to accelerate the flow upstream of the turbine. [8] examined a Darrieus VAWT with a specific shape and investigated torque, power coefficient, and flow characteristics by comparing the results of wind tunnel tests and three-dimensional numerical analysis. According to the previous studies, the numerical analysis results were significantly similar to the experimental results. However, the results from previous studies were primarily obtained by using specific shapes and only certain parameters of interest. Numerical approaches have also been used within a very limited range, such as with turbulence models, which tend to be inconsistent with other works.

This paper describes a design optimization study conducted on a Darrieus blade by considering various parameters such as chord length, rotor diameter, pitch angle, blade thickness ratio, and helical angle using ANSYS FLUENT®, three-dimensional CFD commercial software. According to previous studies, it is clear that the performance estimations and comparisons with experimental data for small Darrieus-type VAWTs of 500 W have been extremely insufficient. In this study, a wind tunnel test was also conducted based on a Darrieus VAWT with NACA airfoil blades. The experimental results of this wind tunnel experiment were verified in conjunction with numerical results. This study proposes an optimum shape for a Darrieus VAWT showing maximum power under different design variables and aims to analyse flow characteristics caused by interactions between the blade and the induced flow with respect to design parameters, temporal flow, and pressure characteristics for wind load. This study also highlights the fluid dynamic characteristics around the blade design that yield the maximum output power.

2. Numerical analysis and experimental method in wind tunnel

2.1. Darrieus numerical model

The Darrieus blade profiles used in this study primarily consist of the NACA series; in particular, NACA0015. The detailed specifications of the VAWT used in the wind tunnel experiment are as follows: airfoil, NACA0015; chord length, 150 mm; rotor diameter (D), 740 mm; length (L), 600 mm; and aspect ratio (L/D), 0.81. The turbine consists of three blades with identical airfoil shapes. The three blades are connected to a centre shaft. A schematic diagram of the Darrieus VAWT used in this study is shown in Fig. 1. Several design parameters for the Darrieus VAWT include blade thickness ratio (t/c), pitch angle (ϕ), solidity (NC/D), and helical angle. According to the design parameters, this study considers several different cases as follows: three different cases with varying thickness ratios of 0.15, 0.18, and 0.21, and varying solidity values of 0.4, 0.6, and 0.8. In addition, the study examined six different cases at varying blade pitch angles of −6°, −3°, −2°, −1°, −0°, and 3°, and four different cases at varying helical angles in range 0°~30° with an interval of 10°.

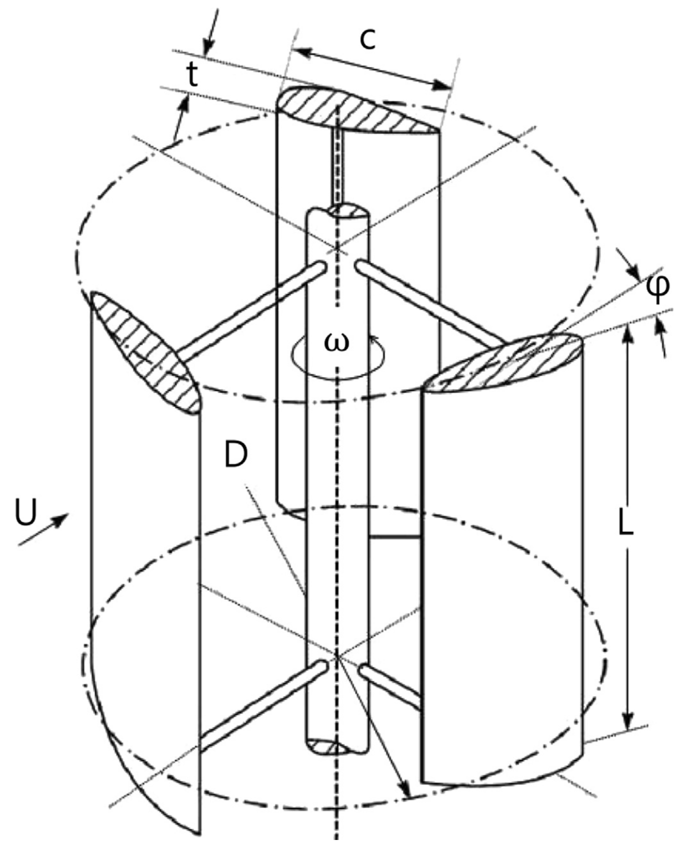

Fig. 1. Schematic diagram of Darrieus-type vertical axis wind turbine.

2.2. Computational grids

The computational mesh consists of a tetrahedron shape in most areas, but a partly hexahedron shape close to the blade surface for better accuracy. For proper simulation of the wind turbine, several separate zones are considered and the rotating region of the wind turbine mainly moves relative to the other zones (stationary regions). Fig. 2 indicates the computational grid with rotational and stationary regions. The number of grids for the calculation was 1,500,000 for the rotational region, 500,000 for the stationary region, and approximately 2,000,000 for the total domain. The full size of the computational domain is the same, with the real wind tunnel size located in the Pusan National University (PNU) (i.e., $2m^{width} \times 2m^{height}$) for comparison with the wind tunnel test.

2.3. Governing equation

The governing equation used in this study is the Navier–Stokes equation and the discretization method is the finite-volume method. In unsteady Reynolds-averaged Navier–Stokes (RANS) modelling, the flow properties are disintegrated into their mean and fluctuating components by Reynolds decomposition and substituted into the Navier–Stokes equations, which yield the time-averaged RANS equations for incompressible Newtonian fluids as follows: