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Study of Several Design Parameters on Multi-blade Vertical Axis Wind Turbine

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This paper describes the experimental resultsof a multi-blade vertical axis wind turbine. A vertical axis wind turbine (VAWT) of a diameter of 205 mm with multiple blades is installed in an open-type small-scale wind tunnel with the aim to study the variation of several wind design parameters (i.e., length and angle) the system. This VAWT was tested at various wind speeds of 5 to 30 m/s in steps of 5 m/s. The results show that the efficiency of this system increases with increasing wind velocities up to approximately 25 m/s, after which the efficiency drops rapidly. Moreover, because the system was found to be dependent on various parameters, skew-normal distribution was applied to predict the rotational speed as a function of several design parameters. The use of an equation for predicting the blade tip speed is discussed in this paper. Parametric surveys of the wind blade design are underway to fully understand the aerodynamic characteristics of the VAWT depending on the number, angle of attack, and chord length (W) of the blades.Regarding the efficiency, the performance depends highly on the blade angle and it has a maximum value at 45º, but when the blade angle is set to on 45º, the case of W/R = 0.39 has the highest, around a factor of 7 higher λ comparing with other cases. Regarding the effect of the oncoming wind speed, the ë ratio against the number of blades showed a typical tendency of an increase, a peak in the middle, and a gradual decrease.

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NOMENCLATURE

C_p = power coefficient of turbine blade
ρ = the air density
A = the area of the wind turbine
U = the tip speed of multiple blades
V_∞ = the freestream wind speed
λ = the tip speed ratio
D = the diameter of VAWT
H = the height of VAWT
W = the chord length of the blades
R = the radius of VAWT
α = the angle of blade
$\varphi(x)$ = the probability density function
$\Phi(x)$ = the cumulative distribution function
β = the skew normal distribution parameter
ξ = location parameter of the probability density function
ω = scale parameter of the probability density function

1. Introduction

Energy, required for maintaining modern life, has become a critical resource often prematurely assumed to be available for future prosperity. Oil has reached a record-high $112 a barrel, which is the highest level since 2008. This exigency, coupled with global warming concerns, has led to substantial research in creating inexpensive energy generation through renewable energy sources (Wells 2007).

In the design of the various functional elements of a wind turbine, blade design is given the highest priority. Therefore, in many respects, the aerodynamic and dynamic properties of the blade decisively influence the entire system. The capability of the rotor drive to convert a maximum proportion of wind energy into mechanical energy for blade rotation is obviously the direct result of its aerodynamic properties. These features, in turn, largely determine the overall efficiency of energy conversion in the wind turbine.

Although most recent designs are of the horizontal axis type, vertical axis wind turbines (VAWTs) have several advantages for direct mechanical drive applications. VAWTs usually needno tail or yaw mechanism for orientation into the wind. Further, power is easily transmitted via a vertical shaft to a load at ground level. Blades may have uniform, untwisted sections, making them relatively easy to fabricate or extrude. Conversely, the blades of horizontal axis wind turbines (HAWTs) should be twisted and tapered for optimal performance.In addition, VAWTs tend to be safer and easier to fabricate. Because they are mounted close to the ground, VAWTs handle turbulence much better than do HAWTs. Two main types of VAWT are the Darrieus, which uses lift forces generated by aerofoils, and the Savonius, which uses drag forces. The latter is the more common type and is an extended version of a wind speed anemometer (see Mojola 1985 and Menet and Bourabaa 2004). According to a current study, Savonius-type VAWTs are unique, fluid-mechanical devices that have been the subject of numerous investigations since the 1920s. These turbines have been used to generate electric power on deep-water buoys, which require small amounts of power and very little maintenance. Their design is simplified because, unlike that required of HAWTs, no pointing mechanism is needed to allow for shifting wind direction, and the turbine is self-starting. In addition, VAWTs excel in water pumping and other high-torque, low-rpm applications, and they are not usually connected to electric power grids. Moreover, VAWTs are occasionally equipped with long helical scoops for smooth torque.

Recent developments in numerical and experimental technologies have led to further research in VAWT design optimization. Several researchers have attempted to improve designs for large-scale wind tunnels (for tunnel measurements, see Menet and Bourabaa 2004 - Grinspan et al. 2004, and more recent papers Sargolzaei 2007, Altan et al. 2008, Chilugodu et. al. 2012). The study by Saha et al. (2008) is one of the most recent studies related to this study. They investigated the aerodynamic performance of multi-stage, multi-blade Savonius rotor systems with a low-speed, open-type wind tunnel at various wind speeds. Interestingly, the optimum number of blades and stages for the current study was determined to be two for both cases. These results could serve as a reference database for comparison with future modelling resources. The typical shape of the Savonius-type wind turbine creates limitations resulting in, for example, drag force, and is, therefore, fairly uniform.

A new VAWT design was recently proposed Kim et al. (2006) with a geometry based on the simple, multi-blade Savonius. Figure 1 shows a prototype VAWT model, which will be used for designing and analysing small-scale models. This prototype is equipped with pivoting panels on each rotating blade frame to simplify the design for maximum harvesting of wind energy. These panels support wind forces on the windward side and are open on the leeward side. Because information on this type of design is insufficient, most approaches were directed to industrial applications. Therefore, recent studies on this specific topic have appeared in specialized publications and not in general engineering literature. Nonetheless, the results of this preliminary investigation indicate high promise for wider multi-blade VAWT applications.

These aspects illustrate the importance of rotor aerodynamics on the entire system. Obtaining a clear understanding of wind turbine operation would be impossible without at least some knowledge of the aerodynamic characteristics of the rotor and its more important

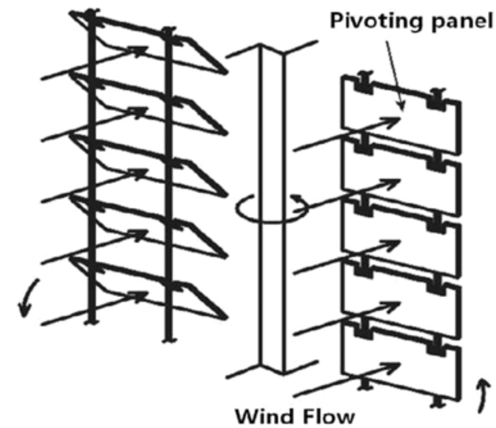


Fig. 1 Principle of pivoting panels

parameters. In addition, the rotor of a wind turbine is, to a certain extent, system specific with unique design and construction characteristics; previous examples from other fields of technology are inapplicable. In this paper, the effects of blade number, angle of attack, and chord length, in addition to tip speed ratio— hereafter referred to as λ—are discussed. Based on numerical investigation, an assumed asymmetric straight Savonius wind turbine is proposed to improve the average power coefficient.

For this reason, a comparatively large part of this paper is devoted to the aerodynamic characteristics of multi-blade VAWTs. However,the paper is notgoing to provide a detailed description of the theory of rotor aerodynamics, but rather to illustrate the relationship between the essential design parameters of the multi-blade VAWT and its properties as an actuator disc, i.e. a mechanical energy converter. In this study, wind tunnel experiments were performed on a series of 3D multi-blade VAWTs of various blade sizes and at various locations over a wide range of wind speeds, namely, 5 to 30 m/s in steps of 5 m/s. This paper is organized in the following manner: Section 2 outlines the basic configuration and experimental parameters of various blade models. Section 3 describes the parametric analysis of VAWTs under uniform wind flow. Section 4 explains the effect of oncoming wind speed on multi-blade VAWTs, and Section 5 gives the major conclusions.

2. Design of wind tunnel experiment

2.1 Oncoming wind conditions - uniform wind flow

Since the VAWTs have a rotational axis perpendicular to oncoming airflow, the aerodynamic design are more complicated than that of the more conventional HAWTs. The main benefit of this layout is the independence of wind direction. The main disadvantages are that it needs to consider the high local angles of attack and the wake originating from the blades and the support. To understand and address these issues, we analysed the aerodynamic performance of a VAWT model with pivoting panels to capture the maximum wind energy. The most effective approach for future applications would be to manufacture an equivalent model or a model with a similar scale. For convenience, however, this study modified specific characteristics of VAWTs into a simplified device that can be improved for more complicated research in the future.

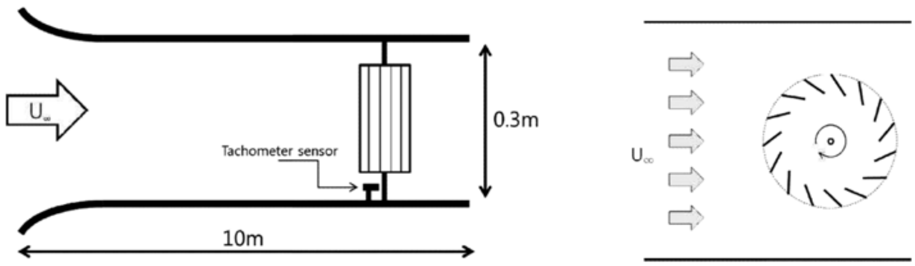


Fig. 2 Schematic diagram of wind tunnel test section (left figure) and simplified VAWT model (right figure) placed in an on coming flow

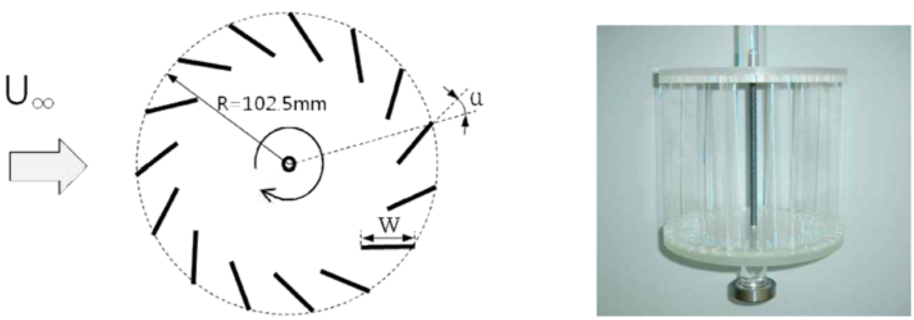


Fig. 3 Specification andthe scaled model of wind turbine with multiple blades

Figure 2 shows a schematic diagram of a VAWT model and flow conditions used in the wind tunnel experiment. In this case, the flow was generally uniform for a simple approach. Each segment of the VAWT blades was fabricated from Plexiglas sheets attached equidistantly to the inner circumference of the circular panels at each end. As shown in the figure, the fabricated multi-blade VAWTs were located at the centre of a cross-section in the wind tunnel. To create uniform wind flow, the wind tunnel measurements were carefully designed for a stable, reliable wind profile. This approach sufficiently justifies proper experimentation as well as simplification of the scaled VAWT models.

2.2 Wind tunnel test

Wind tunnel tests on multi-blade VAWTs were conducted in an open-circuit, low-speed wind tunnel with a working section dimension of $0.3\ \mathrm{m}^{\mathrm{wide}} \times 0.3\ \mathrm{m}^{\mathrm{high}} \times 10\ \mathrm{m}^{\mathrm{long}}$ and a maximum wind speed of approximately 33 m/s at the Pusan National University (PNU) in South Korea. The tunnel consisted of a wind blower equipped with a three-phase 7.5-kW AC motor, a diffuser with a monotonic expansion, and a contraction nozzle to reduce the level of turbulence in the working test section. This apparatus was suitable for generating a stable, low-turbulence wind flow and was equipped with modern hot-wire anemometry (HWA; IFA100) and a PIV system for optical airflow measurement. (Results from the PIV system will be discussed in future publications.) A frequency converter controlled the air speed at the working section of the tunnel (wind speed) such that it varied from 0 to 33 m/s. The contraction nozzle was shaped, designed, and manufactured based on a third-order polynomial equation. (see Morel 1975)

2.3 Force and velocity measurement system

A set of digital tachometers (accuracy: ± 1 rpm) were used to measure the rotational speed of the rotor. Standard tube connections to a Furness FC-012 micromanometer allowed for measurement of mean surface pressures. Mean velocity and turbulent intensity data within freestream wind flow of the wind tunnel around the fabricated VAWTs were obtained using HWA. Calibrations were performed against a standard pitot-static tube using the same micromanometer as that used for the static pressure measurements. All analogue signals were digitized and transferred to a desktop computer.

2.4 Scaled models with multiple blades

The design specification for a wind turbine generally contains a power or torque curve with guaranteed availability. From an engineering perspective, however, the aerodynamic characteristics of multi-blade VAWTs were obtained in this study. The determination of the number, angle of attack, and chord length of blades involved design considerations of aerodynamic efficiency, component costs, system reliability, and aesthetics. Noise emissions are generally affected by blade location upwind or downwind of the tower and the speed of the rotor. For example, given that noise emissions from the blades' trailing edges and tips vary by the fifth power of blade speed, a small increase in tip speed can make a large difference.

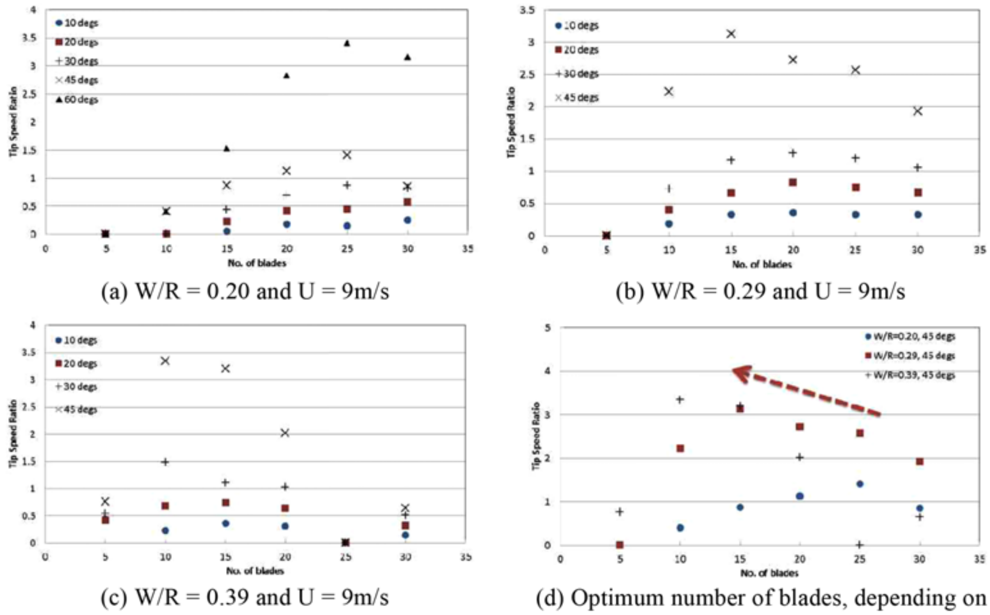
A typical non-dimensional parameter used to understand wind energy is the power coefficient Cp, which can be obtained from the wind power (P). A power coefficient is then defined as

$$C_p = \frac{P}{0.5 \rho A V_\infty^3} \tag{1}$$

where C_p is the power coefficient, ρ is the air density, A is the area of the wind turbine, and V_∞ is the freestream wind speed. Equation (1) shows two important dependents. The first is the tip speed of the multiple blades of the VAWT, U, which could be non-dimensionalized by the freestream wind speed. The tip speed ratio (λ) is determined as follow:

$$\lambda = \frac{U}{V_\infty}. \tag{2}$$

The parameter λ is widely used because of its simplicity and



(a) W/R = 0.20 and U = 9m/s

(b) W/R = 0.29 and U = 9m/s

(c) W/R = 0.39 and U = 9m/s

(d) Optimum number of blades, depending on the of chord length to radius

Fig. 4 Influence of multiple blade angles on ë and the optimum number of blades, depending on the width to radius ratio (U = 9m/s)

usefulness. Therefore, a large part of this paper is devoted to the aerodynamic characteristics of the multi-blade VAWTs.

Figure 3 shows a schematic diagram of the wind turbine with multiple blades, which was used in this study. The main geometric parameters of the model VAWT were diameter (D = 205 mm), height (H = 190 mm), and the projection of area onto a plane (A = 0.038 m^2). Up to 60 blades composed of acrylamide Plexiglas could be mounted simultaneously on the model, and the geometrical limitation the angle of blade (α) enabled manual rotation of 0 to 60°. In addition, the chord length of the blades (W) varied from 20 to 40 mm and the ratio of the chord length to radius of the turbine was 0.193, 0.295, and 0.390, respectively. Wind flow conditions were uniform throughout the study.

2.5 Skew normal distribution

Providing a reliable analysis of the aerodynamic performance, some response surface models have been suggested. In our study, however, the Lambda distribution was not the usual symmetric shape and rather asymmetric so that we tried to fit the universal curve to explain the differences. In particular, in the case of the continuous multivariate observations, such as those in the current experiment where the undetermined size and blade angles change, one aspect that has been little affected in the final result is the overwhelming role played by the assumption of normality that underlies most methods of multivariate analysis. This assumption of normality is generally considered to apply when the experimental condition is ideal, which is not true in most cases and leads to skew. In probability theory and statistics, the skew normal distribution is a continuous probability distribution that generalises the normal distribution to allow for non-zero skewness.

The following is a brief introduction to the skew-normal distribution relative to analytic processing: The skew-normal distribution proposed by Azzalini (2005) is suitable for the analysis of data exhibiting a unimodal empirical distribution function but containing some skewness, a structure often occurring in data analysis. Beginning with a typical skew-normal distribution, the probability density function is given by

$$\phi(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} \tag{3}$$

with the cumulative distribution function given by

$$\Phi(x) = \int_{-\infty}^{x} \phi(t)dt = \frac{1}{2}\left[1 + erf\left(\frac{x}{\sqrt{2}}\right)\right]. \tag{4}$$

The function $\phi(x)$ is defined as a parametric class of probability distributions that includes the standard normal as a special case. Then, the probability density function of the skew-normal distribution with parameter β is given by

$$f(x) = 2\phi(x)\Phi(\beta x)\,. \tag{5}$$

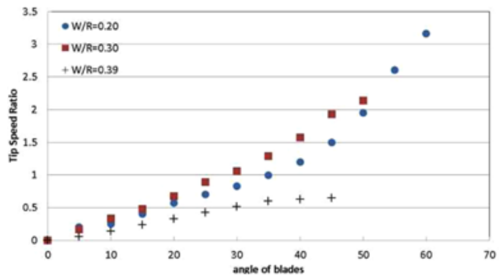
This distribution was first introduced by O'Hagan and Leonhard (1976). To add location and scale parameters, the usual transformation can be made from x to $(x - \xi)/\xi$. This equation can verify that the normal distribution is recovered when $\beta = 0$ and that the absolute value of the skewness increases as the absolute value of β increases. The distribution is right skewed if β is larger than zero and is left skewed if β is less than zero. The probability density function with location ξ, scale ω, and parameter β becomes

$$f(x) = \frac{2}{\omega}\phi\left(\frac{x-\xi}{\omega}\right)\Phi\left(\beta\left(\frac{x-\xi}{\omega}\right)\right). \tag{6}$$

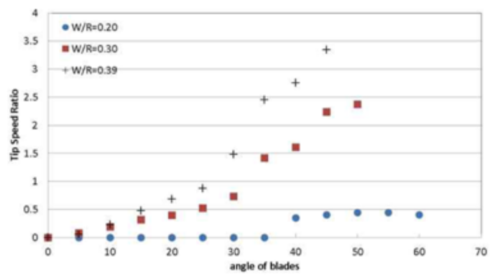
3. Analysis of λ under uniform wind flow

3.1 Effect of angle of attack

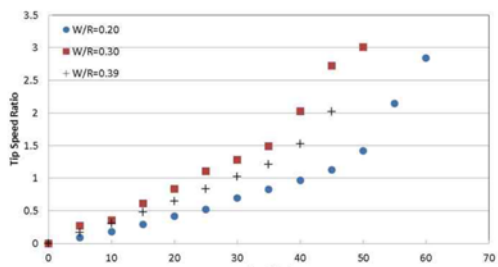
Figure 4 shows the lambda ratio (the ratio of blade tip speed to freestream wind speed; hereafter, λ) of the wind turbines for a freestream wind speed of 9 m/s, while the number of blades and the W/R ratio are in the range 10 - 30 and 0.195 - 0.390, respectively. When α was set to zero, obviously, there was no rotation, and the 5° angle of



(a) Number of blades = 10



(b) Number of blades = 20

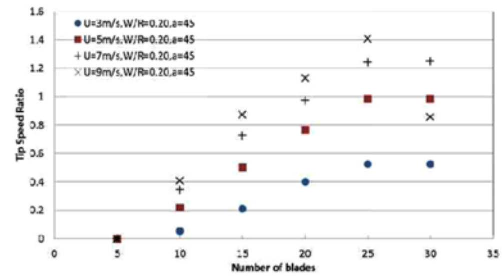


(c) Number of blades = 30

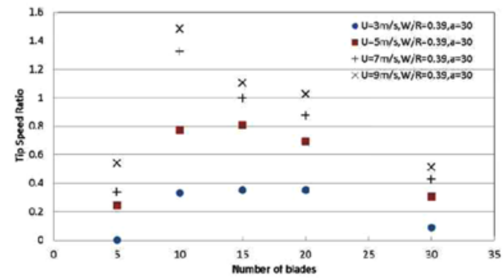
Fig. 5 Influence of the width to radius ratio of the multiple blades on λ and the optimum angles of multiple blades, depending on the number of blades (U = 9 m/s)

wind pressure gradually drove the blade rotation. The variation in λ with α and the number of blades is shown in Fig. 4(a), for a fixed ratio (0.20) of the chord length to the rotational radius. In this figure, as the number of the blades increases, λ also gradually increases, and the maximum value of λ could be obtained at 50° - 60°, depending on the conditions, but with the current condition of experiment the maximum value of λ would be further reached. That is, in the wind tunnel experiment,the variation in α was limited to a maximum of 60°. Further experimentation was not performed; however, it was confirmed that the maximum λ increased with α.

As shown in Fig. 4(a), λ also increased with the number of blades, and as the width to radius (W/R) ratio increased, the maximum λ occurred for $\alpha = 45°$, which is within the possible angle measurement range. Figures 4(b) and 4(c) show the λ variation depending on the number of blades for the case in which the ratio of chord length to blade radius varies from 0.29 to 0.39. Interestingly, the result shows that the peak of the ë distribution tends to reduce when the variation in the W/R ratio increases. Figure 4(d) shows that the different W/R ratios of 0.20, 0.29, and 0.39 for the same α of nearly 45° have different peak positions with blade numbers of 25, 15, and 10, respectively. That is, as the W/R ratio decreases, the λ distribution tends to be positively skewed and vice versa. When α was set to 45° and the number of blades was 10, the maximum obtained λ was approximately 3.5.Regarding the efficiency, it



(a) W/R = 0.2



(b) W/R = 0.39

Fig. 6 Variation in λ with an increase in oncoming flow velocity (W/R = 0.20; α = 30° ~ 45°)

depends highly on the blade angle and it has a maximum value at 45°, butwhen the blade angle is set to on 45°, the case of W/R = 0.39 has the highest, around a factor of 7 higher λ comparing with other cases.

3.2 Effect of chord length on radius ratio (W/R)

Solidity is one of the main parameters controlling the rotational velocity at which the turbine reaches its maximum performance coefficient. Higher solidity generally lowers the maximum lambda ratio and consequently lowers the power coefficient. At low λ, the rotor blades do not interact as strongly with the air flow swept out by the operating blades; however, at high λ, rotor blades begin to strongly interact with the wakes produced by upstream blades.

Figure 5 shows the λ distribution of the wind turbines for the case in which the freestream wind speed and the number of blades were set to 9 m/s and 10 - 30, respectively, while the W/R ratio ranged from 0.20 to 0.39. As previously mentioned, when α was set to zero, the VAWT was stationary. From a 5° angle, however, the VAWT moved slowly at the beginning, increasing speed at higher angles. The λ distribution as a function of the W/R ratio and α shown in Fig. 5(a), for a fixed number of blades (10). The figure shows that as α increases, λ linearly increases at the beginning and then creates different slopes, depending on the W/R ratio. It is easily conjectured that the number of blades relates to a larger projection area for the oncoming wind speed, which could support more wind load and thus harvest more wind energy (i.e., more efficient). On the other hand, this finding is less significant for the other cases (Figs. 5(b) and 5(c)). As α increases, the effect of the projection area is insignificant; therefore, the variation in λ is similar. Interestingly, it could be considered that as both α and the W/R ratio increase, λ does not always follow a similar trend. In Fig. 5(c), for example, when the number of blades is set to 30, the λ distribution has the lowest W/R ratio of 0.39. As α and the W/R ratio increase, the projection area and the solidity of VAWT could be sufficiently large to increase the wind load on the blade of the wind

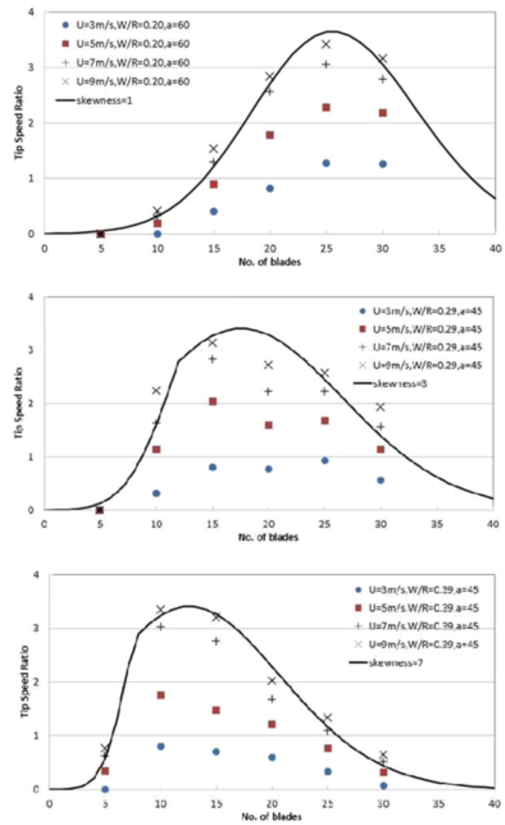


Fig. 7 Variation in maximum λ on the angle of attack with the number of blades

turbine. These factors affect flow direction and cause an increase in surface friction, which explain the lower λ at higher α. Therefore, to create a reasonable design for VAWT blades, it is highly recommended that the W/R ratio, the number of blades, and the blade angle are simultaneously considered for the final product.

4. Analysis of the λ ratio with oncoming wind speed

4.1 Effect of oncoming wind speed

All effective wind turbines must process the massive increases in available power as the wind speed intensifies. In this section, therefore, we will discuss the effect of wind speed. Figure 6 depicts the λ variation against the number of blades with an oncoming wind speed range of greater than an order of magnitude; that is, a factor of 3. The W/R ratio was set to 0.20, 0.29, and 0.39, and α ranged from 30° to 45°. This range was considered for generalized wind tunnel measurement, depending on various parameters. In this figure, the lambda ratio against the number of blades tended to increase in the beginning, peak in the middle, and gradually decrease. As was previously noted, the λ distribution peak similarly moved toward to the lower region of the number of blades when the oncoming wind speed increased. When the W/R ratio was set to 0.20, 0.29, and 0.39, the number of blades showing a λ distribution peak was 25, 15, and 10, respectively. Because the W/R ratios increased, we expect this trend to continue. Regarding the efficiency, it depends on the blade angle and W/R ratio, especially, the case of W/R = 0.39 has the highest ë around 1.5, which is at most 4.3 times higher than other cases.

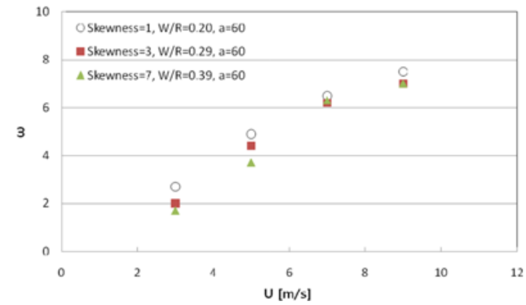


Fig. 8 Scale factor distribution against average wind speeds

4.2 Variation in λ distribution

Figure 7 shows the λ distribution of the wind turbines on the angle of attack with the number of blades conditional on the maximum λ distribution, while the freestream wind speed and W/R ratio was set in the range 3 - 9 m/s (i.e. an order of 3) and 0.20 - 0.39, respectively. During the wind tunnel measurement, α depended on obtaining the maximum λ distribution. Curve fitting is the process of finding a general assumption, defined in the Introduction. Specifically, solid lines have been added in Fig. 7 to generalize the λ distribution and combine the given skew-normal distribution. As previously described, the skew-normal distribution by Azzalini (2005) is suitable for data exhibiting a unimodal empirical distribution so that the line fits reasonably well with the experimental results. In the analysis of skew-normal distribution, the principal parameters used in the calculation were location (ξ), skewness parameter (β), and scale factor (ω). In particular, the location parameters depended on the average location, and the skewness parameter, which was one of the priority variables (i.e. β = 1, 3, and 7), was adapted in each analysis stage. The scale factor, the other priority variable, was then determined in the rest of the tuning stage. Given that a skewness parameter sets a certain number, interestingly, it is observed that the ë distributions are dependent only on scale factors.

The scale factor distribution against average wind speeds is shown in Fig. 8. As the wind speed increased, the scale factors were proportional to the wind speed with a gradual approach to a certain region obtained near 7 m/s. For precise analysis, however, further study on each parameter is necessary.

5. Conclusions

Several salient parameters have been analysed in this paper and have been applied for better performance prediction and design analysis of a VAWT that is equipped with multiple blades and has a diameter of 205 mm. The aerodynamic characteristics of the system were investigated in an open-type small-scale wind tunnel with various wind speeds of 5 to 30 m/s in steps of 5 m/s. The main conclusions drawn from the present study are summarized in the following points:

- As the number of blades increased, λ - the ratio of the tip speed of the blade to freestream wind speed - gradually increased. In addition, the peak of the λ distribution tended to reduce when the variation in the W/R ratio increased.
- As the blade angle (α) increased, ëlinearly increased at the

beginning and then exhibited various slopes, depending on the W/R ratio. This result appeared to be caused by the effect of the projection area, which was a significant factor for increasing α.

- Regarding the efficiency, the performance depends highly on the blade angle and it has a maximum value at 45^o, but when the blade angle is set to on 45^o, the case of W/R = 0.39 has the highest, around a factor of 7 higher λ comparing with other cases.
- Relative to the effect of the oncoming wind speed, the λ ratio against the number of blades showed a typical tendency of an increase, a peak in the middle, and a gradual decrease.
- In the analysis of the skew-normal distribution, the salient parameters used in the calculation were location (ξ), skewness parameter (β), and scale factor (ω). Given that a skewness parameter is set to a certain number, the λ distributions are dependent only on scale factors.

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