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PERFORMANCE TEST OF AN INNOVATIVE VERTICAL-AXIS, TWIN-ROTOR WIND TURBINE SYSTEM

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ABSTRACT

The patented vertical-axis wind turbines for distributed applications have been developed. The wind turbine system is very efficient in terms of the power-to-swept area and works very quiet even for the installation near houses and buildings and in other applications where traditional, three-blade, horizontal axis turbines are not suitable. The technology behind the new VAWT having twin rotors lies in its guided turbine design which combines inlet-guide vanes, a top-guide vane, and an impulse-type rotor. Its functional assembly makes it unique from all the Savonius rotors or their derivatives. To minimize the inertia effect of yawing system for frequent wind direction change, the twin-rotor turbine is designed to align with the wind direction by a stabilizing tail. The objective of this study is to test a 5 kW, twin-rotor VAWT installed at the Kansas site in terms of the performance, noise level, safety, and durability. The twin-rotor, WindJet turbine of the rated capacity of 5 kW resulted in an annual capacity of 26% or more at average wind speed of 6m/s, and a turbine efficiency of 50% or more.

Keywords: Vertical-Axis Wind Turbine (VAWT), Twin-rotor, Power Coefficient, Tip Speed Ratio (TSR)

NOMENCLATURE

A	Projected area of turbine rotor
C_p	Power coefficient
D	Diameter of rotor
r	Radius of rotor
T	Torque
U_∞	Wind speed to turbine rotor
V_{tip}	Rotational velocity at blade tip
Greek symbols	
λ	Tip speed ratio
ρ	Fluid density
ω	Angular velocity of rotor

INTRODUCTION

The emerging wind power business is now driven by energy cost savings, reliability of power, grid support, and reduced environmental impact. The development of a wind turbine should comply with stipulations on noise-levels for the community and a strong need for a reliable system of high capacity (Emerging energy research(1)).

Generally, the Savonius turbine produces torque using a drag force in an upstream blade and makes the flow pass through a downstream blade. However, in a patented jet wheel type turbine disclosed in Korea Patent No. 0810990(2), a high speed incident flow condition capable of realizing an easy energy conversion is provided both by an inlet guide vane and by a side guide vane, and the upper and lower surfaces of the turbine are open, so that an inlet fluid can flow to the hub surface of blades and increase the positive torque and reduce the negative torque, thus improving the turbine performance.

Further, a turbine blade structure for vertical axis wind turbine systems, which can increase the performance of the vertical axis wind turbine system, has been proposed in recent years(3). In the turbine blade structure, a sweep angle distribution is adapted to the blades of the turbine rotor and each blade is twisted to form a twisted shape, so that a rotating force can be continuously transmitted to the turbine and a streamline from a radial direction to an axial direction can be easily formed.

In the jet wheel type turbine, the combined guide vane system having the inlet guide vane and the side guide vane is steered by the tail wing such that the guide vane system can be oriented into the direction of the wind. But the output performance of the small-sized jet wheel type turbine may be strongly influenced by inertia effect of guiding system. The present system is intended to have a dual rotor wind turbine, which is of increased performance and the gravity center of which is located in a downstream portion thereof, thus realizing stable balance, so that a vertical shaft can be stably rotated relative to a fixed shaft for yawing.

The performance of horizontally-rotating, twin-rotor VAWT, which has the guide-vane system yawing as a whole, is not much influenced by frequent wind-direction change. It is completely different from that of the combination system in which two sets of conventional VAT are aligned in the same axis because the tower-tilting by the wind loading on turbine does not cause any increased bearing friction loss due to unbalanced wearing. Furthermore, the low rotational speed of a dual rotor implies that the machine will be quieter than high-rotational HAWTs and therefore possibly more suitable in applications that are close to population centers. Visual aesthetics is a critical issue in location, as the view shed by the wind turbines is an important consideration. High-speed propellers may offend some people in the community, while machines that slowly rotate may be considered as visual art(4).

Twin-rotor wind turbine of AeroNet is comprised of inlet-guide vanes, a top-guide vane, and twin cup-bladed rotors. Its functional assembly makes it unique from all the Savonius rotors or their derivatives. To minimize the inevitable generation of negative torque in the conventional Savonius rotor and to accelerate the incoming jet into the rotor blade cascade, the round inlet-guide vane is placed upstream of the rotor. The top guide-vane also recovers wind energy by collecting the streamlines into the blade; otherwise, the streamlines simply pass by. The design details of the WindJet model can be found in the reference (5). This paper presents performance measurements for a 5kW WindJet dual-rotor wind turbine in late 2009 commissioned at A.L. Huber headquarter site, Overland Park, Kansas.

BASIC THEORY OF WIND TURBINE

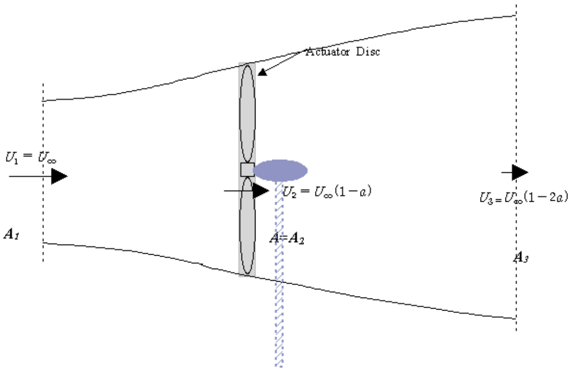

Fig. 1 Stream tube passing through the rotor plane.

The output power, P_T, from a turbine rotor and the wind kinetic energy per unit time, P_W, are given by Eqs. (1) and (2), where T is the torque of the turbine, ω is the angular velocity of the rotor of turbine, ρ is the air density, and V_∞ is the approaching wind speed. As shown in Eq. (3), the rotor power coefficient, C_p, is defined as the ratio of the output power of the rotor to the dynamic power of the air.

$$P_T = T \times \omega \quad (1)$$

$$P_W = 0.5 \times \rho \times V_\infty^3 \times A \quad (2)$$

$$C_p = P_T/P_W = (T \times \omega) / (0.5 \times \rho \times V_\infty^3 \times A) \quad (3)$$

The C_p can generally be expressed as a function of the tip speed ratio, λ, which is defined in Eq. (4), where V_{Tip} is the tip speed of rotor of turbine. The tip speed ratio, λ, at the maximum power coefficient varies according to the type of the turbine.

$$\lambda = V_{Tip}/V_\infty = (r \times \omega) / V_\infty \quad (4)$$

The rotor power coefficient is regarded as the energy transformation efficiency. The WindJet vertical-type wind turbine is designed to operate within 40-70 percents of the free tip speed ratio for achieving the highest possible rotor efficiency.

If a control volume is assumed around a turbine, then the rate of incoming wind-flow should equal that of the outgoing wind-flow to satisfy the law of mass conservation. The distribution of the outgoing wind-speed and the direction of the wind strongly influence the efficiency of the turbine. As can be seen in Fig. 1, due to the rotation of the rotor, the upstream area (A_1) is smaller than the rotor area (A_2) of the same stream tube; this results in an unavailability of wind energy upstream. The transfer of momentum, which can be computed by the difference between the upstream and downstream wind speeds, may be maximized by reducing the wind speed (V_3) in the wake. The inlet guide-vanes and the top-guide-vane of the WindJet turbine are designed to make the streamlines as parallel as possible ($A_1 \approx A_2$), and the wake speed V_3 is minimized by transferring air energy to the rotor (Park et al.(6)).

WIND TUNNEL MODEL TEST

The model of the twin-rotor turbine was tested in an open-type, wind tunnel shown in Fig. 2. The wind tunnel consists of a vane-axial fan, a diffusing part, a reducer and a test section that is wrapped by silencing materials. The test section has a cross-section of 2.3m×2.1m and permits continuous changes in the wind speed from 0 to 16.7m/s at a low level of intensity. The wind speed in the wind tunnel is automatically computed by using a digital micro-manometer with a correction for density through the measurement of the room temperature and humidity.

Figure 3 summarizes the dual-rotor turbine efficiencies for different numbers of rotor-cup. The geometric parameters d/D and H/D are 0.25 and 0.8, respectively where d is the cup diameter and H is the blade width. It is observed that the turbine efficiency increases significantly up to 6 cup-blades by increasing the number of blade.

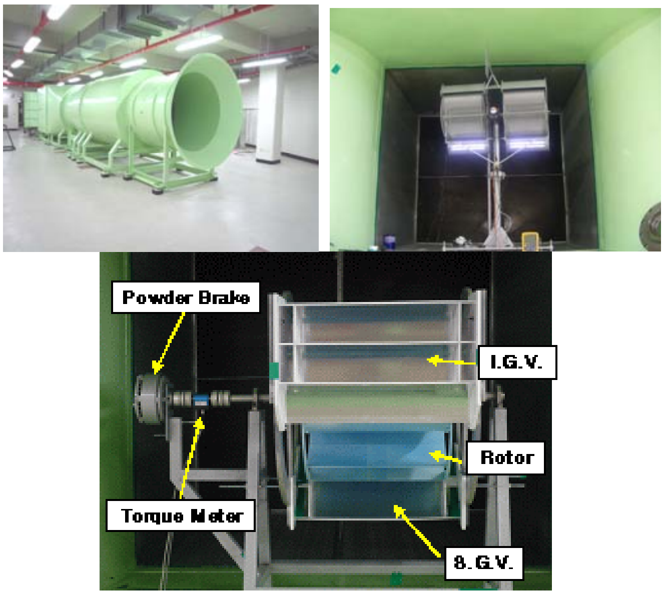

Fig. 2 Photos of open-type wind tunnel and test turbine

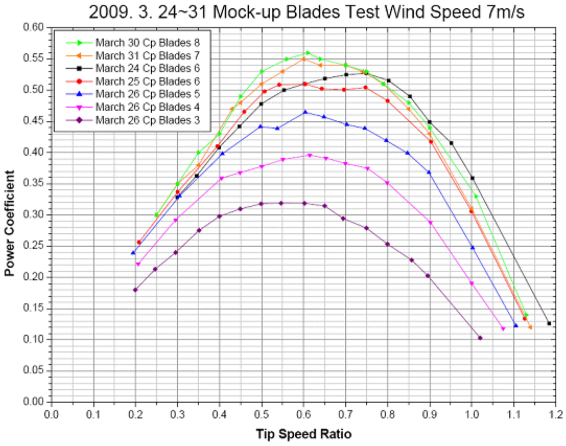

Fig. 3 Comparison of dual-rotor turbine efficiencies for different numbers of cup-blade

To improve the steering efficiency of dual-rotor turbine, the tail wing is installed upwardly downstream of the rotor. It provides the turbine system with restoring force strong enough to overcome the inertia force of the twin-rotor system, together with the gravity center of the twin-rotor system in a downstream portion when yawing.

DESIGN OF TWIN ROTOR WIND TURBINE SYSTEM

The SWT classes are defined in terms of wind speed and turbulence parameter according to IEC61400-12. The design goal of 5kW twin-rotor turbine was to meet the SWT classification of III, which specifies V_{ref}, V_{ave}, and I_{15} as 37.5 m/s, 7.5 m/s, and 0.18, respectively.

Table 1 WindJet model specifications

Model	WindJet 1	WindJet 3	WindJet 5	WindJet 10
Type	Vertical-axis Twin-rotor Turbine			Vertical-axis Quad-rotor Turbine
Rated Capacity	1 kW	3 kW	5 kW	10 kW
Rotor Diameter	1.25 m	2.36 m	3.04 m	3 m
Swept Area	3.3 m^2	8.97 m^2	14.9 m^2	36 m^2
Direction of Rotation	Counterclockwise looking upwind			
Blades (Material)	8 x 2 (Aluminum Alloy)	6 x 2 (Aluminum Alloy)		3 x 4 (Aluminum Alloy)
Rated Speed	132 rpm	53 rpm	41 rpm	45 rpm
Rated Tip Speed Ratio	0.78	0.61	0.59	0.64
Alternator	Permanent Magnet Synchronous Generator			
Yaw Control	Tail Wing			
Grid Feeding	120 / 240 V_{AC} Split 1Ph, 60Hz 120 / 208 V_{AC} 3Ph Compatible			
Braking System	Electronic Brake with Dump Load			
Cut-in Wind Speed	3 m/s (6.7 mph)			
Rated Wind Speed	11 m/s (24.6 mph)			
User Monitoring	RS485 / RS232 (Optional Wireless 2-Way Interface)			

The technical details of WindJet models ranging from 1 to 10kW are described in Table 1. The SWT should be designed to safely withstand the various extreme wind conditions. The extreme wind conditions are applied to determine extreme loads on SWT as shown in Fig.4.

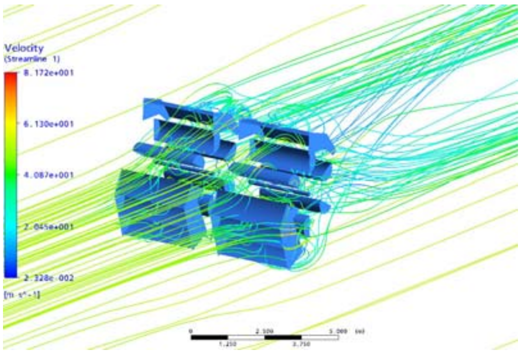

Fig. 4 Streamline Patterns of twin-rotor turbine for Extreme Wind Model (EWM) (42m/s)

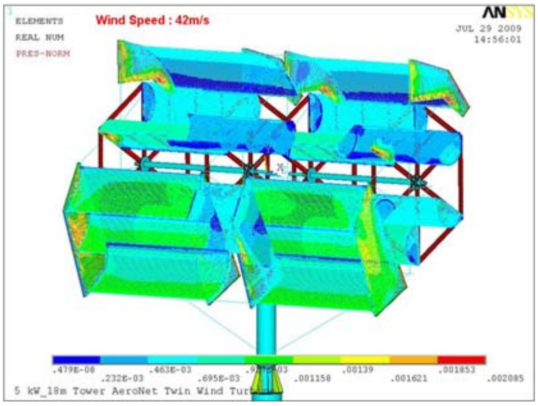

Fig. 5 Stress distribution on blades and guide vanes of WindJet 5 model with 18-meter tower (Maximun Pressure; 2,085 Pa)

In order to analyze the strength of WindJet 5 model with 18 meter tower, the wind force data is produced by CFD analysis using ANSYS CFX and is applied to this analysis as shown in Fig. 5.

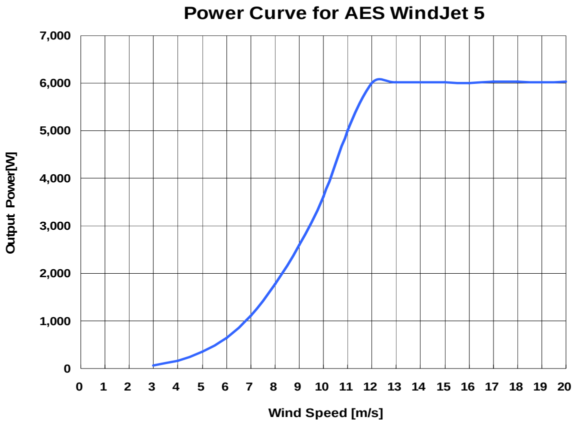

Fig. 6 Power curve of WindJet 5 model

The WindJet 5 model produces the AWEA rated power of 5kW at 11m/s (24.6mph) and the maximum power of 6kW up to cut-out wind speed of 20m/s as shown in Fig. 6.

PERFORMANCE TEST OF DUAL ROTOR WIND TURBINE

AeroNet has a line-up of dual-rotor WindJet models in operation in the range of 1~10kW rated power in Korea and in late 2009 commissioned at A.L. Huber headquarter site, Overland Park, Kansas as shown in Fig. 7. The Huber headquarter site has a temperature range between -20^{o}C and 36 ^{o}C and an average surface wind speed of 3.8m/s with the mean gust wind speed of 10m/s.

The IEC 61400-2 standard requires that the measured data shall be binned into 0.5m/s wind speed bins, and each wind speed bin from 1 m/s below the cut-in wind speed up to twice the average wind speed should have at least 30 data points.

But the new AWEA standard states that each wind speed bin between 1 m/s below cut-in and 14 m/s shall contain a minimum of 10 minutes of sampled data and at least 60 hours of data within the wind speed range.

Table 2 compares all the power measurement specifications by various standards: IEC 61400-2, AWEA9.1, BWEA, and IEC61400-12-1.

Table 2 Standard comparison of power performance measurement method

Standard	IEC 61400-2	AWEA9.1	BWEA	IEC61400-12-1
Data Sets	1 min. period	1 min. period	1 min. period	10 min. period
Wind Speed Range	*Vin* -1 ~ 2*Vave*	*Vin* -1 ~14m/s	*Vin* -1 ~14m/s	1m/s~1.5*V @85% of rated P
Sample Data	At least 30 data in each bin	Min. 10minutes	Min. 10minutes	Min. 30 minutes
Included Data	-	Min. 60hours	Min. 60hours	Min. 180 hours

Figure 8 shows the one-minute and ten-minute average power outputs defined by AWEA new standard. It is observed that ten-minute average powers exceed the predicted ones. The WindJet 5 model has an equivalent diameter of 19.34 m based on a swept area of 14.70 m and results in 34.27 m of the distance between the ground center of the tower and the observation location based on the standard of IEC 61400-11. The WindJet 5kW vertical turbine mounted on 18 meter tower records 45 dBA, which corresponds to L_{AWEA} = 40 dB_A at background noise level 40 dB_A.

Figure 9 shows the computed capacity factor based on Weibull probability distribution with a shape factor k=2 for inland and measured power curve.

Fig. 7 Photo of 5kW dual-rotor vertical wind turbine at Huber site (Overland Park, Kansas)

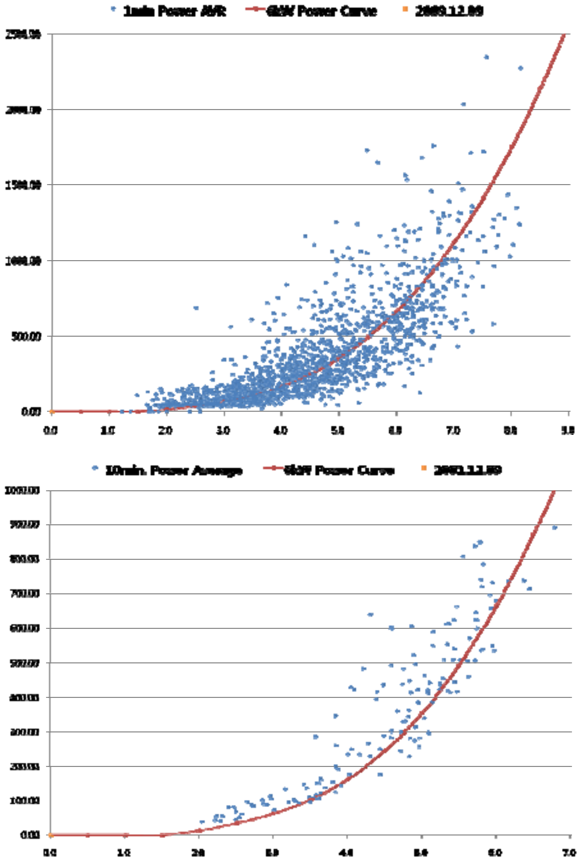

Fig. 8 Site evaluation of electric powers based on 1-minute and 10-minute averages of samples measured for 5kW dual-rotor turbine

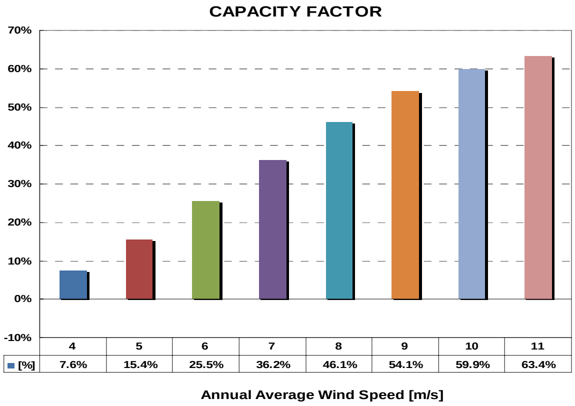

Fig. 9 Capacity factor of WindJet 5kW model at each average wind speed

CONCLUSIONS

The performance of the dual-rotor turbine is optimized in the multi-space formed by the diameter ratio of the blade cup and the rotor, the blade solidity, the diameter-width ratio, and guide-vane angles.

As can be observed, the increase of blade number is effective for customizing the turbine on the site by adjusting power. The other merit is the flexibility of modular assembly by stacking twin-rotors over the other set, e.g. quad-rotor, for the purpose of increasing the capacity. The guided turbine has also the advantage of longer life time due to its low rotational speed than other small horizontal or vertically mounted H-type turbines. And it is safe, attractive, quiet, and avian-friendly.

The twin-rotor WindJet turbine of the rated capacity of 5 kW resulted in an annual capacity of 26% or more at average wind speed of 6m/s at 20 meter height, and a turbine efficiency of 50% or more.

ACKNOWLEDGMENTS

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