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Technical Note

An experimental study of tip-vortex structures behind a small wind turbine with a flanged diffuser

K. Abe†, H. Kihara, A. Sakurai, E. Wada and K. Sato

Department of Aeronautics and Astronautics, Kyushu University, Japan

M. Nishida

Department of Aerospace Systems Engineering, Sojo University, Japan

Y. Ohya

Research Institute for Applied Mechanics, Kyushu University, Japan

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1. Introduction

The power in wind is proportional to the cubic power of the wind velocity approaching the wind turbine and thus even a small amount of acceleration gives a large increase in the energy output. In this respect, many research groups have tried to find a way to accelerate the approaching wind effectively (Igra 1981, Gilbert, *et al*. 1983, Nagai and Irabu 1987, Ushiyama 1997, Phillips, *et al*. 2000). Recently, Ohya, *et al*. (2006) have developed an effective wind-acceleration system introducing a diffuser-shaped structure surrounding a wind turbine. In particular, the feature that distinguishes it from the others is a large flange attached at the exit of diffuser shroud. A flange generates a very low-pressure region behind it, owing to which the flow coming into the diffuser can be effectively concentrated and accelerated (Ohya, *et al*. 2006, Inoue, *et al*. 2002, Abe and Ohya 2004, Abe, *et al*. 2005).

In this study, experimental investigations are carried out for a small wind turbine with a flanged diffuser (i.e. a diffuser-shrouded wind turbine). Special attention is paid to tip-vortex structures generated by wind-turbine blades. Therefore, mean velocity profiles behind the wind turbine are measured using a hot-wire technique and tip-vortex structures are detected.

Keywords: wind turbine; flanged diffuser; tip-vortex structure.

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† Professor, Corresponding Author, E-mail: abe@aero.kyushu-u.ac.jp.

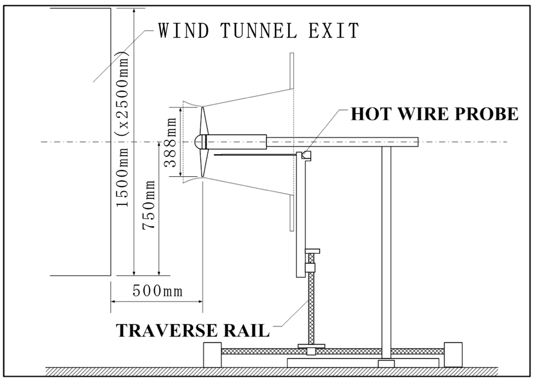


Fig. 1 Overview and measurement system of a diffuser-shrouded wind turbine (blade diameter: 388 mm, diffuser-throat diameter (d_0): 400 mm).

2. Experimental apparatus

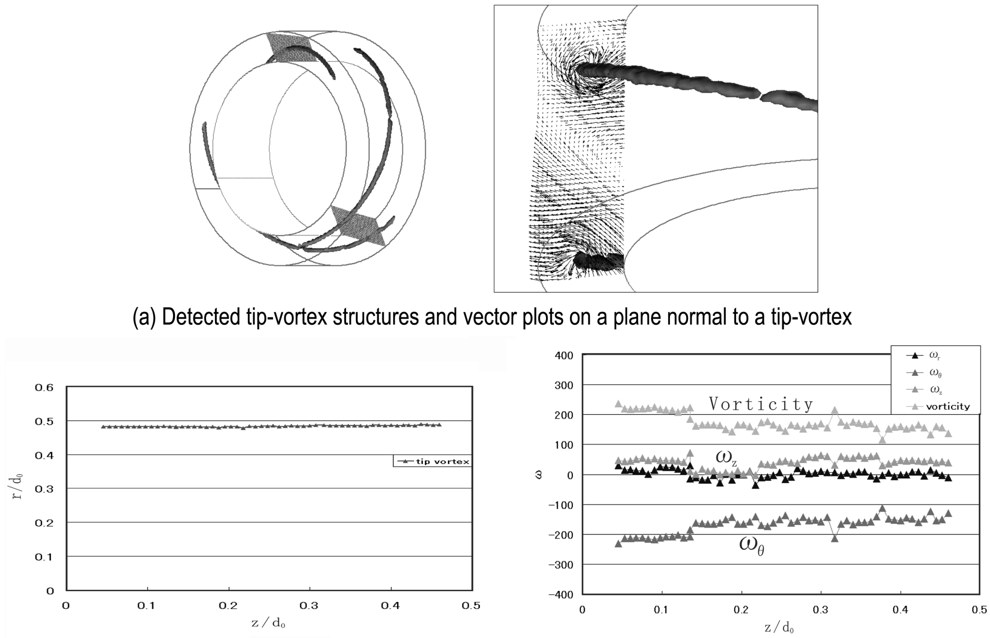
The measurement system is the same as that used in the previous report by Abe, *et al*. (2005). As shown in Fig. 1, the diffuser consists of a main diffuser, a flange attached at the rear of the diffuser and an inlet shroud attached at the front. The velocity fields behind the wind turbine were measured using a hot-wire technique. We performed measurements for both z-θ and z-r components independently to obtain three-dimensional mean velocity fields, where a cylindrical coordinate system was adopted, with z, r and θ being the streamwise, radial and rotational coordinates, respectively (Abe, *et al*. 2005). The probe was traversed in the radial (r) direction and velocity data were obtained in the r-θ plane. Moreover, to obtain velocity distributions for downstream regions, the probe was traversed in the streamwise (z) direction. The free stream velocity was specied as 11 m/s and 6.8 m/s for the bare wind turbine and the diffuser-shrouded wind turbine, respectively. Further detailed description of the measurement system is given in Abe, *et al*. (2005).

3. Results and discussion

To investigate vortex structures behind a wind turbine, we must accurately pick them up from whole the velocity-field data obtained. To do this, in this study, we adopted what is called "λ_2 denition method" proposed by Jeong and Hussain (1995). According to this method, a vortex structure can be defined using the eigenvalues of the symmetric tensor

$$S_{ik}S_{kj} + \Omega_{ik}\Omega_{kj} \quad (1)$$

where S_{ij} and Ω_{ij} are respectively the strain-rate and the vorticity tensors. Since Eq. (1) is symmetric, it has real eigenvalues, λ_1, λ_2 and λ_3. Assuming $\lambda_1 \geq \lambda_2 \geq \lambda_3$, a vortex structure can be detected by searching a region of $\lambda_2 < 0$ (Jeong and Hussain 1995). Following this definition, tip-vortex structures for the bare wind turbine are picked up in Fig. 2(a). Tip-vortex structures are successfully identified. The picture of the detected tip vortices flowing downstream corresponds well to known results by the previous experimental studies (see for example, Vermeer, *et al*. 2003). Velocity-vector plots in a plane almost perpendicular to the detected tip vortex are also shown in Fig. 2(a). The velocity vectors reasonably form a vortex-like circulation around the detected tip



(a) Detected tip-vortex structures and vector plots on a plane normal to a tip-vortex

(b) Radial locations of tip vortex

(c) Vorticity variations

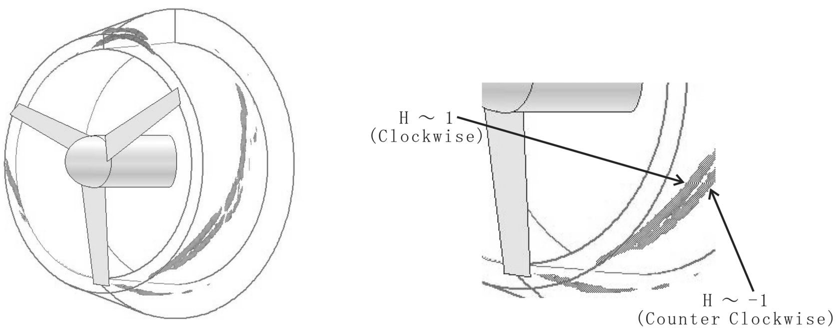
Fig. 2 Detailed information of tip vortex for bare wind turbine

vortex. The locations of the tip-vortex center in r direction are plotted in Fig. 2(b), from which it is found that the vortex-center location is almost unchanged in r direction. Fig. 2(c) shows the evaluated vorticity components, with ω_z, ω_r and ω_θ being the vorticity component in the streamwise (z), radial (r) and rotational (θ) directions, respectively. In the figure, the wording "vorticity" means the absolute value of the vorticity vector. Note that all the vorticity components are normalized by the free stream velocity and the representative length d_0. It is clearly understood that ω_θ is the strongest among all the components. A notable feature is that the strong tip-vortex structure can be seen even in the downstream region, where the vorticity still shows a considerable level, which is about 70% of that just behind the turbine blades.

Next, the same methodology (Jeong and Hussain 1995) was applied to the flow fields for the diffuser-shrouded wind turbine. The detected vortex structures behind the tip of the turbine blades are shown in Fig. 3. In contrast to the bare wind turbine, a pair of two vortex structures can be seen in the figure. These two vortex structures have different rotating directions, which are distinguished by the normalized helicity H defined as

$$H = \frac{\vec{U} \cdot \vec{\omega}}{|\vec{U}||\vec{\omega}|} \tag{2}$$

where $\vec{U}$ and $\vec{\omega}$ are respectively a velocity vector and a vorticity vector. From the definition, this value ranges $-1 \leq H \leq 1$. If $|H|$~1, the vorticity vector almost aligns with the velocity vector and it also means a longitudinal vortex structure. On the other hand, H~0 means a lateral vortex structure and the vorticity vector is almost perpendicular to the velocity vector. From the evaluation by Eq. (2), it has been found that one of the vortex structures shows H~1 (clockwise) and the other shows

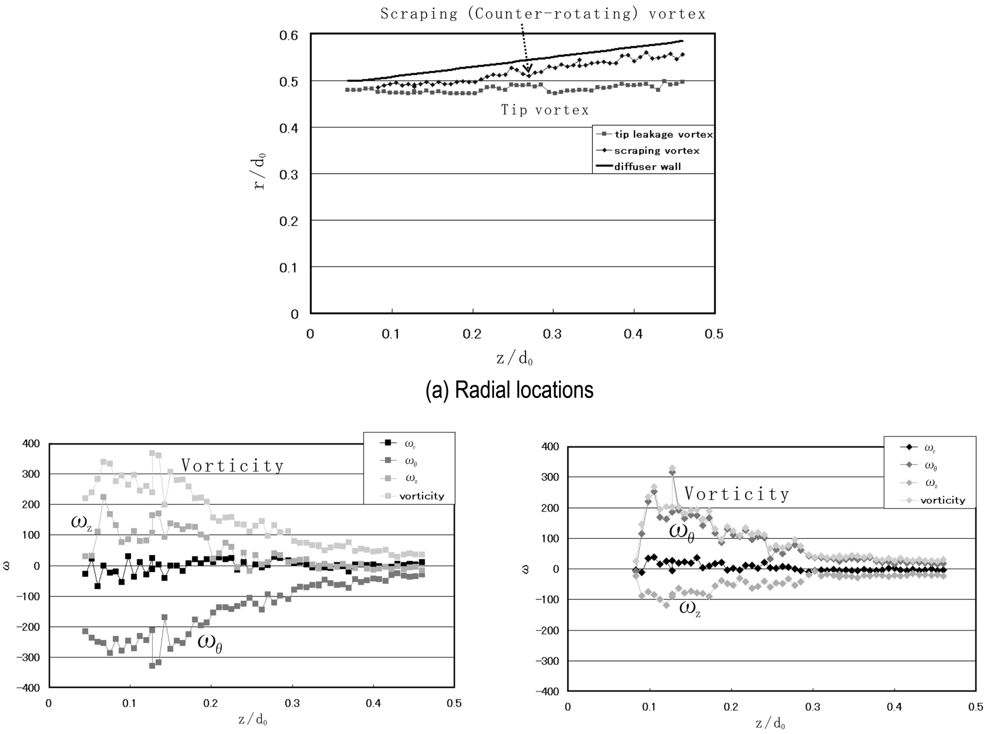


(a) Overview (b) Detailed view

Fig. 3 Detected tip and counter-rotating vortices for diffuser-shrouded wind turbine

H~−1 (counter-clockwise) (see Fig. 3(b)). Note that the tip vortex for the bare wind turbine in Fig. 2 is found to be H~1 (clockwise). From these results, the clockwise-rotating vortex structure (H~1) in Fig. 3 can be recognized as the tip vortex as seen in Fig. 2. On the other hand, the other counter-clockwise vortex (H~−1) is thought to be generated by the interaction of the tip vortex and the diffuser wall. In the narrow region between them, very strong velocity gradient is induced and then a strong counter-rotating vortex structure is generated just behind the turbine-blade tip.

Fig. 4 summarizes detailed information of the tip and counter-rotating vortices for the diffuser-



(b) Vorticity variations of tip vortex (c) Vorticity variations of counter-rotating vortex

Fig. 4 Detailed information of tip and counter-rotating vortex structures for diffuser-shrouded wind turbine shrouded wind turbine. The center locations of these vortices in r direction are plotted in Fig. 4(a). Similarly to the bare wind-turbine case, the location of the tip-vortex center for the diffuser-shrouded wind turbine is almost unchanged in r direction. On the contrary, the center location of the counter-rotating vortex shows a different aspect that it moves downstream rather along with the diffuser wall. The vorticity components evaluated from both the tip and counter-rotating vortices are shown in Fig. 4(b) and (c), respectively. Similarly to the bare wind-turbine case, ω_θ is the main component for both the tip and counter-rotating vortices. As is clearly understood from Fig. 4(b), however, a considerable difference is seen in the destruction process of the tip vortex between the bare wind turbine and the diffuser-shrouded wind turbine. The tip vortex in the diffuser-shrouded wind turbine (Fig. 4(b)) destructs very rapidly compared with that in the bare wind turbine (Fig. 2(c)). This rapid destruction of the tip vortex may be explained by the interaction between two vortices shown in Fig. 3. The generated vortex between the tip vortex and the diffuser wall is counter-rotating and thus these two vortices may tend to cancel their strength from each other. Due to this effect, the strength of the tip vortex for the diffuser-shrouded wind turbine becomes weak very rapidly in the down- stream region. Such a rapid destruction of the tip vortex by interaction with the counter-rotating vortex may strongly influence the noise reduction of a wind turbine.

In summary, a considerable difference was seen in the destruction process of the tip vortex between the bare wind turbine and the diffuser-shrouded wind turbine. The knowledge presently obtained is interesting and important from the viewpoint of the wind engineering.

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