Effects of blade section on performance of butterfly wind turbines as double-blade VAWTs

Yutaka HARA*, Takahiro SUMI*, Takanori EMI*, Mutsuko YOKOYAMA*, Hiromichi AKIMOTO**, Takafumi KAWAMURA*** and Takuju NAKAMURA****
*Graduate School of Engineering, Tottori University
4-101 Koyama-Minami, Tottori 680-8552, Japan
E-mail: hara@damp.tottori-u.ac.jp
**Division of Ocean Systems Engineering, KAIST
291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea
***Computational Fluid Dynamics Consulting Inc.
2-1-1-1111 Namiki, Tokorozawa, Saitama 359-0042, Japan
****New Business Development, MODEC Inc.
Nihonbashi Maruzen Tokyo Building, 2-3-10 Nihonbashi, Chuo, Tokyo 103-0027, Japan

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Abstract
A butterfly wind turbine (BWT) is a kind of vertical axis wind turbine (VAWT) with closed-loop blades. These blades form a double-blade structure, which is expected to improve self-starting properties and reduce energy costs because of their simple construction. Two models of micro BWTs (diameter: 0.4 m; height: 0.3 m) were built and subjected to wind tunnel testing. One of the models had a symmetrical blade section and the other had a cambered blade section with a mean line that followed a curved path in a flow curvilinear relative to the blade. Experimental results showed that the cambered blade rotor was superior to the symmetrical blade rotor in terms of torque and power coefficients at higher tip speed ratios (TSR). However, at low TSRs, the performance of the symmetrical blade rotor tended to be higher than that of the cambered blade rotor. To investigate the effects of blade section on the performance and flow field of the double-blade rotor, two-dimensional computational fluid dynamics (2D-CFD) analysis was carried out for two double-blade rotors with symmetrical and cambered blades. Although 2D-CFD analysis is not suitable for the quantitative performance analysis of the three-dimensional BWT, the CFD results showed the same tendency of the torque and power performance as the experimental results. If the outer blades alone are considered, the cambered blades generate larger torque (or power) than the symmetrical blades at all TSR values, in the case of a large chord-to-radius ratio as with the present rotors. On the other hand, the inner symmetrical blades generate more torque (or power) than the inner cambered blades at TSRs less than 1.5. A TSR of 0.75, at which the symmetrical blade rotor showed the highest torque coefficient, was intensively analyzed in terms of the aerodynamic forces and torques calculated by the 2D-CFD. Under this condition, the inner blade of the symmetrical blade rotor generated positive torque at a wider range of azimuth angles than the cambered blade rotor.

Key words: Butterfly wind turbine, VAWT, Double-blade structure, Cambered blade, Symmetrical blade, CFD, Flow curvature, Wind power, Self-start

1. Introduction

Installation of small-scale wind turbines is easier than large-scale wind turbines; however, they are not very popular because they offer a relatively low generating efficiency at a high initial cost per unit of power. Recently, in addition to conventional horizontal axis wind turbines (HAWTs), small-scale vertical axis wind turbines (VAWTs) have been the target of extensive research and development (van Bussel and Mertens, 2005; Islam et al., 2007; Howell et al., 2010;
Yamada et al., 2011). Additionally, in the offshore large-scale wind turbines sector, VAWTs have begun to receive attention because they can be equipped with heavy equipment, such as generators, at low altitudes (Akimoto et al., 2011, 2012; Sandia National Laboratories, 2012; Nakamura et al., 2013; Shires, 2013). VAWTs may reduce the cost of energy by simplifying construction for any turbine size because these turbines do not require yaw control, which is unavoidable for HAWTs. However, the self-starting performance of lift-driven VAWTs is usually poor (Islam et al., 2007). In many cases, measures are taken to improve self-starting performance, such as increasing the number of blades or enlarging the blade chord length. A double straight-bladed VAWT (Hara et al., 2014a) is an example of a turbine design aimed at improving self-starting performance. One of the authors of this paper proposed a new type of VAWT that is armless (i.e., strut-free) and forms a double-blade structure using looped curvilinear blades (Hara, 2012). This new type of VAWT is called a butterfly wind turbine (BWT), because its shape as it rotates around the vertical axis is similar to that of a butterfly.

Our group investigated the characteristics of the double straight-bladed VAWT and the BWT by blade element momentum (BEM) theory and computational fluid dynamics (CFD) analysis; these approaches showed that double straight-bladed VAWTs might offer superior self-starting performance (Hara, 2012; Hara et al., 2014a). Our group also built a small BWT model with a symmetrical blade section by stereolithography and performed wind tunnel testing (Hara et al., 2013). However, the expected high power coefficient ($C_p$) could not be obtained, although good self-starting performance was shown in the experiments. Since the low $C_p$ of the symmetrical blade BWT was considered to be mainly caused by the flow curvature effects (see Fig. 1; Migliore et al., 1980; Furukawa et al., 1990; Akimoto et al., 2013) due to the large chord-to-radius ratio ($c/R$), 2D-CFD was performed in the same study in order to analyze the difference between two 2D double-blade rotors, each having either symmetrical or cambered blade sections. However, satisfactory CFD results were not obtained, especially in the high tip speed ratio (TSR) region. The effects of the blade section on the power characteristics of VAWTs with a large chord-to-radius ratio were recently investigated by 2D-CFD by our group (Hara et al., 2014b) for small-scale rotors of non-double-blade structures with symmetrical or cambered blades. The prediction of $C_p$ by the 2D-CFD analysis showed that the cambered blade section was superior to the symmetrical blade section at high TSR values of 1.0 or more, although at low TSR values between 0.75 and 1.0, the torque and power characteristics of the symmetrical blade were superior to those of the cambered blade.

In this paper, a new experimental model of a small-scale BWT with cambered blade sections has been built. The mean line of the cambered section at the equatorial plane follows a curved path in a flow curvilinear relative to the blade, as in the upper blade section in Fig. 1 (b). The torque and power performance of the model is measured by wind tunnel testing and compared with the performance of the previous BWT model with a symmetrical blade section. In order to investigate the effects of blade sections on the performance of double-blade rotors, 2D-CFD analysis is carried out with a longer calculation time than the previous analysis, corresponding to at least 11 rotations of a rotor, because the previous CFD analysis for the double-blade rotors (Hara et al., 2013) is considered not to have obtained the unstable behavior of the torque and power coefficients of the rotors due to the short calculation time of up to 5 rotations of the rotor. This study focuses on the differences between the aerodynamic effects of the symmetrical and cambered blade sections at each rotor (outer or inner) of the double-blade structure.
2. Nomenclature

\[\begin{align*}
A & \quad \text{rotor swept area [m}^2]\] 
C_n & \quad \text{normal force coefficient (}= F_n/[0.5\rho V^2D])
C_p & \quad \text{rotor power coefficient (}= P/[0.5\rho AV^3])
C_q & \quad \text{rotor torque coefficient (}= Q/[0.5\rho AV^2R])
C_l & \quad \text{tangential force coefficient (}= F_l/[0.5\rho V^2D])
C_{Ql} & \quad \text{torque coefficient of a blade with unit span length (}= Q_l/[0.5\rho V^2DR])
c & \quad \text{chord length [m]}
c_t & \quad \text{chord length of the outer blade of a 2D double-blade rotor [m]}
c_i & \quad \text{chord length of the inner blade of a 2D double-blade rotor [m]}
c_{root} & \quad \text{chord length at the base portion of the butterfly wind turbine blade [m]}
c_{tip} & \quad \text{chord length at the tip portion of the butterfly wind turbine blade [m]}
D & \quad \text{rotor diameter [m]}
F & \quad \text{resultant force of } F_n \text{ and } F_t \text{ [N]}
F_n & \quad \text{normal fluidic force acting on a blade [N]}
F_t & \quad \text{tangential fluidic force acting on a blade [N]}
H & \quad \text{rotor height [m]}
h_c & \quad \text{local height from the equatorial plane [m]}
L & \quad \text{parameter designating height-level of a blade section}
P & \quad \text{rotor power [W]}
Q & \quad \text{rotor torque [Nm]}
Q_l & \quad \text{torque exerted on a blade with unit span length [Nm]}
R & \quad \text{rotor radius [m]}
R_1 & \quad \text{outer rotor radius of a 2D double-blade rotor [m]}
R_2 & \quad \text{inner rotor radius of a 2D double-blade rotor [m]}
Re & \quad \text{rotor Reynolds number (= } DV/\nu)\]
Re_b & \quad \text{blade Reynolds number (= } cR\omega/\nu)\]
r & \quad \text{local radius [m]}
V & \quad \text{upstream wind velocity [m/s]}
X, Y, Z & \quad \text{coordinates [m]}
x_0 & \quad \text{ratio of distance between blade-attachment point and leading edge to the chord length [%]}
y^* & \quad \text{wall distance normalized by viscous length}
\end{align*}\]

Greek symbols

\[\begin{align*}
\delta & \quad \text{slant angle of blade surface [°]}
\zeta & \quad \text{angle designating the direction of fluidic force F [°]}
\kappa & \quad \text{tip speed ratio (= } \omega R/V)\]
\nu & \quad \text{kinematic viscosity [m}^2\text{/s}] 
\rho & \quad \text{air density [kg/m}^3]\] 
\omega & \quad \text{rotor rotational speed [rad/s]}
\psi & \quad \text{azimuth [°]}
\end{align*}\]

3. Experimental apparatus

In this study, two experimental BWT models (rotor diameter \(D\): 0.4 m; rotor height \(H\): 0.3 m) were used. One of the models was made of epoxy resin and was built by stereolithography (see Fig. 2 (a)). The turbine model has three blades with symmetrical sections, each of which is a closed curve. Since the blades can be directly attached to a flange installed on the axis of rotation, the struts necessary for straight-bladed VAWTs are not present. This BWT model was used in the first experiments on BWTs (Hara et al., 2013). Another model was made of fiber-reinforced plastics using
vinylon, a synthetic fiber produced from polyvinyl alcohol. The use of vinylon fiber is a trial of the application of a low cost and environmentally friendly plastic to wind turbine blades in this study. The new model has three blades with cambered sections. The dimensions of these two BWT models are almost identical, and the common major sizes of the blades are shown in Fig. 3. As shown in Fig. 4, for the sake of convenience, each blade is divided into two portions according to the local radius \( r \); these portions are called the outer and inner blades. The chord length of the outer blade is 0.11 m, and the chord length of the inner blade increases from the common edge between the two portions to where the blade joins the flange (0.05 m from the rotational axis), where the chord length becomes 0.18 m (see Fig. 3).

All the cross sections of the symmetrical blade rotor shown in Fig. 2 (a) are the symmetrical airfoil NACA 0018. On the other hand, the blade section at the equatorial plane of the cambered blade rotor shown in Fig. 2 (b) has a shape that was transformed from the NACA 0018 airfoil by conformal mapping (Furukawa et al., 1990; Akimoto et al., 2013). The blade section that has a non-zero slant angle \( \delta \) is determined by the transformation of Eq. (3), defined in the paper by Hara et al. (2014b), in order to avoid a large drag force caused by a large slant angle. Blade sections at several height levels of the outer and inner blades of each BWT rotor are shown in Fig. 5. The height level \( L = 10 \) corresponds to the rotor equatorial plane (\( h_c = 0 \)). Note that the blade camber of the cambered blade rotor decreases with increasing absolute value of local height \( h_c \) from the equatorial plane, except for the blade section at \( L = 10 \) of the inner division.

Tables 1 and 2 list the values of the main parameters at several height levels in each case of the symmetrical and cambered blade BWT rotors, respectively.

A schematic diagram of the experimental setup is shown in Fig. 6. An Eiffel-type wind tunnel (square outlet: 650 \( \times \) 650 mm) was used for the present experiments. A BWT rotor was placed 1 m from the wind tunnel outlet and

![Fig. 2 Butterfly wind turbine (BWT) rotors with (a) symmetrical blade section and (b) cambered blade section. The white model (a) was made of epoxy resin by stereolithography and the blue model (b) was made of fiber-reinforced plastics with vinylon fiber.](image)

![Fig. 3 Common major sizes of blades of two experimental BWT rotors in the present study.](image)
Fig. 4  Expedient division of a BWT blade into the inner and outer blades. $L$ is a parameter designating the height level of the blade sections in each division. The definition of slant angle $\delta$ of the blade section at each height level $L$ is also shown.

Fig. 5  Blade sections at several height levels of the outer and inner blades of each BWT rotor with symmetrical or cambered blade sections. The height level $L = 10$ corresponds to the rotor equatorial plane ($h_c = 0$). In the case of the cambered blade rotor, the camber decreases with increasing absolute value of local height $h_c$ from the equatorial plane, with the exception of the blade section at $L = 10$ of the inner division.

Table 1  Values of the main parameters at several height levels in the case of symmetrical blade BWT rotor

| Type   | Outer | Symmetrical blade | Inner |
|--------|-------|-------------------|-------|
| $L$    | $h_c$ [m] | $r$ [m] | $x_0$ [%] | $\delta$ [deg] | chord [m] | pitch [deg] | camber [%] | $h_c$ [m] | $r$ [m] | $x_0$ [%] | $\delta$ [deg] | chord [m] | pitch [deg] | camber [%] |
| 0      | 0.143 | 0.182 | 31.3 | 31.6 | 0.110 | 0.0 | 0.0 | 0.143 | 0.160 | 33.0 | -43.3 | 0.117 | 0.0 | 0.0 |
| 2      | 0.114 | 0.192 | 30.6 | 11.2 | 0.110 | 0.2 | 0.0 | 0.114 | 0.141 | 34.4 | -29.4 | 0.128 | 0.0 | 0.0 |
| 4      | 0.086 | 0.196 | 30.3 | 6.3 | 0.110 | 0.4 | 0.0 | 0.086 | 0.126 | 35.0 | -28.0 | 0.137 | 0.0 | 0.0 |
| 6      | 0.057 | 0.198 | 30.1 | 3.6 | 0.110 | 0.6 | 0.0 | 0.057 | 0.110 | 36.8 | -30.1 | 0.146 | 0.0 | 0.0 |
| 8      | 0.029 | 0.200 | 30.0 | 1.7 | 0.110 | 0.8 | 0.0 | 0.029 | 0.091 | 38.1 | -37.1 | 0.156 | 0.0 | 0.0 |
| 10     | 0.0  | 0.2  | 30.0 | 0.0 | 0.0 | 1.0 | 0.0 | 0.0  | 0.05 | 41.3 | -90.0 | 0.189 | 0.0 | 0.0 |

Table 2  Values of the main parameters at several height levels in the case of cambered blade BWT rotor

| Type   | Outer | Cambered blade | Inner |
|--------|-------|----------------|-------|
| $L$    | $h_c$ [m] | $r$ [m] | $x_0$ [%] | $\delta$ [deg] | chord [m] | pitch [deg] | camber [%] | $h_c$ [m] | $r$ [m] | $x_0$ [%] | $\delta$ [deg] | chord [m] | pitch [deg] | camber [%] |
| 0      | 0.143 | 0.182 | 31.3 | 31.6 | 0.110 | 4.6 | 5.4 | 0.143 | 0.160 | 33.0 | -43.3 | 0.117 | 4.1 | 5.3 |
| 2      | 0.114 | 0.192 | 30.6 | 11.2 | 0.109 | 6.2 | 6.9 | 0.114 | 0.141 | 34.4 | -29.4 | 0.127 | 6.0 | 8.5 |
| 4      | 0.086 | 0.196 | 30.3 | 6.3 | 0.109 | 6.6 | 7.1 | 0.086 | 0.126 | 35.0 | -28.0 | 0.135 | 6.8 | 10.5 |
| 6      | 0.057 | 0.198 | 30.1 | 3.6 | 0.109 | 6.9 | 7.1 | 0.057 | 0.110 | 36.8 | -30.1 | 0.143 | 7.5 | 12.5 |
| 8      | 0.029 | 0.200 | 30.0 | 1.7 | 0.109 | 7.1 | 7.1 | 0.029 | 0.091 | 38.1 | -37.1 | 0.154 | 7.9 | 14.6 |
| 10     | 0.0  | 0.2  | 30.0 | 0.0 | 0.0 | 7.3 | 7.1 | 0.0  | 0.05 | 41.3 | -90.0 | 0.180 | 0.0 | 0.0 |

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connected to an induction motor via a torque detector to be revolved at an arbitrary rotational speed controlled by an inverter. The wind speed, which was measured in advance at the location of the center of the BWT rotor by a pitot tube under experimental conditions without the BWT model, was set at 1 m/s intervals between 2 and 6 m/s. For each wind speed condition, the torque and rotational speed were recorded at a constant rotational speed, and then with the rotational speed increasing gradually. Independently, the resistance torque generated by the bearings was measured by changing the rotational speed under experimental conditions without the blades; this measurement was used to determine the pure aerodynamic torque generated by the turbine blades. The performance of the symmetrical blade rotor (Fig. 2 (a)) was newly measured in this study, because the reliability of the wind speed settings of the previous experiments (Hara et al., 2013) was suspect.

![Experimental setup for the wind tunnel test of the BWT models. The distance between the center of the BWT rotor and the wind tunnel nozzle outlet was approximately 1 m. Torque was measured by using an induction motor to rotate the BWT model at a constant rotational speed under a constant wind speed.](image)

4. Experimental results

The experimentally obtained performance curves of the symmetrical and cambered blade rotors in terms of torque coefficients \( C_q \) and power coefficients \( C_p \) are shown in Figs. 7 and 8, respectively. The Reynolds number based on the rotor diameter \( D = 2R \) is \( Re = 1.6 \times 10^5 \) at a wind speed of 6 m/s; the blade Reynolds number \( Re_b \) based on the chord length of the maximum rotor radius is between \( 2.2 \times 10^4 \) and \( 1.1 \times 10^5 \) at the same wind speed. As shown in Fig. 7 (a), since there are no negative torque regions, also known as “dead bands” (Islam et al., 2007), for tip speed ratios below the one at which the maximum torque is achieved, the BWT rotor with a symmetrical blade section has good self-starting performance. On the other hand, the torque curve of the cambered BWT rotor at a wind speed of 2 m/s (see Fig. 8 (a)) shows that the rotor is in a dead band around \( \lambda = 0.25 \). However, at wind speeds of 3 m/s or more, the torque coefficients of the cambered blade rotor show high positive values and there is no dead band. Figures 9 (a) and (b) compare the performance curves of the two rotors at a wind speed of 6 m/s in terms of \( C_q \) and \( C_p \) respectively. At tip speed ratios of 0.6 or more, both the \( C_q \) and \( C_p \) of the cambered blade rotor are higher than those of the symmetrical blade rotor; the maximum power coefficient of the present micro BWT has been greatly improved by adopting the cambered blades. However, at tip speed ratios of 0.35 or less, the torque coefficients of the symmetrical blade rotor show higher values than those of the cambered blade rotor, as shown in Fig. 9 (a). This means that the symmetrical blade rotor is superior to the cambered blade rotor in terms of self-starting performance. In addition, this tendency is different from the case of the low center of gravity wind turbines (Hara et al., 2014b) with a non-double-blade structure, in which the torque coefficients of the cambered blade rotor were almost the same as or higher than those of the symmetrical blade rotor in every region of the tip speed ratio.
Fig. 7 Experimental results of the symmetrical blade BWT rotor for (a) torque coefficients and (b) power coefficients. These performance curves were measured at constant wind speeds from 2 m/s to 6 m/s. The horizontal axis of each graph is the tip speed ratio $\lambda$.

Fig. 8 Experimental results of the cambered blade BWT rotor for (a) torque coefficients and (b) power coefficients. These performance curves were measured at constant wind speeds from 2 m/s to 6 m/s. The horizontal axis of each graph is the tip speed ratio $\lambda$.

Fig. 9 Comparison of BWT characteristics for symmetrical and cambered blade sections at a wind speed of 6 m/s for (a) torque coefficients and (b) power coefficients.
In order to investigate the effects of blade sections on the performance of the double-blade rotors numerically, in the following section, the characteristics of two 2D double-blade rotors with symmetrical and cambered blades are analyzed by 2D-CFD. Although 3D-CFD analysis should be carried out to obtain the numerical results corresponding to the experimental models, 2D-CFD analysis was adopted to investigate the effects of blade sections under the simple double-blade configurations and to save calculation cost in this study. Since two-dimensional analysis can exclude the three-dimensional effects of blade tips and rotor center portion and so forth, pure effects of blade sections on the double-blade structure could be estimated. In addition, as the outer and inner portions are separated in 2D rotor-models, aerodynamic forces acting on each blade portion can be easily analyzed. Furthermore, adoption of 2D-CFD analysis is convenient for comparison with the previous 2D-CFD analysis of non-double-blade rotors with symmetrical or cambered blades (Hara et al., 2014b).

5. Two-dimensional CFD analysis

Owing to its blade shape, the double-blade structure of the BWT rotor varies across its height. As a representative configuration of the micro BWT’s double-blade structure, we used a cross section at 25% of the total height, taken from the bottom of the micro BWT. Two double-blade rotors, one with a symmetrical blade section and one with a cambered blade section (shown in Fig. 10), were selected as the objects of the 2D-CFD analysis in this study. In both cases, the radius $R_1$ of the outer rotor was 0.2 m and the radius $R_2$ of the inner rotor was 0.12 m. In the case of the symmetrical blade section, the chord lengths of the outer and inner blades were 0.110 m and 0.140 m, and their pitch angles were 0° at 30% and 36%, respectively, along the chord. In the case of the cambered blade section, which was obtained by conformal mapping from the symmetrical blade section (Furukawa et al., 1990; Akimoto et al., 2013), the outer and inner blades had cambers 7.1% and 15.4%, chord lengths 0.109 m and 0.132 m, and pitch angles 6.3° and 9.4° at 30%

![Fig. 10 Double-blade rotors for 2D-CFD analysis. Rotor blade sections are (a) symmetrical or (b) cambered.](image)

![Fig. 11 Calculation domain: a rectangular static region (48D × 64D) and a circular region of motion (radius 1.5D).](image)
and 36% along the chord, respectively. The rotational axis was not taken into consideration. The direction of rotor revolution was chosen as counterclockwise. The calculation domain consisted of a static rectangular region and a circular region of movement with a radius of 0.3 m; this is shown in Fig. 11. For outer rotor diameter $D$, the size of the static region was $48D$ wide by $64D$ long with the center of the rotor located $24D$ units from the inlet; the diameter of the circular region of motion was $1.5D$.

STAR-CCM+ ver. 8 was used as the solver, and a Reynolds-averaged Navier-Stokes analysis was carried out under the assumption of two-dimensional, transient, incompressible, viscous flow, using the shear stress transport $k-\omega$ turbulence model. Figures 12 (a) and (b) show example calculation meshes in the region of motion and the vicinity of an inner cambered blade. The cell numbers were approximately 81,000 in the static region and 150,000 in the region of motion; these were the same for both rotors. Unstructured polyhedral meshes were adopted for most of the calculation domain; structured prism layer meshes of 20 layers were used for the region very close to the blade surface. The minimum mesh size on the wall surface of a blade was approximately $1.5 \times 10^{-7}$ m (equivalent to $1.4 \times 10^{-6} \text{c}$ and a maximum of $y^+ = 0.17$). For the boundary conditions, a constant flow velocity of 6 m/s was set at the inlet and a constant gage pressure of 0 Pa was set at the outlet. The sides of the static region were made to satisfy the slip wall condition, while the surfaces of blades were made to satisfy the no-slip wall condition. Eleven full rotations of the rotor were calculated in this study, except at low tip speed ratios of 0.625 or less, for which 13 to 19 full rotations were calculated. The torque and power coefficients of the rotor were obtained by averaging the calculated results over the final 6 rotations. Figure 13 shows examples of torque coefficients of the double-blade rotors calculated during each

**Fig. 12** Computational meshes for (a) region of motion and (b) periphery of an inner cambered blade.

**Fig. 13** Examples of variations in torque coefficients calculated by 2D-CFD. Unstable variation was large at higher tip speed ratios in the case of the symmetrical blade rotor. In the present study, the torque coefficients were averaged over the last 6 rotations (i.e., the 6th to 11th turns in the above examples).
rotation at tip speed ratios of 1 and 2. Large unstable variation in the torque coefficient was observed at higher tip speed ratios in the case of the symmetrical blade rotor. The Reynolds numbers of the 2D double-blade rotors at a wind speed of 6 m/s are the same as those of the experimental rotors. That is, the rotor Reynolds number is \( Re = 1.6 \times 10^5 \), and the tip-blade Reynolds number \( Re_b \) is between \( 2.2 \times 10^4 \) and \( 1.1 \times 10^5 \).

6. Results of CFD analysis and discussion

The total torque and power coefficients of the two 2D double-blade rotors obtained by CFD analysis are shown in Figs. 14 (a) and (b), respectively. Although the torque (or power) peaks and the maximum tip speed ratios calculated by the 2D-CFD are different from the experimental results shown in Fig. 9, the characteristics obtained by the numerical simulation and the experiments agree qualitatively in terms of the superiority of the cambered blade at high tip speed ratios and the superiority of the symmetrical blade at low tip speed ratios. Most of the difference between the numerical (Fig. 14) and the experimental (Fig. 9) results can likely be attributed to the differences between 2D and 3D rotor shapes. The continuously changing inner-rotor radius and the 3D shapes at the top, bottom, and joint of the blade in the experimental models can cause a large aerodynamic drag force.

Figures 15 (a) and (b) show the torque and power characteristics of the outer rotors, which are larger when generated by a cambered blade than when generated by a symmetrical blade for all tip speed ratios. This shows that a cambered blade with mean line along curvilinear flow has more desirable properties than a symmetrical blade for a large chord-to-radius ratio; the present micro BWT is of this sort. It is interesting to compare the previous 2D-CFD analysis of non-double-blade rotors (Fig. 14 in Hara et al., 2014b) with the present results (Fig. 15) of the outer-rotor of double-blade structure. Both analyses are consistent in terms of superiority of cambered blades at high tip speed ratios (\( \lambda > 1 \)). However, at low tip speed ratios, the torque and power coefficients of the non-double-blade rotor with symmetrical blade section showed higher values than those in the case of cambered blade section. This discrepancy between the non-double-blade rotor and the outer-rotor of double-blade structure may have a relationship with the following discussions.

Figures 16 (a) and (b) show the torque and power predictions for the inner rotors for both symmetrical and cambered blade sections. All CFD predictions show a tendency to have negative torque and power coefficients at tip speed ratios of 1.75 or more. In Fig. 16, the inner blade of the 2D double-blade rotors contributes positively to the torque at tip speed ratios less than 1.5, except for the cambered blade case at a tip speed ratio of 0.5, and contributes negatively at tip speed ratios higher than 1.75. At a tip speed ratio of 0.75, the positive contribution from the symmetrical blades of the inner rotor is particularly large. This inner blade contribution causes the superiority of the symmetrical blade rotor in the lower tip speed ratio region of the whole 2D double-blade rotor, as shown in Fig. 14. Therefore, the superiority of the self-starting performance of the experimental rotor with symmetrical blades can be attributed to the high torque coefficient at low tip speeds of the inner rotor. However, why does the inner symmetrical blade generate a higher torque at a low tip speed ratio? In order to consider the causes, we will first survey the flow field around the 2D double-blade rotors below.

Figures 17 (a)-(e) show vorticity distributions, and Figs. 17 (f)-(j) show pressure distributions of the symmetrical blade rotor at the tip speed ratios of 0.5, 0.75, 1.25, 1.75, and 2.25, respectively. The vorticity and pressure distributions in the case of the cambered blade rotor are similarly shown in Figs. 18 (a)-(j). At high tip speed ratios of 1.75 or more, a vortex sheet shed from an outer blade, which meets interference from and is cut off by the following blade, flows roughly downwards along the mainstream flow in the case of the cambered blade rotor. Low pressure regions in the wake also flow almost straight, as shown in Fig. 18. On the other hand, the vortex distribution of the symmetrical rotor seems to expand in the wake, as shown in Figs. 17 (d) and (e); the low pressure regions flow a bit slanted toward the rotational direction of the rotor in the wake, as shown in Figs. 17 (i) and (j). The very low pressure in the inner rotor with the symmetrical blade section is an marked difference from the cambered blade rotor. From these differences, the symmetrical blade is considered to generate more drag than the cambered blade, and the pressure difference likely causes the inferiority of the symmetrical blade section at high tip speed ratios.

It is difficult to determine the causes that explain the superiority of the symmetrical blade rotor at low tip speeds by comparisons of vorticity or pressure. What we can understand from the vorticity and pressure distributions is that, in both rotor cases, distinct vortices due to dynamic stall (Paraschivoiu, 2002) are generated at the suction sides of the outer and inner blades that are in the upwind half-cycle (at 120° in azimuth) at a tip speed ratio of 0.75. The definition
Fig. 14 Comparison of total rotor characteristics, (a) torque and (b) power coefficients, obtained by CFD for 2D double-blade rotors with symmetrical (black) and cambered (red) blade sections. Wind speed = 6 m/s.

Fig. 15 Comparison of outer-rotor characteristics, (a) torque and (b) power coefficients, obtained by CFD for 2D double-blade rotors with symmetrical (black) or cambered (red) blade sections. Wind speed = 6 m/s.

Fig. 16 Comparison of inner-rotor characteristics, (a) torque and (b) power coefficients, obtained by CFD for 2D double-blade rotors with symmetrical (black) or cambered (red) blade sections. Wind speed = 6 m/s.
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Fig. 17  Vorticity and pressure distributions for a symmetrical blade rotor at $\lambda = 0.5, 0.75, 1.25, 1.75$, and $2.25$. 
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Fig. 18  Vorticity and pressure distributions for a cambered blade rotor at \( \lambda = 0.5, 0.75, 1.25, 1.75, \) and 2.25.
Fig. 19 Definitions of azimuth $\psi$, tangential ($F_t$), and normal ($F_n$) components of fluidic force $F$, and angle $\zeta$.

Fig. 20 Torque variations of an outer blade, an inner blade, and both outer and inner blades during one full rotation of (a) the symmetrical or (b) the cambered blade rotors, at a wind speed of 6 m/s and $\lambda = 0.75$. Dotted lines show the total torque variations of all 6 blades, i.e., the whole rotor.

Here, we focus on the tip speed ratio of 0.75. Figures 20 (a) and (b) show torque variations of an outer blade, an inner blade, both an outer and an inner blade, and the sum of all six blades (whole rotor) in the symmetrical and the cambered rotors, respectively, at the tip speed ratio of 0.75. An inner blade of the symmetrical rotor generates a large positive torque at a wider azimuth region than that of the cambered rotor. This boosts the sum of the torques from the inner and outer blades and the whole rotor torque.

Variations in tangential and normal forces that act on an outer or inner blade are shown in Fig. 21. The vertical axes of Figs. 21 (a) and (b) are the force coefficients $C_t$ and $C_n$ defined by Eqs. (1) and (2).

$$C_t = \frac{F_t}{0.5 \rho V^2 D}$$

(1)

$$C_n = \frac{F_n}{0.5 \rho V^2 D}$$

(2)

The definitions of the tangential and normal forces $F_t$ and $F_n$, the resultant force $F$, and the angle $\zeta$, which shows the direction of the fluidic force $F$, are designated in Fig. 19. The tangential force coefficients $C_t$ were calculated by averaging the tangential force components over the boundary cells of a blade section. On the other hand, the torque coefficients $CQ$ of the blade were calculated by averaging the product of the tangential force component and the radial
Variations in tangential and normal forces that act on an outer or inner blade: (a) symmetrical blade rotor, (b) cambered blade rotor. Wind speed = 6 m/s and $\lambda = 0.75$.

Variations in angle $\zeta$ of the resultant of the tangential and normal forces: (a) symmetrical blade rotor, (b) cambered blade rotor. Wind speed = 6 m/s and $\lambda = 0.75$. Under these conditions, the azimuth range in which the absolute value of the angle is less than 90° is larger for the symmetrical blade rotor than for the cambered blade rotor. This means that the inner blade of the symmetrical blade rotor generates positive torque for a wider range of azimuth values. The distance from the rotational center to a boundary cell along the boundary of the blade section. Therefore, the variations of the two differ slightly. Note that the tangential force of an inner blade of the symmetrical rotor (solid curve in red) is a positive value in the wide azimuth region of the upwind half-cycle, whereas that of the cambered rotor is nearly zero or a negative value.

Figures 22 (a) and (b) show the variations in the directional angle $\zeta$ of the fluidic force $F$ acting on a blade in an outer or inner rotor in the cases of the symmetrical and cambered blade sections, respectively. The azimuth range in which the absolute value of the angle $\zeta$ is less than 90° for the inner blade of the symmetrical blade rotor is larger than that of the cambered blade rotor. This means the inner blade of the symmetrical blade rotor contributes to the driving
Fig. 23  Vorticity distributions (left) and relative velocity vector maps (right) around the cambered blades at $\lambda = 0.75$. Figures (a), (b), and (c) show the conditions corresponding respectively to azimuth angles of 40°, 70°, and 100° of the blades in the direction #1.

force of the rotor at wider range of azimuth values. In the region where the azimuth is between 90° and 180°, the difference between the symmetrical blade and the cambered blade is large in terms of the generation of the driving force by the inner blades. That is, in that region, although the inner blade of the cambered blade rotor can hardly generate positive torque since the angle $\zeta$ is $\sim$90° or less, the inner blade of the symmetrical blade rotor does generate
Fig. 24  Vorticity distributions (left) and relative velocity vector maps (right) around the symmetrical blades at $\lambda = 0.75$. Figures (a), (b), and (c) show the conditions corresponding respectively to azimuth angles of $40^\circ$, $70^\circ$, and $100^\circ$ of the blades in the direction #1. The relative velocity vector patterns enclosed in red circles in Figs. (a) and (b) indicate smoother flows along the inner blade surfaces than in the cambered blade case shown in Fig. 23. The flow pattern in a red circle in Fig. (c) seems to produce a larger driving force due to drag than that in Fig. 23 (c).

Fig. 24 shows the vorticity distribution and relative velocity vector maps around the symmetrical blades at $\lambda = 0.75$. Figures (a), (b), and (c) correspond to azimuth angles of $40^\circ$, $70^\circ$, and $100^\circ$ respectively. The flow patterns in red circles indicate smoother flows along the inner blade surfaces in Figs. (a) and (b) compared to the cambered blade case shown in Fig. 23. The flow pattern in a red circle in Fig. (c) produces a larger driving force due to drag than that in Fig. 23 (c).

The driving torque, as shown by the small absolute value of the angle $\zeta$, which is less than $90^\circ$. The driving force of the inner blade for azimuth values between $90^\circ$ and $180^\circ$ is considered to be primarily generated by the drag force, because...
the tip speed ratio is 0.75 and the angle of attack is presumed to be around 90° to 180°. The drag force of the symmetrical blade can be enhanced more than that of the cambered blade due to the blade shape.

Figure 23 shows the vorticity distributions and relative velocity vector maps around the cambered blades at $\lambda = 0.75$. Figures (a), (b), and (c) show the conditions corresponding respectively to the azimuth angles 40°, 70°, and 100° of the blades in the direction #1. Figures 24 (a), (b), and (c) show the corresponding vorticity and relative velocity vector maps for the symmetrical blade rotor in the same way as Fig. 23. The relative velocity vector patterns enclosed in red circles in Figs. 24 (a) and (b) indicate smoother flows along the inner blade surfaces than those for the cambered blades shown in Fig. 23. The smooth flow along the blade surface produces high surface shear stress in the rotational direction. The flow pattern in the red circle shown in Fig. 24 (c) seems to produce a larger driving force due to drag than that in Fig. 23 (c). As shown in Fig. 24 (c), the flow in the mainstream direction goes toward the trailing edge of the inner blade in the direction #3 (azimuth angle: 220°) and produces a larger separation near the trailing edge than the rear part of the outer blade. On the other hand, in the case of the cambered blade rotor shown in Fig. 23 (c), the separation near the trailing edge of the inner blade is smaller than that near the outer blade in the direction #3.

7. Conclusions

Wind tunnel experiments on the butterfly wind turbine (BWT) with closed-loop blades, which creates a double-blade structure without arms, were carried out for both symmetrical and cambered blade sections. The experimental results showed the superiority of the cambered blade section at high tip speed ratios and the better self-starting performance of the symmetrical blade section. CFD analysis was also carried out for 2D double-blade rotors that corresponded to the cross sections of the quarter height of the 3D experimental models with symmetrical and cambered blade sections. The analysis yielded the same tendency as the experimental results and showed that cambered blades generated more torque than symmetrical blades at the outer rotors for large chord-to-radius ratios and that the inner blades of the symmetrical blade rotor contributed to the driving force more than the cambered blade rotor at low tip speed ratios. When the tip speed ratio was 0.75, at which the highest torque coefficient of an inner blade was obtained in the symmetrical rotor, the inner blade generated positive torque for a wider range of azimuth values than the cambered blade rotor. The difference between the performances of the blade sections was particularly large in the region where the azimuth lay between 90° and 180°. The drag force of the symmetrical blade in the inner rotor was considered to be enhanced in that azimuth region more than the cambered blade due to the blade shape. These flow characteristics found in the 2D analysis can qualitatively explain the influence of the blade section observed in the model experiments.

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