Performance of vertical-axis type straight-bladed Darrieus turbine with elastic blades
(Performance improvement by deformation of blades)

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Abstract
The characteristics of a straight-bladed Darrieus turbine (Gyro-mill turbine) with elastic blades are experimentally studied. The same structured turbine with rigid blades is also studied for comparison. The turbine with elastic blades is shown to have the following characteristics. When the T.S.R. (tip speed ratio) is small, less than 1, it generates very large torque like a drag-type turbine, and it can start by itself. On the other hand, when the T.S.R. is large, it shows the ordinary characteristics of the lift-type turbine, but the T.S.R. is limited less than 2. The deformation of the turbine blades is observed by a high-speed video movie, and it is shown that the torque rises not because of the wind drag but of the lift due to the deformation when the T.S.R. is small. The starting torque is also increased. Operation under too high rotation speed, which is sometimes dangerous, is also avoided by the deformation due to the centrifugal force which becomes significant when the rotation speed is high.

Key words : Darrieus turbine, Elastic blade, Efficiency, Wind tunnel test, Renewable energy, Fluid dynamics

1. Introduction
Vertical axis wind turbines (VAWT) are very effective in environments where the wind direction changes frequently, because they can generate torque without adjusting the direction of the wind turbine. There are various types in VAWT (Bhutta, et al, 2012), and some of them are used as the hydro-turbine, not as the wind turbine (Fukawa, et al, 1998, Li and Calisal, 1986, Takamatsu, et al, 1984, 1991, and Yang and Shu, 2012).

There are two types of VAWT, one is the drag type such as Savonius type (Savonius, 1928), and the other one is the lift type such as Darrieus type (Darrieus, 1931). The drag type turbines have characteristics that self-starting torque is large, so rotate even at low wind speed, but it can not operate at high T.S.R. (T.S.R.: tip speed of blade / wind speed), and the efficiency is generally smaller than the lift type turbines.

On the other hand, the lift type wind turbines can operate at high efficiency when the wind speed is high, but do not rotate at low wind speed because their starting torque is small (Erich, 2000). Sometimes Darrieus type turbine with straight blades are called the gyro-mill type turbine or straight-bladed Darrieus turbine. This type of wind turbine has been studied actively; for example, the characteristics of this turbine has been studied using the momentum theory by Betts (1920) or Wilson and Lissaman (1974) and using the actuator disk theory by Horlock (1978), Those are...
summarized by Paraschivoiu (2002). Recently, studies have spread to the flow around the turbine and self-starting performance (Kiwata, et al, 2010, Beri and Yao, 2011, Untaroiu et al. 2011, Tanaka, et al, 2008, and Kawaguchi, et al, 2007).

For the practical use, the straight-bladed Darrieus wind turbine is sometimes combined with drag type turbines such as the Savonius turbine to increase the starting torque. However, the straight-bladed Darrieus wind turbines can operate in high efficiency only at high T.S.R. where the output of drag type turbine is almost zero or minus power. That is, the drag type turbine is used to start only and is wasteful when the straight-bladed Darrieus turbines operate in ordinary condition. On the other hand, the straight-bladed Darrieus wind turbine has another problem, that is, the high efficiency is reached generally at high rotating condition. This fact means that the centrifugal force acting on the wind turbine blades becomes large and the noise from the blades also becomes large.

As to the elastic blades or deformable blades, it is famous that the first powered airplane invented by Wright brothers used elastic wings, and this technology has been succeeded to the modern aerospace engineering as ‘morphing’ and ‘active aeroelastic control’ (AAC) for fixed-wing (Pendleton E., 2000). For axial-flow turbines, some studies using elastic blades have been reported such as Minami.Y., et al. (2012). The application to cross-flow fluid machinery is rather rare. The flows around blades of cross-flow turbines such as Darrieus turbines that will be considered in this paper are completely unsteady, and the elastic deformation of the blades are very effective. For flying or swimming of animals or insects, the flows are unsteady and they use the elastic wings or fins, and the deformability works very effectively.

One of the authors (Tsutahara M. and Kimura T. 1990) has presented a ship’s propulsion equipment and a blower using springs to change the setting angle of the blade automatically against the flow and shown this technique improve the characteristics of the devices. The same idea is used to the elastic blades for a cross-flow fan (Tsutahara M. and Kimura T. 1994).

In this paper, the authors show that by adding a deformable elastic material to the rear part of each blade of a straight-bladed Darrieus turbine, this turbine can increase the starting torque, increase the efficiency at low T.S.R., and prevent the rotation speed from becoming too high.

2. Experimental Set-up and Methods

2.1. Turbine Model

The aerofoil for the blade is based on the NACA0015 whose span length is 500 mm, chord length is 75 mm, and the maximum thickness is 11.25 mm. Each blade is divided into two parts, the rigid part and the elastic part. The rigid part is made by an engineering plastic (nylon) occupying 60 % of the overall chord length, and a slot of 1mm wide is placed in the rear side along the chord for installing the elastic part. The elastic part is a polyethylene terephthalate resin (PET) sheet of 0.35 mm thickness which is inserted into the slot and deformed by the wind pressure and the centrifugal force. Overall chord length is 135 mm, and the cross section of the blade is shown in Fig. 1. For comparison, rigid blades were also used and the solid blades have the same structure and the elastic plate is replaced by a rigid plate (SUS304) of the same size.

The deformability of the elastic part was measured simply as follows. Weights were connected with the trailing edge of the plate through a string, and changing the weights and the displacements were measured. The relationship between the load and the displacement is linear up to the displacement 20 mm, and is 10 mm / N. This displacement is due to the concentrated load but not the distributed load like the aerodynamic force or the centrifugal force. However, this data will be useful for obtaining a rough image of the deformability.

The present Darrieus wind turbine has three blades as shown in Fig. 2. It is supported by aluminum circular plate of diameter 580mm at both ends (tips), the diameter of pitch circle of the blades is 550 mm. Angle of mounting the blade is changeable but we experimented with only one case of 5 degrees measured at the intersection of the radius and the chord line of the wing. The reason for fixing the mounting angle is that this study is concerned with only clarifying the effect of deformability of the rear part of the blade.

2.2. Spec of Wind Tunnel

The experiment was performed using a Goettingen type low-speed wind tunnel apparatus of Faculty of Engineering, Department of Mechanical Engineering, Osaka Prefecture University. Figure 3 shows the installation
status of the test model of wind turbine. The test section has a cross-section of $1.0 \times 1.5$ m, section length of 3.0 m, and its maximum wind speed is about 25 m/s.

Fig. 1 The cross section of the blade for the straight-bladed Darrieus turbine with elastic or rigid part. The base aerofoil is NACA 0015 whose chord length is 75 mm and a plate of 0.35 mm thickness is attached as the elastic part.

Fig. 2 Schematic view of the test model for the straight-bladed Darrieus turbine with elastic blades.

Fig. 3 The position of the turbine in the test section, (a) Schematic view of positional relation of the test section of wind tunnel and the turbine model, and (b) the photograph of the test section from the downstream direction.
Fig. 4 Experimental setup for measurement.

The projected area of the model is 0.275 m$^2$, then the blockage ratio is 0.2. This value is not small enough, but this study concerns the effect of the deformability of the blade, so that the effect of the blockage ratio is not considered. Figure 4 shows the experimental set up. After squeezing the flow by the nozzle, the honeycomb is installed at entrance of the test section for straightening the flow. Experiments were carried out in the range of wind speed $U$ from 4 m/s to 10 m/s. In this paper, we present the results for $U = 5.0, 7.0,$ and $8.5$ m/s mainly.

2.3. Measuring System

As shown in Fig. 4, the axial lower end of the rotor model is connected via a coupling to the phase difference method torque detector (Ono Sokki SS-005). The other end of the torque meter is driven by an AC servo motor (Oriental Motor BHF series) via a timing belt and the shaft is connected to the three phase AC generator. A variable enamel resistor is connected in delta connection to the three-phase generator. The rotation speed of the turbine is controlled directly by the AC servo motor, or by changing the value of the resistor in the circuit of the generator.

The procedure of the experiment is as follows. We set the wind tunnel velocity $U$, and control the revolution of the model using AC motor under this wind speed. Torque generated by the rotor was detected and for avoiding the noise from the fluctuation the duration time for measurement was set 15 seconds. The revolution of the rotor was detected using revolution detector (Ono Sokki MP-981). Analog signal of torque was converted through the torque converter (Ono Sokki TS-2700) and the signals were recorded in the computer at 500 Hz sampling frequency using a data interface (Kyowa Electronic Instruments PCD-320A).

2.4. Experimental Results

2.4.1. Characteristic of Turbines

Figure 5 shows the relationship between the torque and the rotation speed (r.p.m.) for turbines with the elastic blades in (a) and with the rigid blades in (b) for the wind speed 5, 7, and 8.5 m/s. Figure 5 (a) clearly shows that the torque of the elastic-blade turbine is remarkably high when the rotation speed is small and it becomes the maximum value for high wind seed cases higher than 7m/s. On the other hand, the torque becomes the maximum when the rotation speed is high for the turbine with the rigid blades. It should be noted that the torque of the former drops very sharply when the rotation speed exceeds the value giving the maximum value of the torque.
Fig. 5 Relationship between the torque and the rotation speed for turbines with the elastic blades in (a) and with the rigid blades in (b).

These phenomena are explained by the deformation of the elastic part, and the relationship between the performance and the deformation will be explained later.

The performance curves for the turbines are shown in Figs. 6, and 7, where the torque and power coefficients are shown as functions of T.S.R. for the turbine with the elastic blades in (a) and that with the rigid blades in (b). These curves are calculated by the definitions below.

The output power \( P_w \) is

\[
P_w = T \cdot \omega
\]

where \( T \) is the torque on the rotor and \( \omega \) is the angular velocity. The torque coefficient \( C_T \) and the power coefficient \( C_p \) are defined as

\[
C_T = \frac{T}{A \cdot R \frac{1}{2} \rho U_w^3}
\]

\[
C_p = \frac{P_w}{A \frac{1}{2} \rho U_w^3}
\]

where \( U_w \) is the velocity of uniform flow, \( \rho \) is the density of the air, \( R \) is the radius of the pitch circle and is 0.275 m, and \( A \) is the projection area of the model and is 0.275 m\(^2\). The tip speed ratio \( \lambda \) is defined as

\[
\lambda = \frac{R \omega}{U_w}
\]

and is the ratio of the tip speed of the blade to the incoming wind speed.

Figure 6 shows the relationship between \( C_T \) and T.S.R., that are non-dimensional variables, for three wind speeds. The curves are almost overlapped for the turbine with rigid blades, which means that a similarity exists for this turbine. On the other hand, the turbine with elastic blades does not show such similarity, but the tip speed ratio at which the maximum torque coefficient reaches is almost the same and about 1.2, and as stated earlier the torque coefficients drop sharply when the T.S.R. is higher than 1.2 This fact is effective for avoiding the operation in too high rotation speeds.

All the characteristics of the performance of the turbine with the elastic blades are due to the deformation of the blades, and it will be discussed later.
Figure 7 shows the power coefficients (efficiency) for both turbines. The turbine with rigid blades shows the similarity, and the efficiencies become the maximum at T.S.R. about 1.2 for all wind speeds, and high efficiency region extends to higher T.S.R. region, as is expected by the torque coefficient shown in Fig. 6. The turbine with rigid blades is shown to be efficient enough for only high T.S.R. region.

For the turbine with elastic blades, the efficiency reaches the maximum value at T.S.R. about 1.2 which is almost the same as that of the turbine with rigid blades. The maximum value of the power coefficient is almost 1.3 times larger than that of the turbine with rigid blades. The power coefficients for T.S.R. less than 1 are much larger, and they depends on the wind speed. The reason why the coefficient is large when the wind speed is high will be explained by larger deformation of the elastic blades.

2.4.2. Observation of the blade deformation with the high-speed video

In order to observe the behavior of the elastic blade, we took a high speed movie by using the Casio EXILIM
EX-F1, whose shooting speed was 1200 fps and the number of pixels of frame is $336 \times 96$.

Figure 8 shows the state of the blade in case of sufficiently small T.S.R. ($\lambda = 0.13$). Figure 8 (a) shows still images of deformation of the blade in various azimuth angles (see Figure 10 for definition) which are extracted from the high-speed video. From the azimuth angle of -45 degrees to 60 degrees, the trailing edge of the blade was displaced inward due to the effect of incoming flow. In this region, the elastic plate was also observed to vibrate one or two times by the side wind like flatter phenomena.

From the azimuth angle of 90 degrees to 180 degrees, the elastic plate of the blade was displaced to the outside direction. In this region, small vibration of two or three times was also observed. Thereafter, from the azimuth angle of 200 degrees to 310 degrees, the plastic plate was kept straightforward.

Figure 8 (b) shows the displacement of the elastic plate of the blade schematically. The deformation is large when a blade is on the upwind side (about the azimuth angle of 0 degree) and receives the wind from the side, but on the downstream side the deformation becomes maximum just before the blade reaches the most downstream point (the azimuth angle of 180 degrees). The deformation is not necessarily static but dynamic to some extent, and the elastic plate might be vibrate, but this motion is not considered in this study.

Fig.8 States of deformation of the blade of the straight-bladed Darrieus turbine with elastic blades, (a) cut frames of turbine model in the wind tunnel from high speed movie and (b) schematic diagram of the motion of blade tailing edge for $U_w = 8.0 \text{ m/s}$ and the rotation speed is 35 rpm (T.S.R. $\lambda = 0.13$).
This turbine has very large torque when the T.S.R. is small, but the mechanism is completely different from the drag type turbines. When the turbine starts to rotate, the elastic plate of the blade on the upstream-side and/or on the downstream-side, deforms towards the flow's direction, and then the blade generates lift, whose direction is the rotating direction.

The characteristics of the turbines with elastic blades and the rigid blades are similar to each other for large T.S.R., and in this situation the deformation effect is small. On the other hand, after the turbine with the elastic blades reaches the maximum performance, the torque and the power fall rapidly as the T.S.R increases, that does not happen for turbine with the rigid blades. This is considered to be due to deformation of the elastic plate by the centrifugal force. This deformation gives the blades the same effect as the change of the attack angle, and in this case gives the same effect as setting the blades leading edge inward. Then the turbine drops the performance for high rotation speed.

Figure 9 shows the effect of the centrifugal force on the deformation without incoming flow and it is clearly seen that the trailing edge moves outward significantly when the rotation speed becomes large.

### 2.5 Starting Torque

When the wind speed is low, the starting torque of the turbine is very significant factor, and the starting torque of the turbine with elastic blades was studied. In order to clarify the effect of the deformation, the torques acting on single elastic blade and also single rigid blade at rest (non-rotating torques) were measured for various azimuth angles which is defined in Fig. 10. The torque by a single elastic blade are shown in Fig. 11 (a) and that by a single rigid blade in (b), respectively, for wind speed 3m/s, 5m/s, and 7m/s. In these figures the horizontal axis represents the azimuth angle, and it is noted here that the total torque of the turbine may be obtained by adding up the torques of all the member blades at their positions.

Roughly speaking, the curves for rigid blade are symmetric with respect to the point of the azimuth angle of 180 degrees on zero torque line (horizontal axis), but the case of the elastic blade, the ranges of negative torque are smaller.

![Fig.10 Definition of azimuth angle](image-url)
and the positive torque is much larger for 5 and 7m/s. Then the starting torque of the turbine in which the several blades are combined is considered much larger. For the wind speed 5m/s and 7m/s, the torque by the elastic blade is larger all over the range even on the upstream and also downstream sides, and it is seen by observation that the deformation of the elastic part causes the high non-rotating torque.

The characteristics of torque by the elastic blade jumps at about azimuth angle 90 degrees, and this is caused by change of the direction (from inward to outward) of the deformation of the elastic part. The blade receives the drag at this position and the elastic part is on the upstream-side and this part becomes unstable and vibrates or deforms. Even in the case of rigid blade, the curves for 5 and 7m/s change rapidly at 90 degrees, and this may be caused by the movement of the separation points.

2.6 Turbine performance and discussion

As we can see from the torque coefficients shown in Fig. 7, characteristic of the present turbine with elastic blades looks like to show the characteristics of both the drag- and lift-type wind turbines. About the two peaks in the figure, a left peak (at low T.S.R.) corresponds to the performance of the drag type, and a right peak (at high T.S.R.) corresponds to the lift type. However, the high torque is due not only from drag but also lift by the deformation of the elastic parts of the blades, and this fact can be supposed by the non-rotating torque shown in Fig. 11 (a), in which elastic blade generates torque outside of the azimuth angle range from about 45 to 135 degrees.

These two characteristics have connected smoothly near 0.8 of T.S.R. As the T.S.R. increases, the deformation is prevented by the centrifugal force (which is proportional to the square of the revolution speed instead of the T.S.R.), then the turbine behaves as ordinary turbine with the rigid blades whose mounting angle is negative.

It might be considered that the deformation works well only in low T.S.R., but we can obtain better performance by preventing the outward deformation due to the centrifugal force when the T.S.R. is high. But this deformation has an excellent effect for reducing the over revolution that is sometimes dangerous and noisy, so that the control of the deformability will be of importance.

From Figs. 6 (a) and 7 (a) in which the characteristics are not summarized by simple non-dimensional variables, it should be noted that some other non-dimensional parameters including the elasticity or deformability and also the centrifugal force must be added to the analysis for the turbine with elastic blades. However, this task will be not easy, because the dynamical similarity is established among the spaces having geometrical symmetry, and then the similarity does not hold for geometrically changing bodies.

Darrieus turbine is generally designed to obtain high efficiency by operating at high peripheral speed, i.e., high rotation speed. The present turbine with elastic blades can avoid the high rotating speed operation, and this type of turbine has higher efficiency at low T.S.R. and at even high T.S.R. The efficiency is higher than the ordinary type with rigid blades.

Fig.11 Relationship between non-rotating torque for one blade and azimuth angle

(a) elastic blade

(b) rigid blade
3. Conclusion

We have investigated the performance of the vertical axis straight-blade Darrieus turbine with blades having elastic deformable plates in their rear part. By comparison with the turbine with rigid blades, it is shown that this type of turbine has very high performance when the T.S.R. is small like a drag type turbines, and the starting torque is very high. This phenomenon is explained by the deformation of the blades. On the other hand, the torque of this turbine drops very rapidly after reaching the maximum torque, that is also the effect of the deformation of the blades. This effect is very useful to suppress automatically the over rotation under strong wind. This turbine also has large starting torque and can start without any auxiliary turbines such as the Sabonus turbine.

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