Improvement of Self-Starting of Darrieus Turbine by Pitch Variation

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***Abstract*—Darrieus turbine with straight blades has an advantage over a horizontal-axis turbine in the simplicity and in independency to a current direction. In order to improve the self-starting performance of Darrieus turbine, the pitch angles of the blades are varied and tested in a low-speed wind tunnel. First, the pitch angles of the blades are varied coarsely to evaluate the possibility of the improvement. The generated torque on the turbine is measured by the torque meter in a tip-speed ratio from 03 to 1.2. Then, based on the obtained results, the pitch angles of the blades are again varied but in a range from -15 to 15 degrees. As a result, it is found out that the pitch angle of -10 degrees gives the largest torque below 0.8 in a tip-speed ratio. Once the turbine reaches 1 in a tip-speed ratio, then the blades with a pitch angle of 4 and 6 degrees are advantageous to accelerate the turbine.**

***Keywords*— Darrieus turbine, vertical-axis turbine, self-starting, pitch variation, torque**

I. INTRODUCTION

An ocean current is an attractive renewable energy source for a country surrounded by sea, like Japan. In the ocean currents, a tidal current can reach to a speed above five meters per second, which has an equivalent energy with a wind of typhoon, nearly 47 meters per second. Moreover, the occurrence of a tidal current is highly periodical and easily predicted. A tidal current changes its flow direction by 180 degrees with regular intervals. The Darrieus-type water turbine is suitable for such situation because of its independency to a current direction, as well as simplicity. Actually, the Darrieus turbine is adopted in the demonstration of power generation from a tidal current at Kanmon Strait [1].

There are some drawbacks for the Darrieus-type turbine. One of them is the lower efficiency of the power generation, as compared to the horizontal-axis turbines. This is one of the reason why the Darrieus turbine is not commonly used in real situations. The attachment of a device that collects a current into the turbine is an option to enhance the efficiency [2]. The incapability of self-starting is also a known problem for a turbine that uses a lift force, which is also true for Darriues turbine.

Thus, the improvement both in self-starting capability and in efficiency of the Darrieus-type turbine is desirable. Varying a pitch angle of the blades is one of the options. Actually, the efficiency improvement is tried by an active control of the pitch angle during one rotation of the turbine [3]. However, it is too busy to change the pitch angle during one rotation of the turbine, especially in high-speed revolution. Thus, it is more realistic to vary the blade pitch angle accordingly to a tip-speed ratio.

II. EXPERIMENTAL SETUP

The Darrieus turbine with straight blades is made for the present experiments. Fig.1 depicts the outline of Darrieus-type turbine. The specifications of the Darrieus turbine built for the experiments are summarized in Table 1.

NACA0018 is selected as the section shape of the straight blades of the Darrieus turbine. It is suitable for the evaluation of an effect of pitch angle of the blades, since it has a symmetrical shape.

Fig.2 shows the experimental setup in the low-speed wind tunnel of the space dynamics laboratory, Kyutech. The wind tunnel is used for generating a stream instead of a water because of the simplicity. The Darrieus turbine is mounted vertically in the tunnel, and it is driven by the AC motor which is mounted beneath. The torque generated by the stream is detected by the torque meter, by subtracting the driving torque from the measured one.

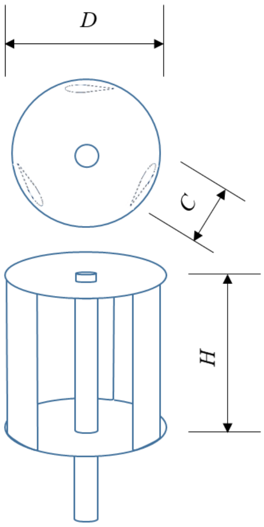

Fig.1 The outline of Darrieus turbine with straight blades

TABLE I
SPECIFICATIONS OF DARRIEUS TURBINE

Blade profile	NACA0018
Turbine diameter *D* [mm]	400
Height *H* [mm]	350
Chord length *C* [mm]	75
Number of blades *Z*	3
Solidity $\sigma = ZC/(2\pi R)$	0.179

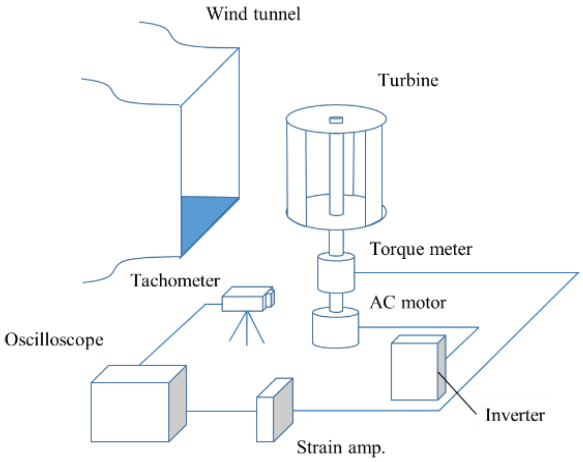

Fig.2 Experimental setup in low-speed wind tunnel

The solidity of 0.179 is matched to that of our past turbine[1]. The revolution numbers of the turbine is measured by the tachometer, from which the tip-speed ratio of the turbine can be calculated.

The tip-speed ratio is defined as follows.

$$\lambda = \frac{2\pi R n}{V} \quad (1)$$

where radius of the turbine $R = D/2$, revolution number of the turbine n and free-stream velocity V, respectively.

The measured torque Q is converted into the torque coefficient C_t.

$$C_t = \frac{Q}{0.5\rho A V^2 R} \quad (2)$$

where the turbine area $A = DH$.

The power coeffcient C_P is obtained by the following relationship.

$$C_p = \frac{\omega Q}{0.5\rho A V^3} = \lambda C_t \quad (3)$$

where the angular velocity of the turbine ω.

III. EXPERIMENTAL RESULTS

A. *Nominal Performance*

Initially, the pitch angle of the blades is set to zero degrees. It is a completely symmetrical case. With this configuration, the torque is measured in three different wind velocities, 13, 11 and 9 meters per second. The torque coefficients are plotted against the tip-speed ratio. Below 1 in tip-speed ratio a significant drop is recognized in all the wind velocities. Especially in 11 m/s, the torque becomes even negative. This means that the stream generates the torque on the turbine to turn in reverse direction. As the tip-speed ratio approaches to 1, the torque increases rapidly and reaches to the maximum beyond 2 in tip-speed ratio. After that it gradually decreases to zero.

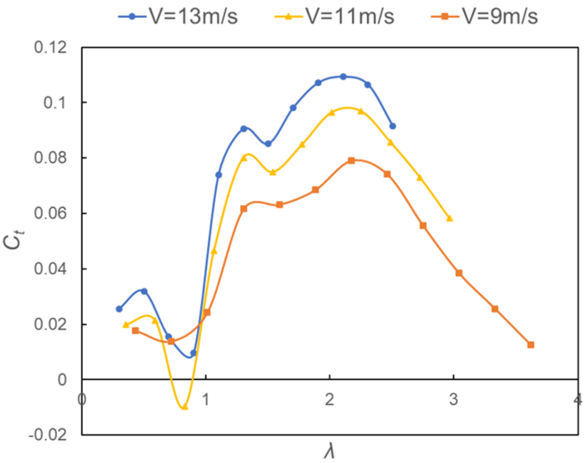

Fig.3 Torque coefficients vs. tip-speed ratio in three different wind velocities (V=9, 11, 13m/s)

The power coefficients can be obtained based on the relationship in Eq. (3). Fig.4 shows the power coefficients as a function of the tip-speed ratio.

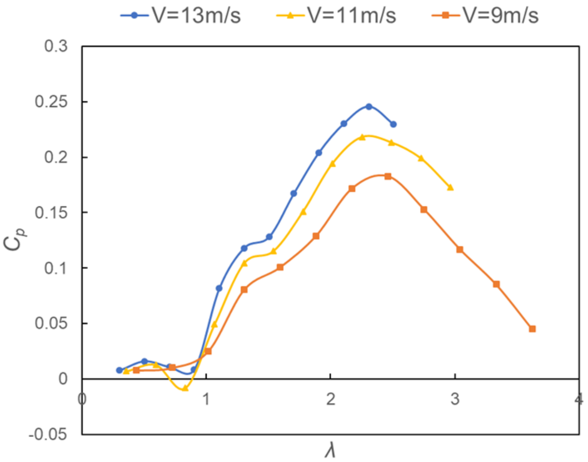

Fig.4 Power coefficients vs. tip-speed ratio in three different wind velocities (V=9, 11, 13m/s)

It is clear that below 1 in tip-speed ratio the power absorbed by the Darrieus turbine from the stream is quite low in all the three wind velocities. Once the turbine rotates about 1 in tip-speed ratio the power becomes large and reaches to the maximum around 2.4 in tip-speed ratio. There are some differences in the peak power and peak locations between the three different wind velocities. In V=11 m/s case, the power coefficient becomes negative at 0.8 in tip-speed ratio. This means that the turbine dissipates the kinetic energy into the stream at tip-speed ratio of 0.8.

Secondly, the turbine is set to run freely in a free stream. The turbine starts to rotate by the torque purely generated by the free stream. Fig.5 shows the achieved tip-speed ratio under various free-stream velocities. Even increasing the stream velocity over 20 m/s the achieved tip-speed ratio remains about 0.62. The Darrieus turbine should operate at the highest power peak which is about 2.4 in tip-speed ratio, however, the achieved tip-speed ratio during the free run is too small. This is also the evidence that the Darrieus turbine has difficulty in the start-up process.

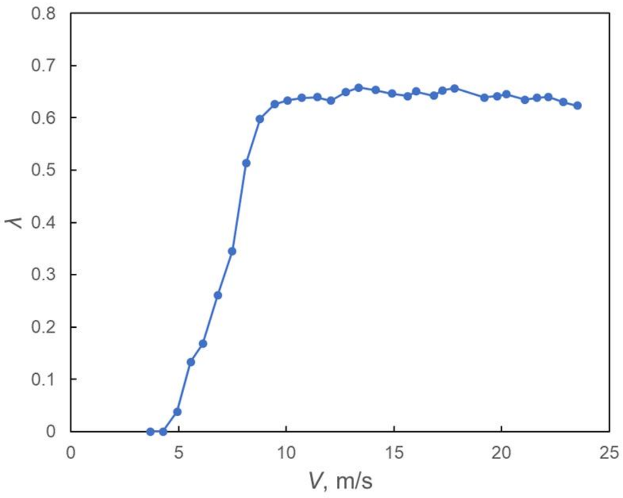

Fig.5 Achieved tip-speed ratio during the free run at various stream velocities

B. *Coarse Variation in Pitch Angle*

Originally, the straight blade is aligned along the tangential line of the circle which centers the axis of rotation. This is zero degrees in pitch angle. In order to evaluate roughly the dependency of the pitch angle on the self-starting capability, seven different pitch angles are chosen, -40, -30, -20, -10, 10, 20, 30 degrees. The positive pitch angle is clockwise from the direction of the rotation, as shown in Fig.6.

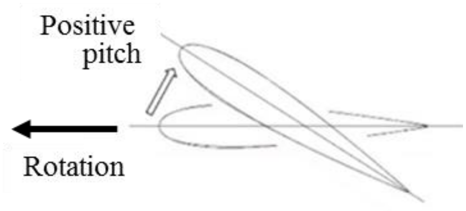

Fig.6 Definition of pitch angle of the Darrieus blade

The adjustable plate is specially designed to vary the pitch angle easily and precisely. Fig.7 shows the Darrieus blade attached in positive pitch angle with a help of the adjustable plate, which allows the blade to vary -90 to 90 degrees in pitch angle.

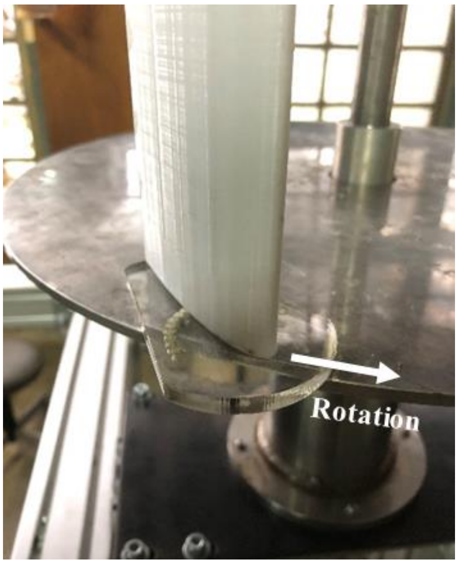

Fig.7 Darrieus blade in positive pitch angle

Again, the experimental setup in Fig.2 is used to obtain the torque characteristics as a function of the tip-speed ratio. Only the start-up capability is of interest in the experiment, and the torque is measured between 0.3 and 1.2 in tip-speed ratio. The free-stream velocity is set to 7 m/s.

Measured torque is shown in Fig.8 in a form of torque coefficient. As seen in Fig.8, the blades with positive high pitch angle spoil the torque drastically. Contrary, the blades with negative pitch angle enhance the torque below 0.8 in tip-speed ratio. Especially, the blades with -10 degrees give the best torque over a range of tip-speed ratio up to 0.7.

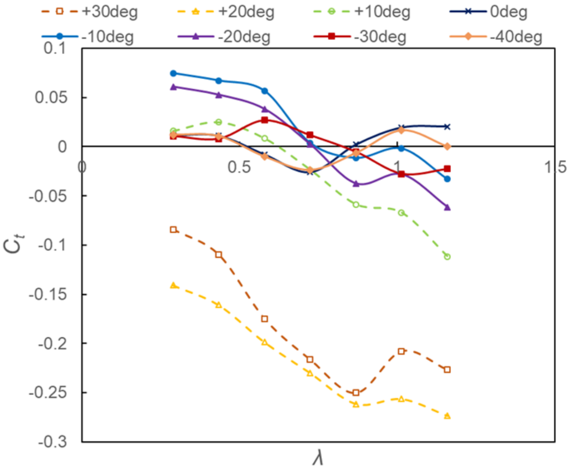

Fig.8 Torque coefficients of blades with eight pitch angles as a function of tip-speed ratio

The blades with -30 degrees in pitch angle generate larger torque than the nominal blades from 0.7 to 0.9 in tip-speed ratio. Beyond 0.9 in tip-speed ratio the nominal blades generate the better torque.

Similarly, the power coefficients can be obtained based on the relationship in Eq.(3). Fig.9 shows the power characteristics with the blades in eight different pitch angles. The combinations of the -10, -30 and 0 degrees in pitch angle should smoothly achieve the self-starting from a stationary state.

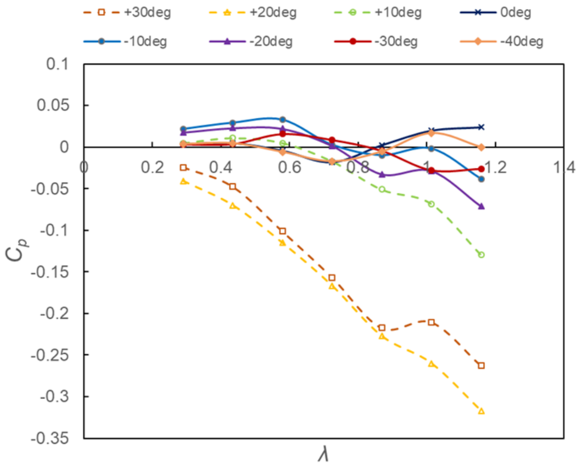

Fig.9 Power coefficients of blades with eight pitch angles as a function of tip-speed ratio

C. Fine Variation in Pitch Angle

In the previous section the dependency of the blade pitch angle on the self-starting capability is obtained. However, the variation in pitch angle is fairly large. It is also of interest how a small change in pitch angle affects the start-up process. Thus, another adjustable plate is newly designed so as the blade to vary the pitch angle between -15 to 15 degrees. The positive pitch angle is clockwise from the direction of rotation.

Again, the experimental setup in Fig.2 is used. Fig.10 shows the obtained torque coefficient with the blades of -8, -6, -4, -2, 0, 2, 4, 6, 8 degrees in pitch angle as a function of tip-speed ratio. It is obvious form Fig.10 that the blades with small pitch angles still have the negative torque between 0.7 and 1.1 in tip-speed ratio. Even in the range below 0.6 in tip-speed ratio the blades with small pitch angles have little gain on the starting-up torque.

However, the improvement can be found beyond 1.1 in tip-speed ratio. The blades with 4 and 6 degrees in pitch angle generate larger torque. Once the turbine reaches 1 in tip-speed ratio, it is advantageous to take 4 or 6 degrees in pitch angle to increase the tip-speed ratio.

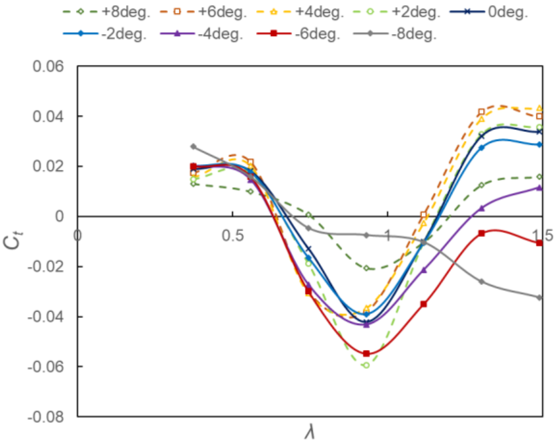

Fig.10 Torque coefficients of blades with nine pitch angles as a function of tip-speed ratio

From the obtained results in sections C and D, it is considered advantageous to vary the pitch angle of the straight blades of Darrieus turbine accordingly to the tip-speed ratio. From the stationary state the blades with pitch angle of -10 degrees are advantageous. The blades with -30 degrees in pitch angle is advantageous from 0.7 to 0.9 in tip-speed ratio. From 0.9 to 1.1 in tip-speed ratio the nominal blades are advantageous. At higher tip-speed ratio above 1 the blades with pitch angle of 4 or 6 degrees are advantageous to accelerate the turbine to the operational range.

IV. CONCLUSIONS

Darrieus turbine with straight blades has an advantage over a horizontal-axis turbine in the simplicity and in independency to a current direction. In order to improve the self-starting performance of Darrieus turbine, the pitch angles of the blades are varied and tested in a low-speed wind tunnel. First, the pitch angles of the blades are varied coarsely to evaluate the possibility of the improvement. The generated torque on the turbine is measured by the torque meter in a tip-speed ratio from 03 to 1.2. Then, based on the obtained results, the pitch angles of the blades are again varied but in a range from -15 to 15 degrees. As a result, it is found out that the pitch angle of -10 degrees gives the largest torque below 0.8 in a tip-speed ratio. The blades with -30 degrees in pitch angle is advantageous from 0.7 to 0.9 in tip-speed ratio. From 0.9 to 1.1 in tip-speed ratio the nominal blades are advantageous. At higher tip-speed ratio above 1 the blades with pitch angle of 4 or 6 degrees are advantageous to accelerate the turbine to the operational range.

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