Blade Force Measurement and Flow Visualization of Savonius Rotors*

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The mechanism of rotation of Savonius rotors which have two semicylindrical blades is studied experimentally. The force acting on a blade is measured in a water tank for both cases where a rotor is at rest and where it is rotated. A flow around the rotor is observed by using aluminum powder floating on the water surface. Although the Savonius rotor is classified as a resistance type, the lift produces a torque in a pretty wide range of blade angles relative to the flow.

Key Words : Fluid Machine, Energy Engineering, Wind Turbine, Savonius Rotor, Blade Force Measurement, Flow Visualization.

1. Introduction

Since the flow around Savonius rotors changes every moment complicatedly, it is very difficult to treat it theoretically. Therefore no theoretical studies are done except by Ogawa⁽¹⁾ who uses the discrete vortex method. The great majority of studies on Savonius rotors are experimental ones, and most of them are on the overall performance such as torque and power. Thus, very few studies⁽²⁾ give the basic information about the mechanism of rotation of Savonius rotors.

This study is concerned with Savonius rotors which have two semicylindrical blades. It is intended to clarify the mechanism of rotation of Savonius rotors by measuring forces acting on a blade and visualizing the flow around a rotor in a water tow tank for both cases where a rotor is at rest and where it is rotated.

2. Experimental Apparatus and Procedure

Figure 1 shows the experimental apparatus. A pair of parallel rails are mounted over the water tow tank, whose depth is 0.6 m, the width 1.5 m and the length 3 m. A carriage ① equipped with two blades of a Savonius rotor ⑧ whose blade chord is 120 mm and the span is 400 mm can slide on these rails.

A variable speed motor ② mounted at one end of the tank drives the carriage along the rails by winding up a wire rope ③ extended from the carriage. On the

other side of the carriage, another wire rope ④ is attached to be connected to a coil spring ⑥ and a weight ⑦ via a 3 meter-high pole ⑤. The weight rises with the movement of the carriage and the load on the motor is kept constant, so that the fluctuation of speed of the carriage is avoided. The coil spring is a buffer which can decrease the change in tensile force of the wire rope occurring at the starting instant. The blade rotor of a Savonius turbine is driven by another variable speed motor ⑨ mounted on the upper position of the carriage.

The fluid force acting on the blade is divided into a component normal to the chord F_n and a component along the chord F_t , which are measured by the strain gage bridges placed on the plate-springs ⑩ and ⑪. Two plate-springs are assembled parallel to each other so that the posture of the blade to the flow may not change with the deflection of springs. Slip rings ⑫ are used in the case where a rotor is rotated. Three rotors which have different overlap ratios $G/D=0.21$, -0.04 and -0.51 (see Fig. 2) are used in the experiment.

Choosing three towing speeds (i. e., flow speeds) of 10 cm/s, 15 cm/s and 20 cm/s, the relationship between the fluid force acting on a blade and the blade angle relative to the flow (inclinator angle) was examined. The Reynolds number $Re = U(2D-G)/\nu$, ν : Kinematic viscosity was in the range from 1.8×10^4 to 5.0×10^4 . Since the rotating speed was as small as 3.9 rpm ~ 15 rpm, the centrifugal force was negligible compared with the measured values of F_t . A flow around the rotor in both cases where the rotor was at rest and where it was rotated was observed by the aluminum powder floating method and photos were taken with a camera mounted on the carriage. Shutter speed was set at 1/4 second, and by using a winder, two frames per second could be taken successively. An instantaneous change in the flow was observed by examining these photos.

* Received 28th March, 1985.

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3. Experimental Results

3.1 Fluid force acting on stationary blades

Forces F_n and F_t are reduced as follows:

$$C_n = \frac{F_n}{\frac{1}{2}\rho U^2 DL}, C_t = \frac{F_t}{\frac{1}{2}\rho U^2 DL} \dots \dots \dots (1)$$

where D is the blade chord (diameter of a semicylinder) and L is the span of a blade. The inclinatory angle θ is measured as shown in Fig. 2 and the positive signs of F_n (C_n) and F_t (C_t) are taken in the direction of arrows in Fig. 2, that is, F_n is taken positive when it rotates the rotor clockwise, and F_t is defined positive when it is directed from the center of a rotor toward the outside.

Figure 3 shows the change in C_n and C_t for rotors of $G/D=0.21$ and -0.51 against the inclinatory angle. As found from Fig. 3, at inclinatory angle $\theta=60^\circ$, a very large C_n acts on the blade of $G/D=-0.51$ compared with C_n which acts on the blade of $G/D=0.21$. The reason is explained as follows: For the rotor of $G/D=0.21$, the flow toward the advancing blade ($\theta=60^\circ$) is blocked by

the retreating blade ($\theta=240^\circ$). For the rotor of $G/D=-0.51$, the frontal blade ($\theta=240^\circ$) works as a guide vane rather than as a blockage. At $\theta=270^\circ$, C_n is positive for the rotor of $G/D=0.21$, but negative for the rotor of $G/D=-0.51$. As shown in a photo of flow visualization (Fig. 4) of the rotor of $G/D=0.21$, the flow on the lower side of the advancing blade ($\theta=270^\circ$) runs along the blade chord, and then it is bent downward by the retreating blade ($\theta=90^\circ$). Thus, since the flow is smooth, a positive lift takes place. On the other hand, for the rotor of $G/D=-0.51$, the flow on the lower side of the advancing blade runs along the blade chord, then collides with the retreating blade and moves upward. This seems to cause a negative lift. For the rotor of $G/D=-0.04$, the appearance of the flow is almost the same as the one for the rotor of $G/D=0.21$.

Then for the purpose of making it easy to investigate the contribution of these forces to the torque, the forces acting on the blades at two inclinatory angles θ differing by 180° from each other, for instance $\theta=60^\circ$ and 240° or $\theta=90^\circ$ and 270° , are paired as shown in Figs. 5 and 6. It is easily found that the rotor of $G/D=-0.51$ produces a large positive torque at the pair of inclinatory angles of $\theta=(60^\circ, 240^\circ)$,

(a)

- ① Carriage
- ② Variable speed motor
- ③ Wire rope
- ④ Pole
- ⑤ Coil spring
- ⑥ Weight
- ⑦ Savonius rotor
- ⑧ Variable speed motor
- ⑨ Plate-springs
- ⑩ Slip rings
- ⑪ Gears

(b)

Fig. 1 Experimental apparatus

Fig. 2 Notations for a rotor

Fig. 3 Relationship between C_n , C_t and θ for a stationary blade

and a negative torque which acts to rotate the rotor anticlockwise at the pair of inclinatory angles of $\theta=(90^\circ, 270^\circ)$. Comparing Fig. 5 with Fig. 6, pressure recovery on the concave surface of the blade around $\theta=120^\circ \sim 210^\circ$ by the flow through the overlap portion is recognized for the rotor of $G/D=0.21$.

Taking the attitude angle of a rotor θ as indicated in Fig. 7 and using a pair of measurements of $C_n(\theta)$ and $C_n(\theta+180^\circ)$, the static torque coefficient is expressed as follows:

$$C_Q(\theta) = \{C_n(\theta) + C_n(\theta+180^\circ)\} \frac{1-G/D}{(2-G/D)^2} \quad \dots\dots\dots (2)$$

The estimated results of Eq. (2) are shown in Fig. 8. It has not been confirmed whether the acting center of the force is consistent with the point (the center of a blade) where the measurements were made. Therefore the values in Fig. 8 can include some error, but they show good agreement with the torques measured directly in the wind tunnel⁽³⁾. Thus, it is thought that

the acting point of force does not differ much from the center of a blade.

3. 2 Fluid force acting on rotating blades

Figure 9 shows the relationship between the fluid forces acting on the blade (C_n and C_t) and the inclinatory angle θ for the case where the rotor is rotated with the tip-speed ratio $\lambda=0.8$. Figures 10 and 11 show the combined force of C_n and C_t against the attitude of rotors. Comparing Fig. 9 with the cases of stationary rotors (Fig. 3), fine kinks on curves decrease and the curves become smoother. This tendency becomes remarkable with an increase in the tip-speed ratio. For the rotor of $G/D=0.21$, the pressure recovery by the flow through the overlap portion affects the torque when the rotor is at rest. On the other hand, when the rotor is rotated, the effect of the flow through the overlap portion may be small judging from the direction of the force at the inclinatory angle around $\theta \approx 120^\circ \sim 180^\circ$ shown in Fig. 10. Comparison of a photo of visualization around the stationary blade at $\theta=315^\circ$ (Fig. 12) with one

Fig. 4 Photos of flow visualization for a stationary rotor ($\theta=90^\circ, 270^\circ$)

Fig. 5 Force acting on a stationary blade

Fig. 6 Force acting on a stationary blade

of a rotating blade at almost the same angle [Fig. 13 (d) $\theta \approx 330^\circ$], shows that the flow on the convex surface of the rotating blade is less likely to separate than one on the stationary blade. By the flow patterns around the rotating rotor in the range of $\theta = 270^\circ \sim 330^\circ$ in Fig. 13, it is confirmed that a large positive lift occurs in this range of inclinatory angles. For the rotor of $G/D = -0.51$ at $\theta = 270^\circ$, the forces act to rotate the rotor anticlockwise when the rotor is at rest, but when the rotor is rotated, the forces act to rotate the rotor clockwise. Although for the rotor of $G/D = -0.51$, a positive lift occurs in the range of $\theta = 270^\circ \sim 330^\circ$, the magnitude is considerably smaller than that of the rotor of $G/D = 0.21$ because a part of flow on the concave side curls up through the center of the rotor as seen in Fig. 14. Regardless of the value of G/D , C_n around $\theta \approx 270^\circ \sim 330^\circ$ contributes greatly to the increase in the torque averaged over a single revolution. The torque coefficient C_Q is obtained in the same manner as in the case where the rotor is at rest, and the results are shown in Fig. 15, where G/D is a parameter.

In the wind tunnel experiment, it is not possible to measure the instantaneous

Fig. 7 Attitude angle of a rotor

Fig. 8 Static torque coefficient

Fig. 9 Relationship between C_n , C_t and θ for a rotating blade

Fig. 10 Force acting on a rotating blade

Fig. 11 Force acting on a rotating blade

Fig. 12 Photo of flow visualization
for a stationary rotor
($G/D=0.21$, $\theta=135^\circ$, 315°)

(a)

(b)

(c)

(d)

Fig. 13 Photos of flow visualization for
a rotating rotor ($G/D=0.21$, $\lambda=0.8$)

(a)

(b)

(c)

(d)

Fig. 14 Photos of flow visualization for
a rotating rotor ($G/D=0.51$, $\lambda=0.8$)

Fig. 15 Torque coefficient

value of torque while the rotor is rotating because the change in the torque during a single revolution is averaged by the moment of inertia due to high rotating speed. The average torque coefficients obtained from Fig. 15 show reasonable agreement with the results of the wind tunnel experiment⁽³⁾. As found from Fig. 15, when tip-speed ratio is $\lambda=0.8$, the rotor of $G/D=0.21$ does not produce a negative torque at any attitude angle. The rotor of $G/D=-0.51$ produces a negative torque in a wide range of attitude angles, and thus the average torque during a single revolution is very small.

4. Conclusions

The conclusions are summarized as follows:

(1) When the rotor is at rest, the rotor with overlap ratio $G/D=0.21$ produces a positive torque at any attitude angle. This is because of a positive lift occurring around $\theta=240^\circ \sim 330^\circ$ and a pressure recovery on the concave surface around $\theta=120^\circ \sim 210^\circ$ by the flow through the overlap portion.

(2) The lift around $\theta=240^\circ \sim 330^\circ$ contributes a lot to the torque occurring when the rotor is rotated. Although the Savonius rotor is classified as a resistance type, the lift produces a torque in a pretty wide range of angles relative to the flow.

(3) When the rotor is rotated, the effect of the pressure recovery by the flow through the overlap portion on the lift is little for the rotor of $G/D=0.21$. For the rotor of $G/D=-0.51$, the existence of a flow through the center of the rotor contributes to the production of a negative torque opposing the clockwise rotation.

The authors would like to thank Mr. R. Kato, Engineering Technician of Akita University, for his great help with the manufacture of the experimental apparatus.

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