Wells turbine for wave energy conversion  
- improvement of stall characteristics by the use of 3-dimensional blades -

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Abstract

The effect of 3-dimensional blade on the turbine characteristics has been investigated experimentally by model testing under steady flow conditions and simulated numerically by quasi-steady analysis under sinusoidal flow conditions, in order to improve the stall characteristics of Wells turbine for wave energy conversion in the study. Aim of the use of 3-dimensional blade for Wells turbine is to prevent flow separation on the suction surface near tip. The chord length is constant with radius and the blade thickness increases gradually from hub to tip. The blade profiles are NACA0015 at hub, NACA0020 at mean radius and NACA0025 at tip. The performance of Wells turbine with 3-dimensional blades has been compared with those of original Wells turbine, i.e., the turbine with 2-dimensional blades. As a result, it has been concluded that both the efficiency and stall characteristics of Wells turbine can be improved by the use of 3-dimensional blade.

Key words: Fluid machinery, Wells turbine, Wave energy conversion, Stall, Ocean engineering

1. Introduction

Some of the wave energy devices being studied under many wave energy programs make use of the principle of the oscillating water column (OWC) (Fig. 1). Potentially, the most successful device used in harnessing on wave energy has been the OWC wave energy converter. The OWC chamber, either floating or bottom standing, with the immersed end opened to the action of sea wave. A reciprocating airflow is created by the motion of the free surface of the water within the chamber. The conversion of this airflow into mechanical energy may be achieved by a number of devices in the OWC wave energy converter.

Wells turbine is a self-rectifying air turbine which is expected to be widely used in the OWC wave energy converter (Raghunathan 1995, Setoguchi, et al., 1998a, 1998b, Kaneko, et al., 1986, Setoguchi, et al., 1991, Inoue, et al., 1986, Setoguchi, et al., 2004) (Fig. 2). There are many reports which describe the performance of Wells turbine for both at starting and running characteristics. According to these reports, however, Wells turbine has inherent disadvantages in comparison with conventional turbines: lower efficiency and poorer starting characteristic. Some researchers have suggested measures in order to overcome the drawbacks above. According to previous studies, the postponement of stall can be achieved by setting guide vanes (Setoguchi, et al., 1998a) or porous fences (Setoguchi, et al., 1998b) on the hub near the rotor. However, in these cases, the efficiency deteriorates because of an increase of the pressure difference between before and behind the rotor and a decrease of the torque.
In this study, in order to enhance the characteristics of Wells turbine for wave energy conversion, the effect of 3-dimensional (3D) blade on the turbine characteristics has been investigated experimentally by model testing under steady flow conditions. The chord length is constant with radius and the blade profile changes gradually from hub to tip in the study. The aim of 3D blade is to prevent flow separation on the suction surface near tip and to gain much energy at tip. The blade profiles are NACA0015 at hub, NACA0020 at mean radius and NACA0025 at tip. And then, the characteristics of Wells turbine with 3-dimensional have been compared with those of the original Wells turbine, i.e., the turbine with 2-dimensional (2D) blade.

2. Experimental apparatus and procedure

A schematic view of the test apparatus is shown in Fig. 3. The test apparatus consists of a large piston-cylinder (diameter: 1.4m, length: 1.7m), one end of which is followed by a settling chamber. Turbine testing is done in 300-mm-diameter test section with bell-mouthed entry/exit at both its ends. The piston can be driven back and forth inside the cylinder by means of three ball-screws through three nuts fixed to the piston. All three screws are driven in unison by a D.C. servo-motor through chain and sprockets. A computer controls the motor, and hence the piston velocity to produce any flow velocity. The test turbine is coupled to a servo-motor/generator through a torque transducer. The motor/generator is electrically controlled such that the turbine shaft angular velocity is held constant at any set value. The overall performance was evaluated by the turbine output torque $T_o$, the flow rate $Q$, the total pressure drop across the turbine $\Delta p$, and the turbine angular velocity $\omega$. The flow rate through the turbine $Q$, whether it is inhalation (i.e., flow...
from atmosphere into the settling chamber) or exhalation (i.e., flow from settling chamber to atmosphere), is calculated by measuring the motion of piston, where the value of $Q$ agrees with that obtained by a Pitot tube survey. Tests were performed with the flow rates up to 0.320 m$^3$/s and the turbine angular velocities up to 471 rad/s. The turbine rotor adopted in the experiments is shown in Fig. 4. The chord length, $l = 90$ mm; number of blades, $z = 6$; solidity at mean radius, $\sigma = 0.67$; hub-to-tip ratio, $\nu = 0.7$; aspect ratio, 0.5; tip diameter, 299 mm; casing diameter, $D = 300$ mm; mean radius, $r = 127.5$ mm; width of flow passage, 45 mm. Note that the adopted turbine rotor is the most promising one in previous studies (Raghunathan 1995, Kaneko, et al., 1991, Setoguchi, et al., 1991).

The profile of 3D blade changes gradually from hub to tip in the study. Two types of 3D blade are used in the study. One is that the blade thickness increases with radius. In this case, the blade profiles are NACA0015 at hub, NACA0020 at mean radius and NACA0025 at tip. This blade is named 3D-A in the paper. Another is that the blade thickness decreases with the increase of radius. This blade has the profile of NACA0025 at hub, NACA0020 at mean radius and NACA0015 at tip, named 3D-B in the paper. The characteristics of Wells turbine with 3D blade have been compared with those of Wells turbine with 2D blade. The detail of 2D blade shows Table 1.

![Figure 3: Experimental apparatus and measuring system](image)

![Figure 4: Outline of tested Wells turbine](image)

![Figure 5: Blade shape of tested Wells turbine](image)

<table>
<thead>
<tr>
<th>No.</th>
<th>Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wind tunnel</td>
</tr>
<tr>
<td>2</td>
<td>Piston</td>
</tr>
<tr>
<td>3</td>
<td>Ball-screw</td>
</tr>
<tr>
<td>4</td>
<td>Servomotor</td>
</tr>
<tr>
<td>5</td>
<td>D/A converter</td>
</tr>
<tr>
<td>6</td>
<td>Servo-pack</td>
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<tr>
<td>7</td>
<td>Settling chamber</td>
</tr>
<tr>
<td>8</td>
<td>Turbine</td>
</tr>
<tr>
<td>9</td>
<td>Torque transducer</td>
</tr>
<tr>
<td>10</td>
<td>Servomotor-generator</td>
</tr>
<tr>
<td>11</td>
<td>Pressure transducer</td>
</tr>
<tr>
<td>12</td>
<td>A/D converter</td>
</tr>
</tbody>
</table>

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3. Experimental results

The turbine performance under steady flow conditions is evaluated by turbine efficiency $\eta$, torque coefficient $C_T$ and input coefficient $C_A$ against flow coefficient $\phi$. The definitions of these parameters are as follows:

$$C_T = T_o/\{\rho(v^2+u^2)Ar/2\} \quad (1)$$

$$C_A = \Delta pQ/\{\rho(v^2+u^2)Av/2\} = \Delta pQ/\{\rho(v^2+u^2)/2\} \quad (2)$$

$$\eta = T_o\phi/\Delta pQ = C_T/(C_A\phi) \quad (3)$$

$$\phi = v/u \quad (4)$$

where $A$, $v$, $u$ and $\rho$ denote the flow passage area $= \pi D^2(1-v^2)/4$, circumferential velocity at mean radius $= r\omega$, axial flow velocity $= Q/A$ and density of air, respectively.

Figure 6 shows the experimental results of the effect of blade shape on the turbine characteristics. As shown in Fig. 6(a), in the region of flow coefficient which is smaller than the stall point, the torque coefficient $C_T$ of 2D blade decreases gradually with the increase of blade thickness and $C_T$ of 3D cases is slightly lower than the case of 2D-15. Regarding the input coefficient $C_A$ in the same region in Fig. 6(b), $C_A$ of 3D cases is almost the same to the case of 2D-15. However, the stall point increases with the blade thickness at tip and the stall point in the case of 3D-A is higher than that of 3D-B, as shown in Fig. 6(a). The stall points of 3D-A, 3D-B 2D-15, 2D-20 and 2D-25 are 0.346, 0.270, 0.276, 0.327 and 0.366, respectively. Therefore, the stall characteristic depends on the profile at tip. Furthermore, the turbine of 3D-A is second best for the stall point in the study.

<table>
<thead>
<tr>
<th>Shape</th>
<th>Profile</th>
<th>$d/l$</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>NACA0015</td>
<td>NACA0020</td>
<td>0.15-0.25</td>
<td>3D-A</td>
</tr>
<tr>
<td>NACA0025</td>
<td>NACA0020</td>
<td>0.25-0.15</td>
<td>3D-B</td>
</tr>
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<td></td>
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</tr>
<tr>
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</tr>
<tr>
<td>NACA0025</td>
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<td>0.25</td>
<td>2D-25</td>
</tr>
</tbody>
</table>

Fig. 6 Effect of blade shape on turbine characteristics under steady flow conditions
4. Turbine characteristics under sinusoidal flow conditions

Since the airflow into the turbine is generated by the OWC, it is very important to demonstrate the turbine characteristics under oscillating flow conditions. Here let us simulate the characteristics under sinusoidal flow conditions in order to clarify the effect of blade profile on the turbine characteristics. The steady flow characteristics of the turbine as shown in Fig. 6 are assumed to be valid for computing performance under unsteady flow conditions. Such a quasi-steady analysis has been validated by previous studies (Inoue, et al., 1986). The turbine characteristics under unsteady flow conditions are estimated in the starting and running characteristics.

4.1 Starting characteristics

The starting characteristics of the turbine are evaluated by the variation in rotational speed from the rest point (i.e., \( \omega = 0 \)). The equation of motion for a rotating system of turbine is written by the following equation:

\[
I \frac{d\omega}{dt} + T_l = T_o
\]

(5)

where \( I \), \( t \) and \( T_l \) are the moment of inertia of rotor, time and loading torque. When the turbine is operated under sinusoidal flow conditions, this equation can be rewritten by using geometrical parameters as follows:

\[
S^2X_i \frac{d\omega^*}{dt^*} + X_l = 2C_r \sigma \frac{1 - \nu}{1 + \nu} \left[ \sin^2(2\pi t^*) + \frac{1}{\Phi^2} \right]
\]

(6)

where \( \omega^* \), \( t^* \), \( S \), \( X_i \) and \( X_l \) are the dimensionless angular velocity (\( = \omega T \): period of wave), dimensionless time (\( = t/T \)), dimensionless frequency (\( = f/V \): frequency of wave, \( V \): maximum value of axial flow velocity), dimensionless moment of inertia (\( = I/(\pi\rho r^5) \)) and dimensionless loading torque (\( = T_l/(\pi\rho V^2 r^3) \)), respectively. Equation (6) can be solved numerically as an initial problem when \( C_T \) and a wave motion are given.

The effect of blade shape on starting characteristics under sinusoidal flow conditions is shown in Fig. 7. The results are given in the form of the non-dimensional angular velocity \( \omega^* \) versus dimensionless time \( t^* \). Although all the turbines can start by themselves, the cases of 3D-A and 2D-20 show better starting characteristics. This is because the stall point in the case of 3D-A and 2D-20 is higher than 3D-B and 2D-15. Inertia of rotor in the case of 2D-25 is highest in the calculation and \( C_T \) at just after the stall is negative, though its stall point is highest (Fig. 6(a)).

Fig. 7 Effect of blade shape on starting characteristics under sinusoidal flow conditions
4.2 Running characteristics

When the turbine is in the running conditions, the parameters such as $T_o$, $\omega$, $\Delta p$ and $Q$ vary periodically in a sinusoidal oscillating flow. In this case, the turbine performances should be represented by mean value such as mean efficiency. The running characteristics of the turbine under sinusoidal flow conditions are evaluated by the mean efficiency $\bar{\eta}$ against the flow coefficient $\Phi$, which are defined as follows:

$$\bar{\eta} = \left(\frac{1}{T} \int_0^T T_o \omega \, dt\right) \left(\frac{1}{T} \int_0^T \Delta p \, Q \, dt\right)$$

(7)

$$\Phi = \frac{V}{u}$$

(8)

Equation (7) can be rewritten in a dimensionless form as follows:

$$\bar{\eta} = \frac{\int_0^\phi \left(C_t(1+\phi^2)\sqrt{\Phi^2 - \phi^2}\right) \, d\phi}{\int_0^\phi \left(C_A(1+\phi^2)\phi\sqrt{\Phi^2 - \phi^2}\right) \, d\phi}$$

(9)

In the calculation, the flow coefficient under sinusoidal flow conditions is defined as:

$$\phi = \Phi \sin(2\pi t')$$

(10)

Figure 8 shows the effect of blade shape on mean efficiency $\bar{\eta}$ under sinusoidal flow conditions. As shown in the figure, the peak efficiencies of 3D-A, 3D-B 2D-15, 2D-20 and 2D-25 are 0.449, 0.436, 0.469, 0.443 and 0.381, respectively. According to this result and Fig. 4(a), the peak efficiency in the case of 3D blade depends on the profile at mean radius and the stall characteristic depends on the profile at tip. Furthermore, the turbine of 3D-A is second best for both the peak efficiency and stall point in the study. Therefore, it is considered that this blade can improve the running and stall characteristics at once in comparison with 2D blade with NACA0020 (Setoguchi, et al., 2004).

From the above results of steady and unsteady characteristics of the turbines, one can conclude that the favorable blade shape is 3D-A which the blade thickness increases with radius.
5. Conclusions

In this study, the effect of 3-dimensional blade on the turbine characteristics was investigated experimentally by model testing under steady flow conditions, in order to enhance the performance of Wells turbine for wave energy conversion. As the results, it seems that the turbine characteristic in the case of 3D-A which the blade thickness increases with radius is better than the case of 2-dimensional blade. Further, it can be concluded that the stall characteristic in the case of 3-dimensional blade depends on the profile at tip than that at hub.

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References