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Effect of Blade Shape on the Performance of Wells Turbine for Wave Energy Conversion

Katsuya Takasaki, Manabu Takao, Toshiaki Setoguchi

Abstract**—**The effect of a 3-dimensional (3D) blade on the turbine characteristics of Wells turbine for wave energy conversion has been investigated experimentally by model testing under steady flow conditions in this study, in order to improve the peak efficiency and stall characteristics. The aim of use of 3D blade is to prevent flow separation on the suction surface near the tip. The chord length is constant with radius and the blade profile changes gradually from the mean radius to tip. The proposed blade profiles in the study are NACA0015 from the hub to mean radius and NACA0025 at the tip. The performances of Wells turbine with 3D blades has been compared with those of the original Wells turbine, i.e., the turbine with 2-dimensional (2D) blades. As a result, it was concluded that although the peak efficiency of Wells turbine can be improved by the use of the proposed 3D blade, its blade does not overcome the weakness of stalling.

Keywords**—**Fluid machinery, ocean engineering, stall, wave energy conversion, Wells turbine.

I. Introduction

SEVERAL wave energy devices make use of the principle of the oscillating water column (OWC). Potentially, the most successful device on wave energy has been the OWC wave energy converter. A reciprocating airflow is created by the action of the free surface of the water within the OWC chamber. The conversion of this airflow into mechanical energy may be achieved by an air turbine, which rotates in single direction for the reciprocating airflow.

The Wells turbine shown in Fig. 1 is a self-rectifying air turbine which is expected to be widely used in wave energy devices with the OWC [1]. The rotor of Wells turbine consists of several symmetrical airfoils positioned around a hub with their chord planes normal to the axis of rotation. In general, a 2-dimentional (2D) blade is used as the airfoil of Wells turbine. There are many reports which describe the performances of Wells turbine both in regards to starting and running characteristics. According to these results, however, Wells turbine has inherent disadvantages in comparison with conventional turbines: lower efficiency, severe stalling 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 [2] or porous fences [3] on the hub, near the rotor. However, in these cases, the efficiency deteriorates because of an increase of the pressure difference between the front of and back of the rotor and a decrease of the torque.

On the other hand, according to previous studies, the authors have suggested to use of a new type rotor blade which has a 3-dimensional (3D) shape for the sake of the improvement of turbine performance [4]. The thickness of the proposed blade increases with radius linearly from hub to tip. As a result, it was concluded that the turbine with new blade is better than the case of 2D blade.

In this study, the effect of 3D blade on the turbine characteristics has been investigated experimentally by model testing under steady flow conditions, in order to achieve further improvement of the characteristics of Wells turbine for wave energy conversion. The chord length has a constant with radius and the blade profile changes gradually from the mean radius to tip in this study. The aim of 3D blade is to prevent flow separation on the suction surface near tip. The blade profiles are NACA0015 from the hub to mean radius and NACA0025 at the tip. The characteristics of Wells turbine with 3D blades have been compared with those of the original Wells turbine, i.e., the turbine with 2-dimensional blades.

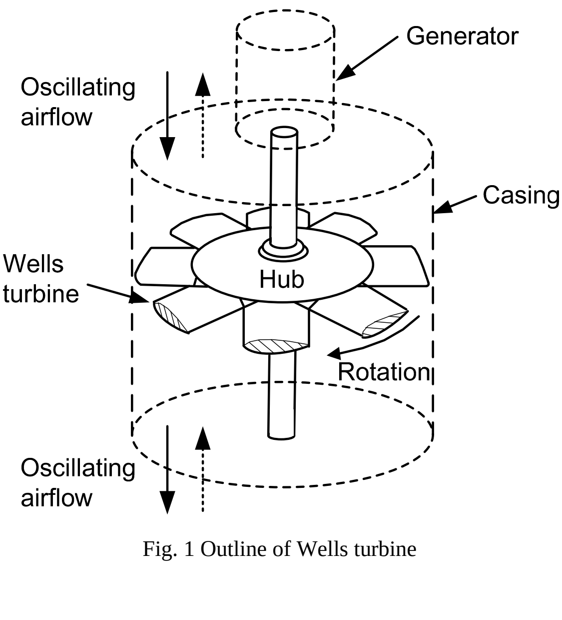

Fig. 1 Outline of Wells turbine

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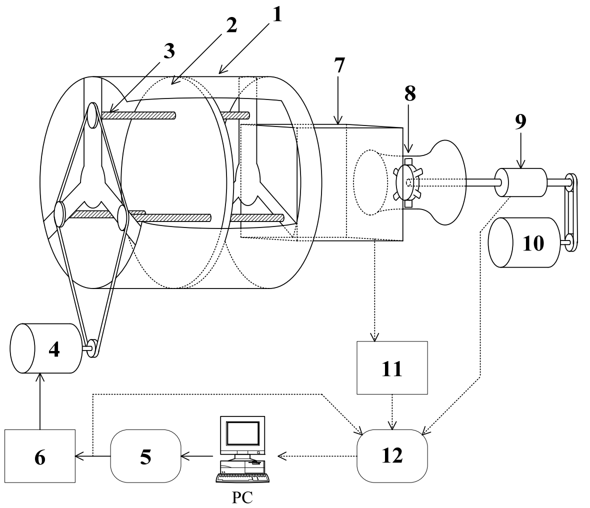
TABLE I
SPECIFICATIONS OF BLADE

Shape	Profile			d/l	Abbreviation
	Hub	Mean radius	Tip		
3-dimensional	NACA0015	NACA0015	NACA0025	0.15-0.25	3D-A
	NACA0015	NACA0020	NACA0025	0.25-0.15	3D-B
2-dimensional		NACA0015		0.15	2D-15
		NACA0020		0.20	2D-20
		NACA0025		0.25	2D-25



1 Wind tunnel
2 Piston
3 Ball-screw
4 Servomotor
5 D/A converter
6 Servo-pack
7 Settling chamber
8 Turbine
9 Torque transducer
10 Servomotor-generator
11 Pressure transducer
12 A/D converter

Fig. 2 Experimental apparatus and measuring system

II. EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic view of the test rig is shown in Fig. 2. The test rig consists of a large piston-cylinder (diameter: 1.4m, length: 1.7m), one end of which is followed by a settling chamber. Turbine testing was 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 an A.C. servo-motor through chain and sprockets. A computer controls the motor, and hence the piston velocity to produce any flow velocity. The tested 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, the flow rate Q, the total pressure drop across the turbine Δp, and the turbine angular velocity ω. 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 Reynolds number based on the blade chord was approximately equal to 2.5×10^5. The uncertainty of efficiency is about ±1%. This uncertainty has been obtained by taking into account dispersions in the measurement of the physical parameters from which efficiency is obtained.

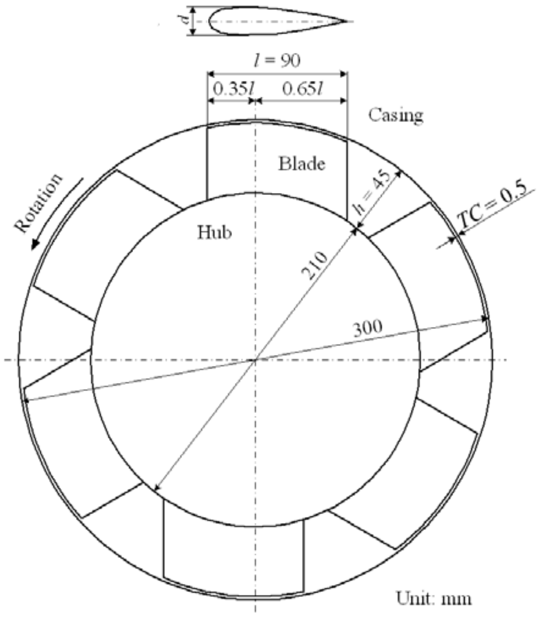
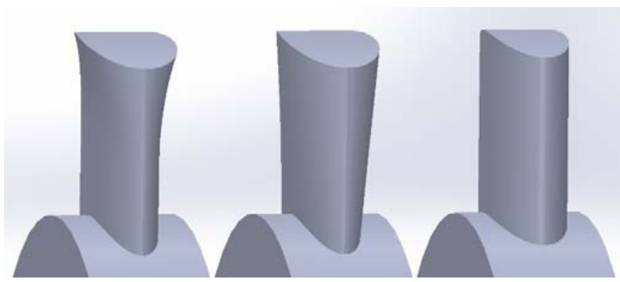


Fig. 3 Tested Wells turbine



(a) 3D-A (b) 3D-B (c) 2D-15

Fig. 4 Tested blade shape

The turbine rotor adopted in the experiments is shown in Fig. 3. The chord length, l = 90 mm; number of blades, z = 6; solidity at mean radius, σ = 0.67; hub-to-tip ratio, ν = 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, h = 45 mm. Note that the adopted turbine rotor is the most promising one in previous studies [1], [4]-[6].

The profile of 3D blade changes gradually from hub to tip in the study, as shown in Fig. 4 and Table I. Two types of 3D blades are used in the study. One is that the blade thickness is constant from the hub to mean radius and increases with radius from mean radius to tip. In this case, the blade profiles are NACA0015 from the hub to tip and NACA0025 at tip. This blade is named 3D-A in the paper. Another is that the blade thickness increases linearly with radius from hub to tip [4]. This blade has the profiles of NACA0015 at hub, NACA0020 at mean radius and NACA0025 at the 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 in the study. The details of 2D blade are shown in Table I.

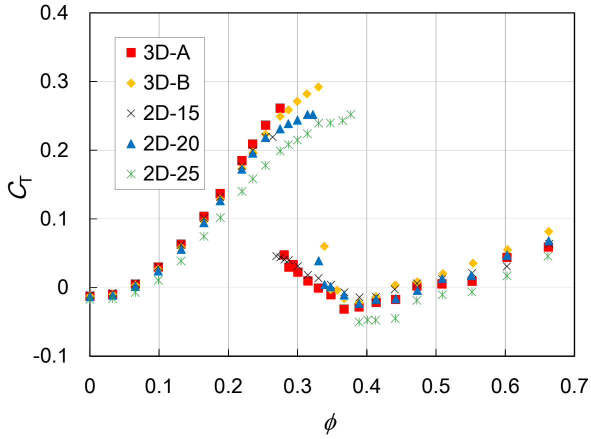
III. Experimental Results and Discussions

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

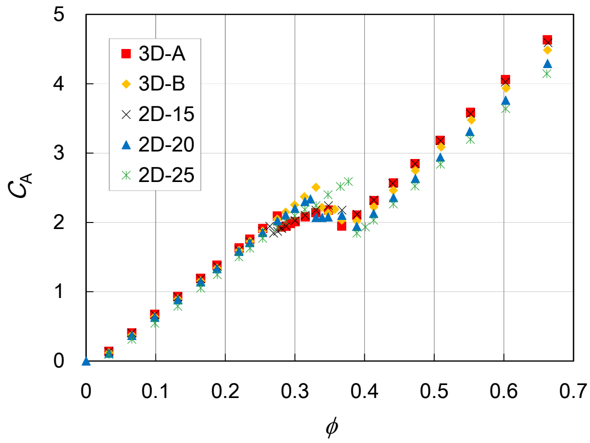
$$C_T = T/\{\rho(v^2+u^2)Ar/2\} \quad (1)$$
$$C_A = \Delta pQ/\{\rho(v^2+u^2)Av/2\} = \Delta pQ/\{\rho(v^2+u^2)/2\} \quad (2)$$
$$\eta = T\omega/(\Delta pQ) = C_T/(C_A\phi) \quad (3)$$
$$\phi = v/u \quad (4)$$

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

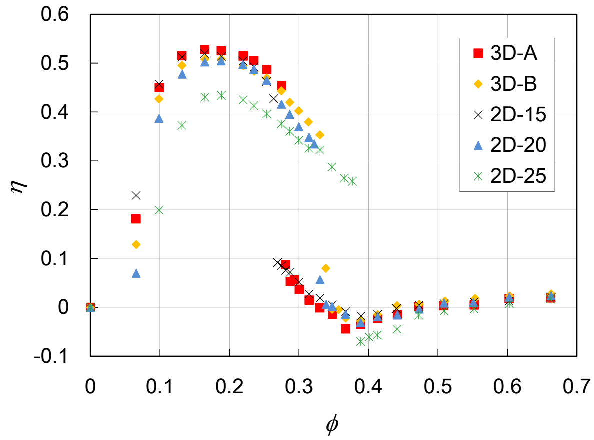
Fig. 5 and Table II show the experimental results of the effect of blade shape on the turbine characteristics. As shown in Fig. 5 (a), in the region of flow coefficient, which is smaller than the stall point, the torque coefficient C_T of 2D blade decreases gradually with the increase of blade thickness and C_T of 3D-A is slightly higher than that of the case of 2D-15. The input coefficient C_A in the same region in Fig. 5 (b) also decreases with the increase of blade thickness in the cases of 2D and C_A of 3D cases is almost the same to the case of 2D-15. However, the stall point increases with the blade thickness. The stall point in the case of 3D-A is almost the same to 2D-15 and smaller than that of 3D-B, as shown in Fig. 5 (a) and Table II. The stall points of 3D-A, 3D-B, 2D-15, 2D-20 and 2D-25 are 0.275, 0.330, 0.264, 0.322 and 0.377, respectively. From Fig. 5 (c) and Table II, the highest efficiency is obtained by 3D-A and the peak efficiencies of 3D-A, 3D-B 2D-15, 2D-20 and 2D-25 are 0.528, 0.508, 0.519, 0.505 and 0.434, respectively. Therefore, in the study, both the peak efficiency and the stall point in the case of 3D blade depend on the profile at mean radius in comparison with the profiles of the hub and tip.



(a) Torque coefficient



(b) Input coefficient



(c) Efficiency

Fig. 5 Effect of blade shape on turbine characteristics

TABLE II
PEAK EFFICIENCY AND STALL POINT

Blade shape	Peak efficiency	Stall point
3D-A	0.528	0.275
3D-B	0.508	0.330
2D-15	0.519	0.264
2D-20	0.505	0.322
2D-25	0.434	0.377

IV. CONCLUSIONS

In this study, the effects of a 3-dimensional (3D) blade on turbine characteristics has been investigated experimentally by model testing under steady flow conditions, in order to enhance the performance of Wells turbine for wave energy conversion,. As a result, it is concluded from the results that Wells turbine can be improved by using the proposed novel blade “3D-A” (see Fig. 4 and Table I) which the blade thickness is constant from the hub to mean radius and increases with radius from the mean radius to tip, when compared to the conventional blade shape. However, the new blade shape does not overcome the weak point of severe stalling.

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