A Comparison of Performances of Turbines for Wave Power Conversion

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A number of self-rectifying air turbines for wave power conversion have been proposed so far. This paper shows the comparison of the performances of all these turbines proposed for use in the near future. As a result, the impulse turbine with self-pitch-controlled guide vanes is found to have the best performance.

Keywords: Wells turbine, Impulse turbine, Wave power conversion, Natural energy, Ocean energy, Fluid machinery

INTRODUCTION

A Wells turbine is a self-rectifying air turbine which is expected to be widely used in wave energy devices with oscillating water–air-column. There are many reports which describe the performance of the Wells turbine both at starting and at running conditions (Inoue *et al.*, 1988; Raghunathan and Tan, 1982). According to these results, the Wells turbine has inherent disadvantages: lower efficiency, poorer starting and higher noise level in comparison with conventional turbines. In order to overcome these weak points, many kinds of turbines have been proposed (Takao and Setoguchi, 1996; Inoue *et al.*, 1989; Setoguchi *et al.*, 1990; 1996). However, the comparison of characteristics of all these has not yet been made so far.

The objective of this paper is to compare the performances of turbines, those that could be used for wave power conversion in the near future. The types of turbine included in the paper are as follows: (a) Wells turbine (Inoue *et al.*, 1988); (b) Wells turbine with guide vanes (Takao and Setoguchi, 1996); (c) Turbine with self-pitch-controlled blades (Inoue *et al.*, 1989); (d) Biplane Wells turbine with guide vanes (Setoguchi *et al.*, 1990) and (e) Impulse turbine with self-pitch-controlled guide vanes (Setoguchi *et al.*, 1996).

The present status of these turbines is as follows. The Wells turbine with guide vanes will be adopted for the project so-called “Mighty Whale” organized by JMSTEC, Japan (Miyazaki, 1993). The turbine with self-pitch-controlled blades is connected with the “Azores Pilot Plant” supported from the

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JOULE II (Falcão *et al.*, 1993), where the turbine has pitch-controlled blades. The project using the biplane Wells turbine is making progress in Islay, UK (Falcão *et al.*, 1993), where the guide vanes are not used for the turbine. The impulse turbine with self-pitch-controlled guide vanes will be constructed by NIOT, India (Santhakumar, 1996).

EXPERIMENTAL METHOD AND PROCEDURE

The test rig consists of a large piston-cylinder, a settling chamber and a 300-mm-dia. test section with a bellmouthed entry and a diffuser exit (Fig. 1) (Inoue *et al.*, 1988; 1989; Takao and Setoguchi,

1996). The turbine rotor with $v = 0.7$ was placed at the center of the test section and tested at a constant rotational speed under steady flow conditions. The test Reynolds number was about 1.5×10^5 based on the relative inlet velocity and chord length of the rotor blade at mean radius. The performance was evaluated by T , Q , ω and Δp . The uncertainties in torque coefficient C_T and input coefficient C_A are $\pm 2\%$, respectively.

The details of turbines adopted in the experiment are as follows: (a) Wells turbine (Fig. 2), NACA0020, $AR = 0.5$, $l_r = 90$ mm and $\sigma_{rR} = 0.79$; (b) Wells turbine with guide vanes (Fig. 3), NACA0020, $AR = 0.5$, $l_r = 90$ mm, $\sigma_{rR} = 0.67$ and $\sigma_{gR} = 1.25$; (c) Turbine with self-pitch-controlled blades (Fig. 4), NACA0020, $AR = 0.5$, $l_r = 90$ mm,

1 Cylinder	9 Turbine
2 Piston	10 Torque transducer
3 Ball-screw	11 Servomotor-generator
4 Servomotor	12 Pressure transducer
5 D/A converter	13 A/D converter
6 Micro-computer	14 Micro-computer
7 Potentiometer	15 Test section
8 Servo-pack	16 Settling chamber

FIGURE 1 Outline of experimental apparatus.

FIGURE 2 Wells turbine: Turbine (a).

FIGURE 3 Wells turbine with guide vanes: Turbine (b).

FIGURE 4 Turbine with self-pitch-controlled blades: Turbine (c).

$\sigma_{TR} = 0.67$ and preset angle of 6° ; (d) Biplane Wells turbine with guide vanes (Fig. 5), NACA0020, $AR = 0.5$, $l_r = 90$ mm, $\sigma_{TR} = 0.45$ and $\sigma_{GR} = 1.25$ and (e) Impulse turbine with self-pitch-controlled guide vanes (Fig. 6), $t_a/S_r = 0.4$, $l_r = 54$ mm, $\gamma = 60^\circ$, $a/b = 3$, $\sigma_{TR} = 2.02$, $\sigma_{GR} = 2.27$, $\theta_1 = 17^\circ$, $\theta_2 = 72.5^\circ$ and $\lambda = -7.5^\circ$. Note here that the geometries considered for these turbines are the ones found to be most promising in the previous studies (Inoue *et al.*, 1988; 1989; Takao and Setoguchi, 1996; Setoguchi *et al.*, 1990; 1996). Furthermore, all of them can start (Inoue *et al.*, 1986) by themselves. Hereafter we will call the turbines shown in Figs. 2–6 as turbines (a)–(e), respectively.

FIGURE 5 Biplane Wells turbine with guide vanes: Turbine (d).

EXPERIMENTAL RESULTS AND DISCUSSIONS

The performance of the turbine is represented by torque coefficient C_T and input coefficient C_A . The variations of C_T and C_A are shown against ϕ in Fig. 7. It is clear that the decrease in C_T due to the stall is observed in the cases of turbines (a)–(d), and the largest flow coefficient at stall point is obtained by turbine (c). On the other hand, there exists no abrupt drop in C_T for turbine (e). This is because there is no stall for the impulse turbine, and means that the starting and transitional characteristics to running condition are improved in the case of turbine (e). Figure 7(b) shows that the C_A is larger in the case of turbines (a) and (b) than those of turbines (c)–(e) over the whole range of ϕ . This means that the thrust generated by the turbine becomes large for the turbines (a) and (b).

In order to compare the performances of the turbines under unsteady flow conditions, the numerical calculation was carried out. The equation of motion for the rotating system of a turbine

FIGURE 6 Impulse turbine with self-pitch-controlled guide vanes connected by links: Turbine (e): (a) schematic view; (b) details of turbine.

FIGURE 7 Turbine characteristics under steady condition: (a) torque coefficient; (b) input coefficient.

in a sinusoidally reciprocating flow is written in a nondimensional form (Inoue *et al.*, 1986) as follows:

$$S^2 X_I (d\omega^*/dt^*) + X_L = 2C_T \sigma_{rR} \frac{1-\nu}{1+\nu} \left\{ \sin^2(2\pi t^*) + \frac{1}{\Phi^2} \right\}. \quad (1)$$

Equation (1) can be solved numerically as an initial problem when C_T and a wave motion are given.

This gives the starting characteristics of the turbine at the beginning and the running characteristics in an asymptotic condition. When the solution is in the asymptotic condition, the turbine performance can be obtained by mean efficiency defined by:

$$\bar{\eta} = \left(f \int_0^{1/f} T\omega dt \right) / \left(f \int_0^{1/f} \Delta p Q dt \right). \quad (2)$$

In the calculation, the flow conditions are assumed to be quasi-steady. Furthermore it is assumed, for simplicity, that there is no delay in the behavior of rotor blades (Fig. 4) (Inoue *et al.*, 1989) and guide vanes (Fig. 5) (Setoguchi *et al.*, 1996), that is, they turn instantaneously to the required orientation corresponding to the flow direction.

Figure 8 presents the comparison of mean efficiency for the five turbines noted above. The efficiency of the impulse turbine (turbine (e)) is higher over the wider range of Φ in comparison with the Wells-type turbines.

FIGURE 8 Comparison of mean efficiency.

FIGURE 9 Comparison of starting characteristics.

The calculated starting characteristics for the five turbines are shown in Fig. 9. The turbine (e) can start in a very short time. Moreover, the rotating speed while in operation is much smaller than those of others. Therefore, it may be possible to design an excellent turbine due to low relative speed, which is desirable from the viewpoints of noise reduction and mechanical advantage.

CONCLUDING REMARKS

The self-pitch-rectifying air turbines for wave power conversion proposed so far were tested from a viewpoint of usefulness. As a result, the impulse turbine with self-pitch-controlled guide vanes is the recommended one.

NOMENCLATURE

AR	aspect ratio
a, b	radii of ellipse for impulse turbine rotor
C_A	input coefficient = $\Delta p Q / (\rho h l_r v_a w_1^2 z / 2)$
C_T	torque coefficient = $T / (\rho h l_r r_R w_1^2 z / 2)$
f	frequency of wave motion
h	blade height
I	moment of inertia of rotor
l_r	chord length of rotor
Q	flow rate
r_R	mean radius
S	nondimensional frequency = $f r_R / V_a$
t	time
t_a	width of flow path
t^*	nondimensional time = $t f$
T	output torque
T_L	loading torque
U_R	circumferential velocity at r_R
v_a	axial velocity
V_a	maximum value of v_a
w_1	relative velocity at inlet
X_I	nondimensional moment of inertia = $I / (\pi \rho r_R^5)$
X_L	nondimensional loading torque = $T_L / (\pi \rho r_R^3 V_a^2)$

z	number of blades
Δp	total pressure drop across turbine
$\bar{\eta}$	mean efficiency
θ_1	setting angle of upstream guide vane
θ_2	setting angle of downstream guide vane
v	hub-to-tip ratio
λ	sweep angle
ρ	density of air
σ_{gR}	chord/space ratio of guide vane at r_R
σ_{rR}	chord/space ratio of rotor at r_R
ϕ	flow coefficient = v_a/U_R
Φ	flow coefficient = V_a/U_R
ω	angular velocity of rotor
ω^*	nondimensional angular velocity = ω/f

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