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Tidal Current Power Generation by a Darrieus Type Water Turbine at the Side of a Bridge Pier

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Abstract. There are several advantages to make use of a bridge pier for the tidal power generation. Current velocity increases near the pier, therefore the tidal power generation becomes more efficient because the power is proportional to the cubic of the current velocity. The pier is convenient for access and maintenance of the hydraulic turbine and the power unit. The project is now underway at the Ikitsuki Bridge in Tatsuno-Seto Strait of Nagasaki Prefecture, where the tidal current was measured by the bottom mount ADCP for almost one year. Model experiments for a Darrieus water turbine with two and three straight blades were carried out in the circulating water channel, in which the power coefficients of the turbine were obtained as a function of blade section and the attaching angle of a blade to the rotor. Those experimental results are discussed to obtain an optimum Darrieus turbine for tidal power generation.

INTRODUCTION

Promotion of the utilization of natural energy is urgent as a countermeasure against the global warming. There are several kinds of energy resources in the ocean but the utilization of the ocean energy is far behind the other natural energies such as wind, solar, ground thermal, small and medium hydraulic plants and biomass. Since the density of water is 800 times greater than air density and the power of the flow is proportional to cubic of the fluid, the power of ocean current of 2 knots is equal to the wind flow of 9m/s. There are some narrow channels in Japan such as Naruto channel, where the maximum current velocity is about 10 knots and the total power of the current is enormous. It is appropriate to propose this kind of project of the utilization of ocean current for the reduction of carbon dioxide.

There are many good locations for the tidal power generation, for example, Naruto Channel, Kurushima Channel and Kannmon Channel in Japan. We propose a tidal power generation making use of a bridge pier, since there are several advantages for the tidal power generation. Current velocity increases near the pier, therefore the tidal power generation becomes more efficient because the power is proportional to the cubic of the current velocity. The pier is convenient for the maintenance of the hydraulic turbine and the power unit. Furthermore, the initial cost of the infrastructure needed for the tidal power unit can be reduced. We think that there are many good sites for tidal power generation making use of a bridge pier in Japan.

The project being underway at the Ikitsuki Bridge in Tatsuno-Seto Strait of Nagasaki Prefecture is introduced and the data of the current measured by a bottom mount ADCP (Acoustic Doppler Current Profiler) is presented. We plan to install a submerged Darrieus turbine by the side of a bridge pier. Model test results of the self-starting torque and the power coefficient of the Darrieus turbine carried out in the circulating water tank are presented in this report.

TIDAL CURRENT POWER GENERATION AT IKITSUKI BRIDGE

Ikitsuki Bridge is a steel-truss bridge of 960m in the length, constructed across the Tatsuno-seto channel between Hirado and Ikitsuki-shima, Nagasaki Prefecture. Tastuno-seto channel is known as a narrow channel with fast current, of minimum width 700m and maximum depth 50m. Ikitsuki Bridge has two piers in the channel and was completed in 1991. The length between piers is 400m and it is the longest in the world for this kind of bridge. Bridge piers are standing on the concrete caisson underneath. The caisson of Ikitsuki-shima side is a cylinder of 25m diameter and 23m height, buried in the sandy seabed. The bridge pier is a pillar of 18m length and 7m breadth which is installed on the caisson shown in Fig.1. The mean water depth is about 7m and the sea bottom is flat because it is the top of concrete caisson.

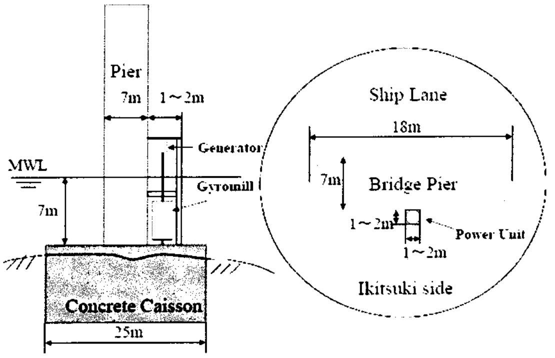

Fig.1 A Darrieus turbine, power generator and bridge pier

Flow Enhance Effect of a Pier

Let us estimate the flow enhance effect of a pier by the FEM (Finite Element Method) in the two dimensional problem.[1] The uniform flow is imposed at the left boundary at x=0. Two kinds of the boundary condition at surface of the pier are examined, which are the free-slip condition and non-slip condition.

The water turbine is planned to be installed about 1m apart from the pier in the middle of the pier. Fig.2 shows the velocity distribution in the middle of the pier. Two curves denote the results by the boundary conditions, free-slip or non-slip on the surface of the pier. The diameter of the turbine is supposed to be 2m and the turbine is installed 1m apart from the pier. The flow enhance effects of the pier is estimated as 1.4 in this case and therefore, the power of the flow is enhanced by about 2.4 because the power is proportional to cubic of the velocity.

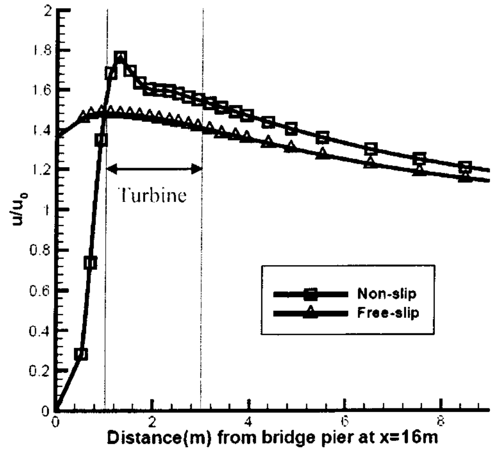

Fig.2 Velocity distribution apart from the bridge pier

FIELD MEASUREMENTS

Tidal Current

Tidal current was measured by an ADCP for more than six month from September 2005. The ADCP uses the Doppler effect to measure current velocity by transmitting a short pulse of sound, listening to its echo and measuring the change in pitch or frequency of the echo. Our ADCP uses three beams of 1MHz ultrasonic. We measured current velocity every ten minutes and we also measured the directional irregular waves by making use of the pressure and orbital velocities of waves every two hours.

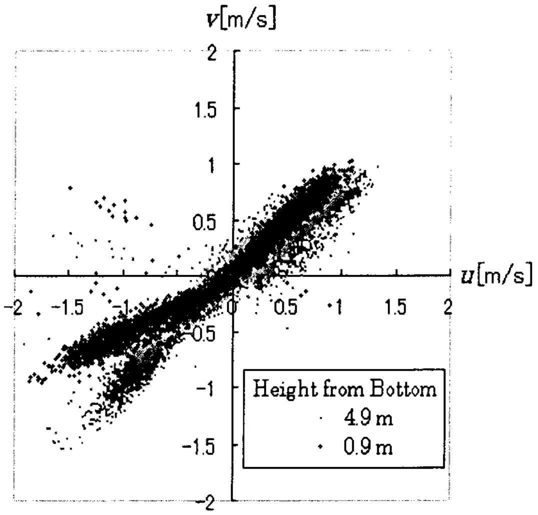

Fig.3 Hodograph of velocity measured near a pier of Ikitsuki-Bridge

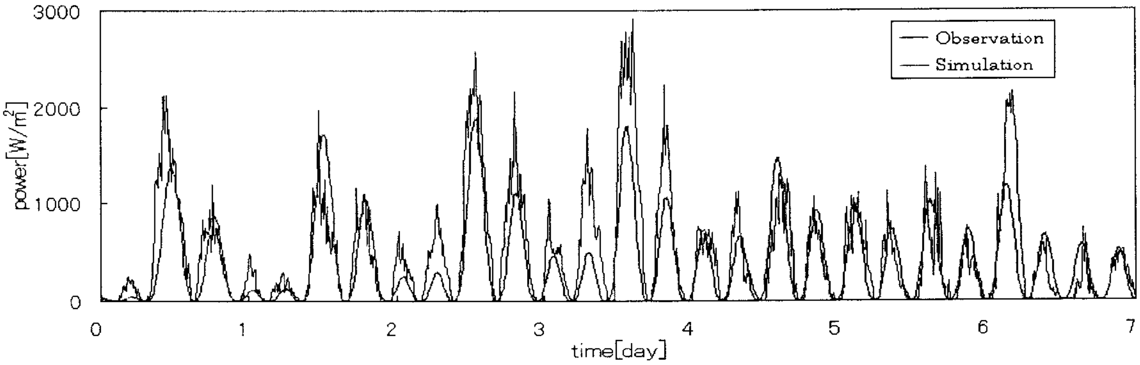

Fig.4 Comparison of the power, observation vs calculation by 4 tidal constituent velocities

Fig. 3 shows the hodograph of the current velocities of two levels at 0.9 m and 4.9m above the bottom. Hodograph data show that the current is asymmetry during the flood tide and ebb tide. Some points scattered to NW direction may be affected by the typhoon (T0514) which passed Kyushu on 6 September 2005.

Measured data were analyzed by the tidal harmonic analysis.

Tidal Current Power Estimation

Theoretical value of the tidal current power par unit sectional area (P_{th}) is given by:

$$P_{th}(t) = \frac{\rho}{2} U(t)^3 \tag{1}$$

where ρ: density of water, $U(t)$: current velocity.

Power generated by an apparatus is described by:

$$P(t) = C_P \cdot \frac{\rho}{2} \cdot A_P \cdot U(t)^3 \tag{2}$$

where C_P: power coefficient, A_P: projected area of a turbine.

Tidal current energy is obtained by integrating the power with respect to time in Fig.4. Average energy per day obtained is as follows:

$$\begin{aligned} \bar{E} &= 11.43\ (KW \cdot h/m^2/day)\ \text{:Observation} \\ \bar{E} &= 9.55\ (KW \cdot h/m^2/day)\ \text{: Calculation} \end{aligned} \tag{3}$$

From this result, we understand that the estimation by 4 tidal constituent velocities goes 15 % lower than that of observation.

Maximum power exceeds 2,000W/m^2 at the spring tide but the peak value is less than 500W/m^2 at the neap tide. This large fluctuation of the power is a disadvantage for the utilization of tidal energy, but the tidal power has an advantage over wind power because it is predictable in advance. Furthermore, if the generated electricity is used for production of the hydrogen, the problem will be resolved. The conversion of tidal energy into hydrogen is also useful for the transportation of the energy from a remote location to a city.

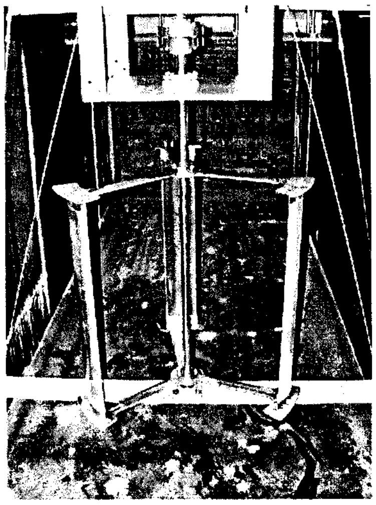

Fig.5 Experimental apparatus in the circulating water channel

MODEL EXPERIMENTS

Experimental apparatus and setup

Experiments were conducted at the circulating water channel of the Research Institute for Applied Mechanics, Kyushu University. The size of the observation section of the water channel is 1.5m in breadth and 1.2m in depth.

Fig. 5 is a photo of the experimental model of the water turbine, which size is 0.6m in diameter and 0.6m in the span length of the blade. We chose a Darrieus water turbine of two- or three-blades, considering the efficiency of the power transformation and the starting torque characteristics in the flow. We tested two wing sections shown in Fig.6 and the particular dimensions are given in Table 1, where one is NACA0018 wing of 0.08m in the chord length and another is a NACA0018 wing of 0.1m in the chord length with the circular camber, hereafter we call it as the circular camber wing.[3]

In Fig.7, we measured the counterclockwise torque, Q about the axis of the turbine in the flow. The velocity of the flow was varied from 0.5m/s to 1m/s by 0.1m/s. The rotation of the turbine was controlled by the motor and the torque on the model was measured by the torque meter.

Let the rotation of the turbine n(rpm) and the mean torque during the rotation Q(N-m), then the torque coefficient and power coefficient are given by:

$$C_Q = \frac{Q}{0.5\rho U^2 rA}, \quad C_P = \frac{Q\omega}{0.5\rho U^3 A} \tag{4}$$

where $\omega = 2\pi n/60$ (rad/s)

The attachting angle of the blade was changed as 0(deg), ± 5(deg), ± 10(deg), where 0 deg. means that the blade was circumscribed to the rotational circle. Plus sign of attaching angle means the nose up of the blade. Torque acting on the turbine with one and three blades was measured for the cases of wing speed ratio, $\lambda = R\omega / U$ is 0, 1.0, 1.5, 2.0, 2.5 and 3.0.

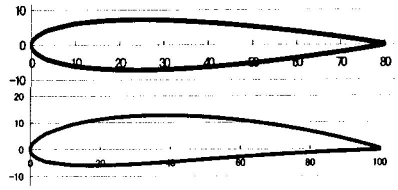

Fig.6 Wing sections (NACA0018 and NACA0018 with circular camber)

Table 1 Dimensions of the blade section

	NACA0018	NACA0018-C
Chord (C) (m)	0.08	0.1
Span (S) (m)	0.6	0.6
Camber	Non	Circular
Solidity (2-Blades)	0.085	0.106
Solidity (3-Blades)	0.127	0.159
material	wood	Aclyl

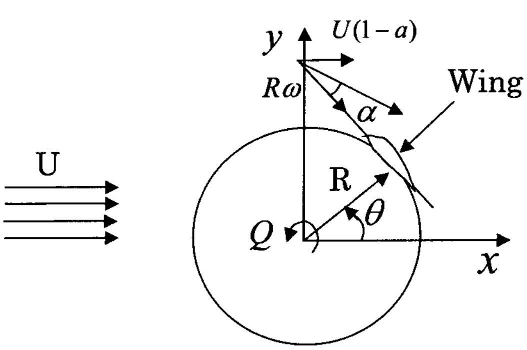

Fig.7 Torque about the origin by a rotating wing

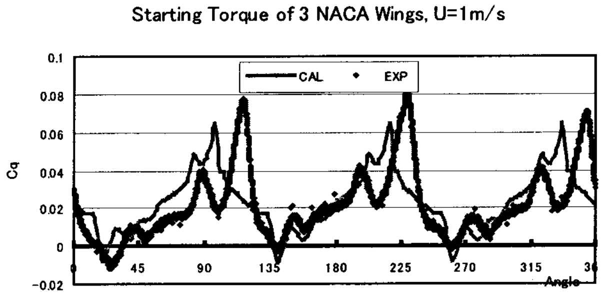

Fig.8 Starting torque of three NACA0018 wings

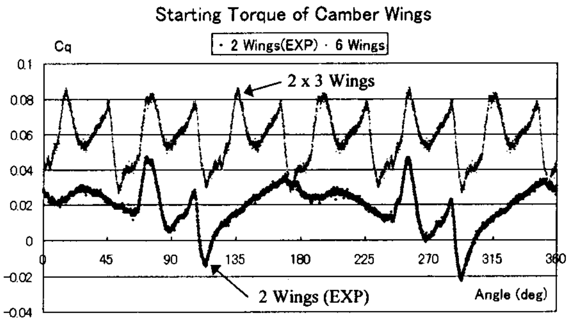

Fig.9 Starting torques of 2 and 2×3 blades turbine

Torque characteristics

A Darrieus water turbine is know as high performance turbine because it is making use of the lift generated by the rotating wing in the flow. But, there is one shortcoming regarding the starting torque.

Fig. 8 shows the starting torque of the turbine with three NACA0018 blades. The attaching angle of the blade is 0 degree. From the symmetry relation, we have 3 cylic wave forms in a rotation. This turbine will stop near angles, 30, 140 and 260 degrees since the negative torque is appeared there. The calculation curve based on the single stream tube theory[2] agrees well with experiments.

Fig.9 shows the starting torque of two and 2×3 wings, which we plan to make three stages of a turbine with 2 blades for the practical experiments in the sea. From this result for 2×3 wings, we can expect the smooth starting of the rotation from the resting condition.

Fig.10 shows the torque variation by one blade of NACA0018 rotating at several velocity ratios, λ. When λ is less than 2, negative torque occures around 120 deg., but the torque shifts to positive as λ increases.

Fig.11 shows the torque variation by three blades of NACA0018 rotating at several velocity ratios. In this case, negative torque does not occur for all angles. Torque shifts to positive and the variation of torque decreases as λ increases. Mean torque over the rotation takes maximum value at $\lambda = 2.0$.

The variation of torque by the single stream tube theory does not agree with the measurements in this case. We want to solve this moving boundary problem by a direct numerical approach in near future.

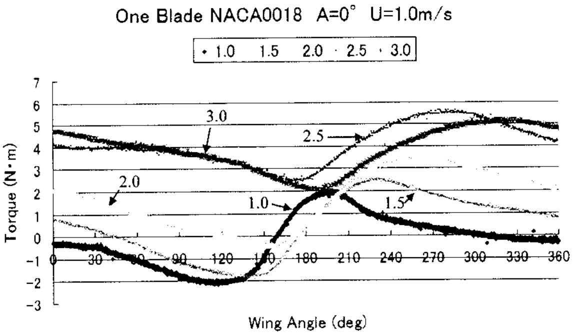

Fig.10 Torque variations of one blade of NACA0018 turbine for several wing velocity ratios

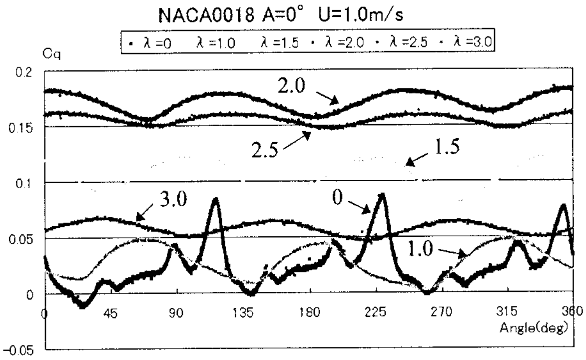

Fig.11 Torque variation of three blades of NACA0018 turbine for several wing velocity ratios

Power coefficient

Fig.12 shows the power coefficients of the turbine with three NACA0018 wings of several attaching angles to the rotor. It is obvious that the attaching angle effect is important on the power coefficient. Optimum attaching angle depends on the velocity ratio, it is 0 degree when λ is smaller than 2 but +5 degree when λ is greater than 2. Maximum power coefficient is attained to $C_P = 0.41$ when $\lambda = 2.3$. This figure is 30% higher than the maximum performance of the similar Darrieus wind turbine, which may be attributed by the blockage effects of the circulating water channel used in our experiments.

Fig.13 shows the power coefficients of the turbine with three circular camber wings. In this case, results of + 5 degree are superior in wide range of λ, the maximum power coefficient is attained to $C_P = 0.42$ when $\lambda = 2.0$. It is interesting that the maximum performance occurs at defferent λ depending on the attaching angle. Comparing with the results of NACA0018 wings, the turbine with circular camber wings of +5 degree attaching angle is recommended for three blades turbine.

Finally, Fig.14 shows the comparison of the power coefficients of the turbine with 2- and 3-blades, for 0 and +5 degrees in attaching angles. Maximum performance for 2-blades turbine is attained to $C_P = 0.42$ at $\lambda = 2.6$, which is the same parformance at $\lambda = 2.0$ by the 3-blades turbine. But, the 2-blades turbine is more advantageous since the higher rotation is preferable for the higher performance of the electric generator.

CONCLUSIONS

We are now conducting three years project of the tidal current generation at a pier of Ikitsuki-bridge of Nagasaki Prefecture, Japan. We have measured tidal current and waves by a bottom mount ADCP at the site for almost one year. From the observation and numerical simulation, we understand that the power of tidal current fluctuates much responding to the flood or ebb tide because the power is proportional to the cubic of the current velocity.

We have studied about the hydrodynamics of the Darrieus turbine experimentally. We understand the mechanism of torque generation by the rotating wings through theory and experiments. The single stream tube theory is good for the estimation of self-starting torque, but it is difficult for the power coefficient of the Darrieus turbine. We finally adopted three stages Darrieus turbine with two blades of circular camber section, 2m in diameter, 1m in span length, the phase of blade is shifted by 120 degree in each stages for the practical experiments in the sea, which is start from November in 2006.

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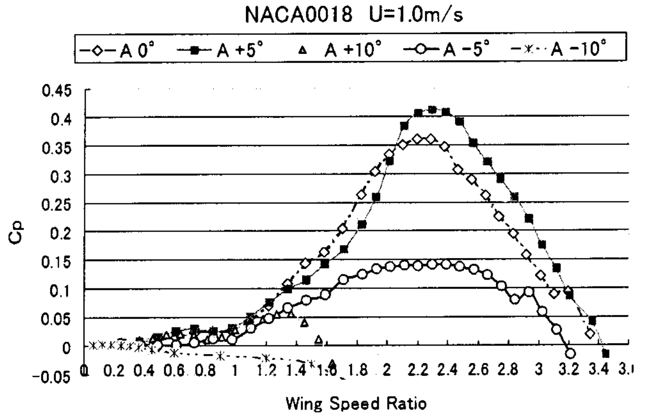

Fig.12 Power coefficients of 3-blades turbine with NACA0018 wing in several attaching angles

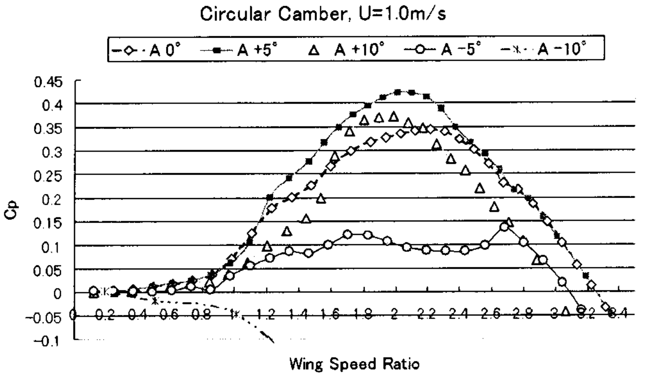

Fig.13 Power coefficients of 3-blades turbine with circular camber wing for several attaching angles

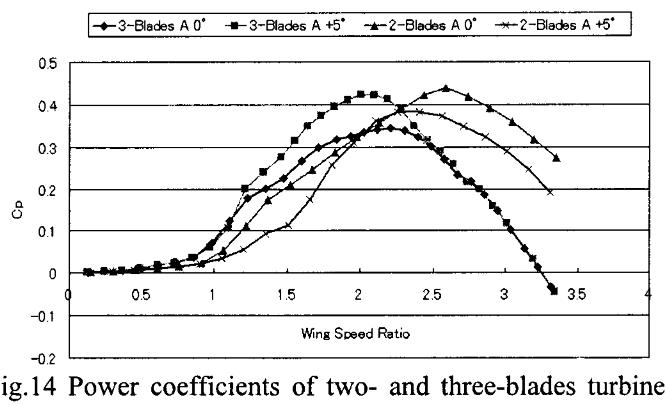

Fig.14 Power coefficients of two- and three-blades turbines with different attaching angles