Development of advanced wave power generation system by applying gyroscopic moment

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Abstract

Authors have been developing a pure mechanical wave power generation system. The principle of the system is the application of the gyroscopic moment produced by the rotation of large flywheels and the swing of a float excited by wave motion. This paper presents the principle of the system, the developing process of prototype systems and their test results. It was confirmed that the system has higher efficiency than conventional OWC wave power generation systems and sufficient reliability for actual application. The system will be applicable for distributed electric source for small island and ports.

Keywords: Wave power generator, Renewable energy, Gyroscopic moment

Nomenclature

C_f	=	Damping coefficient of float by wave generation
C_g	=	Damping coefficient of gimbal
C_z	=	Damping coefficient of float around z axis
G	=	Lateral moment of inertia of gimbal
G_P	=	Poler moment of inertia of gimbal
I	=	Lateral moment of inertia of float
I_P	=	Poler moment of inertia of float
I_f	=	Additional lateral moment of inertia by water
J	=	Lateral moment of inertia of flywheel
J_P	=	Poler moment of inertia of flywheel
K_f	=	Spring constant of float
M_ϕ	=	Input torque around x axis from wave
M_θ	=	Input torque around y axis from wave
T_ζ	=	Input torque for generator
ϕ, θ, ψ	=	Float angular coordinate
ζ	=	Gimbal angular coordinate
ω_s	=	Angular velocity of flywheel

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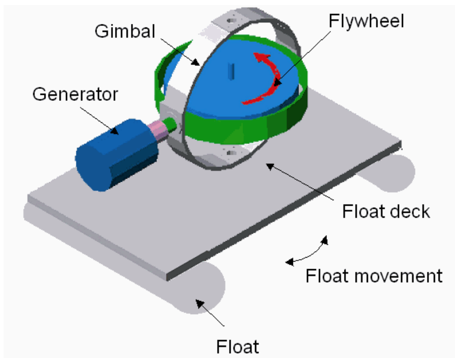
1 Introduction

The importance of renewable energy has been recognized and many kinds of generation systems have been developed and applied. Wave power generation systems are one of the developing systems for this purpose. Many



Waves excite the float.
↓
The float gets angular velocity.
↓
The gimbal of gyro gets the angular velocity.
↓
The gyro produces large gyro moment.
↓
The gyro moment drives the generator in synchronized and phase locked condition.
↓
Electric power is generated.

Figure 1: Principle of gyro wave power generation system

kinds of wave power generation systems were invented and tested [1, 2, 4, 5]. Every system has it's own characteristics and merits and demerits. Practical applications are still under way due to high cost and many social restrictions.

Authors have been developing a pure mechanical wave power generation system having high efficiency and a compact float compared to conventional OWC systems. The principle of the system is the application of the gyroscopic moment of flywheels equipped on a swing float excited by waves. This paper presents the principle, the history of the development, and the field test results of this gyro wave power generation system.

2 Gyro wave power generation system

2.1 Principles of gyro system

The function of this system is shown in Figs. 1 and 2. This system is a kind of a rectifier of kinetic energy of a float excited by waves.

The equations of motion of the system are given via Lagrange equation as follows.

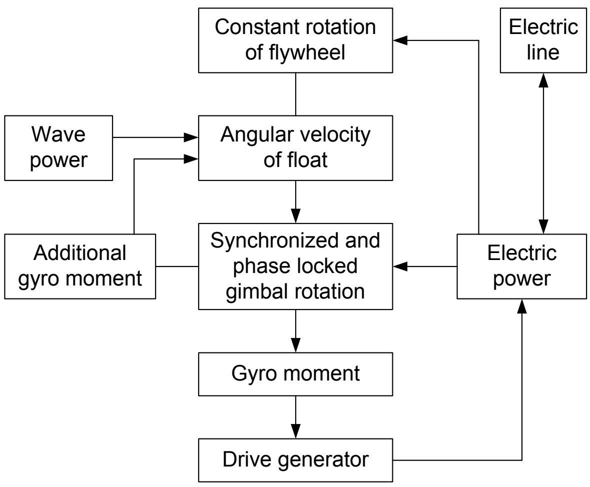


Figure 2: Operation of gyro wave power generation system

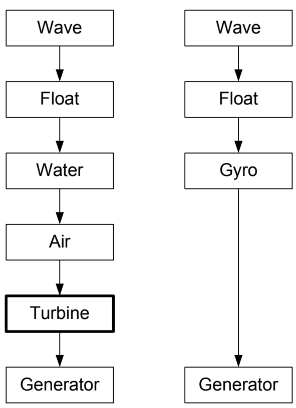


Figure 3: Comparison between OWC and gyro wave power generator

$$
\begin{aligned}
&I\ddot{\phi} + C_f\dot{\phi} + K_f\phi = M_\phi + J_P\omega_s(\dot{\psi}+\dot{\zeta})\sin(\psi+\zeta)\\
&I\ddot{\theta} + C_f\dot{\theta} + K_f\theta = M_\theta - J_P\omega_s(\dot{\psi}+\dot{\zeta})\cos(\psi+\zeta)\\
&I_P\ddot{\psi} + C_z\dot{\psi} = J_P\omega_s\{\dot{\phi}\sin(\psi+\zeta)+\dot{\theta}\cos(\psi+\zeta)\}\\
&(J+G)\ddot{\zeta} + C_g\dot{\zeta} = T_\zeta\\
&\qquad + J_P\omega_s\{\dot{\phi}\sin(\psi+\zeta)+\dot{\theta}\cos(\psi+\zeta)\}
\end{aligned} \tag{1}
$$

In these equations, the external moments M_ϕ, M_θ are given by the relative motion of the float and the wave. Then the moments are given by the following equations.

$$
\begin{aligned}
M_\phi &= I_f(\ddot{\bar{\phi}}-\ddot{\phi})+C_f(\dot{\bar{\phi}}-\dot{\phi})+K_f(\bar{\phi}-\phi)\\
M_\theta &= I_f(\ddot{\bar{\theta}}-\ddot{\theta})+C_f(\dot{\bar{\theta}}-\dot{\theta})+K_f(\bar{\theta}-\theta)
\end{aligned} \tag{2}
$$

In these equations, the appointed gyroscopic moments are given in the following terms.
Moment around x axis : $J_P\omega_s(\dot{\psi}+\dot{\zeta})\sin(\psi+\zeta)$
Moment around y axis : $-J_P\omega_s(\dot{\psi}+\dot{\zeta})\cos(\psi+\zeta)$
Moment around z axis :
$J_P\omega_s\{\dot{\phi}\sin(\psi+\zeta)+\dot{\theta}\cos(\psi+\zeta)\}$
Moment around z axis on generator:
$J_P\omega_s\{\dot{\phi}\sin(\psi+\zeta)+\dot{\theta}\cos(\psi+\zeta)\}$

In these moments, the effective moment for power generation is given by the following equation.

$$T = J_P\omega_s\{\dot{\phi}\sin(\psi+\zeta)+\dot{\theta}\cos(\psi+\zeta)\} \tag{3}$$

Output power is given by the following equation.

$$W = J_P\omega_s\dot{\zeta}\{\dot{\phi}\sin(\psi+\zeta)+\dot{\theta}\cos(\psi+\zeta)\} \tag{4}$$

In case of restricting the swing motion of the float in θ direction only, the output power is expressed as follows.

$$W = J_P\omega_s\dot{\zeta}\dot{\theta}\cos(\psi+\zeta) \tag{5}$$

Maximum output is expressed as follows.

$$|W| = J_P\omega_s|\dot{\zeta}||\dot{\theta}.| \tag{6}$$

As shown in Eqs. 5 and 6, not only the float motion but also the gimbal motion affects the output power. Therefore, in order to generate the maximum output, it is necessary to control the rotation angle of the gimbal. The another additional gyroscopic moment applies disturbance moment to the float. However, the disturbance moment can be canceled by setting the two gyro systems on the symmetrical position of the float.

2.2 Characteristics of the system

Because that the gyro system directly converts wave power into electric power as shown in Fig. 3, the gyro wave power generation system has inherently high efficiency.

The characteristics of the system are listed as follows.

- High efficiency in wide range of wave (wave high: 0.5m-4m)
- Strong float and small anchor for long wave

Table 1: History of gyro wave power generation systems

2000	Invention of the system
2001	Principle model test in Laboratory
2002	On boat test of small principle model
2003	Development of buoy type 5.5kW system
2004	5.5kW system performance test on seismic table 5.5kW system field test in Tottori port (North side of Japan)
2006	22.5kW prototype system develop
2007	22.5kW prototype system field test in Tottori port
2008	45kW prototype system development and field test in Susami port (South side of Japan)

Table 2: Specification of prototype systems

	1	2	3
Generator capacity	5.5kW	22.5kW	45kW
Total weight	7.8ton	22ton	37ton
Float size	$2.2\text{m} \times \phi 6\text{m}$	$9\text{m} \times 6\text{m} \times \phi 1.2\text{m}$	$15\text{m} \times 9\text{m} \times \phi 1.2\text{m}$
Weight of flywheel	480kg	$1.4\text{ton} \times 2$	$2.7\text{ton} \times 2$

- Long life
- No pollution and no influence for life
- Compact (0.3m/kW) and light weight (less than 1 ton / kW)
- Low construction cost
- Low maintenance cost

3 History of development

The history of the development of the gyro wave generator system is summarized in Table 1. The development has started on a small principle model, and continued to large prototype systems. The theory of the gyro system was confirmed by the principle model test.

4 Design of prototype system

Three prototype of the gyro system has been designed. Table 2 shows the main specification of each prototype system.

Figure 4 shows the No. 1 prototype. Typical test results, that is, the electric output of a generator, the rotating frequency of the gimbal, and the angular velocities of the float, are shown in Fig. 5. The principle of the gyro system was confirmed by the test results.

Figures 6 and 7 show No. 2 and No. 3 prototype, respectively.

5 Test results of No. 3 prototype

Fig. 8 shows the schematic diagram of the field test of the No. 3 prototype system.

The typical test results of the No. 3 prototype system are shown in Fig. 9. Fig. 9 presents the angular velocities of the float, the electric output, and the phase angle between the motion of the float and gimbal. The electric output more than 20kW was observed.

It is very difficult to evaluate how much the float can absorb wave power. Therefore, we assume the efficiency of the absorption of the float is equal to 1.0. The evaluated efficiency of the gyro wave generator system is listed in the Table 3 for full load condition. Table 3 shows the evaluation of the conversion efficiency of the gyro-generator part only. In this evaluation, net output is calculated as the maximum generator output minus total loss which measured by individual part operation tests. As a result, this generator system has larger than 50% efficiency for wide range of operating condition.

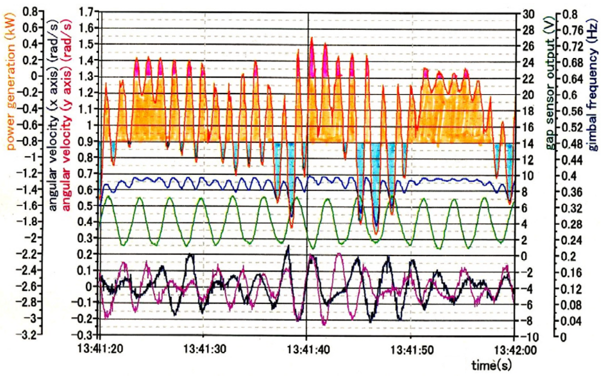


Figure 5: No.1 prototype typical test results

Figure 4: No.1 prototype system

Figure 6: No.2 prototype system

Figure 7: No.3 prototype system

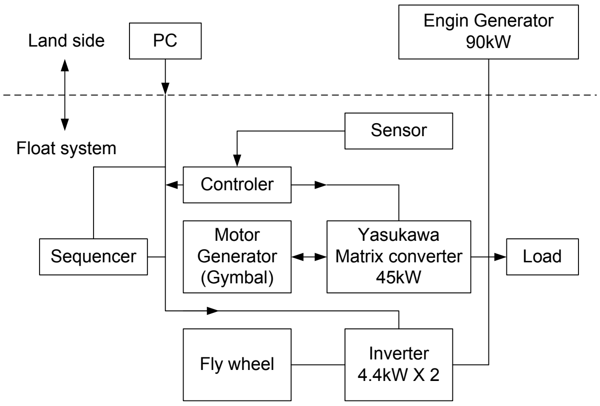


Figure 8: Schematic diagram of field test

Table 3: Efficiency evaluation without float efficiency

Generator capacity	45kW
Generator max output	67.5kW
Generator average output	33.75kW
Generator drive loss	3kW
Flywheel drive loss	3.5kW $\times$ 2
Total loss	10kW
Net total output generator	23.75kW
Converter efficiency	0.96
Net line output	22.8kW
System conversion efficiency	22.8/33.75 $\approx$ 68%

6 Application

The possible applications of this system are listed as follows.

- Energy park for demonstrate low CO2 emission power generation
- Save fuel consumption of diesel generator for isolated island
- Electric source of buoy for signal light
- Pump power source for applications such as desali na- tion unit etc.

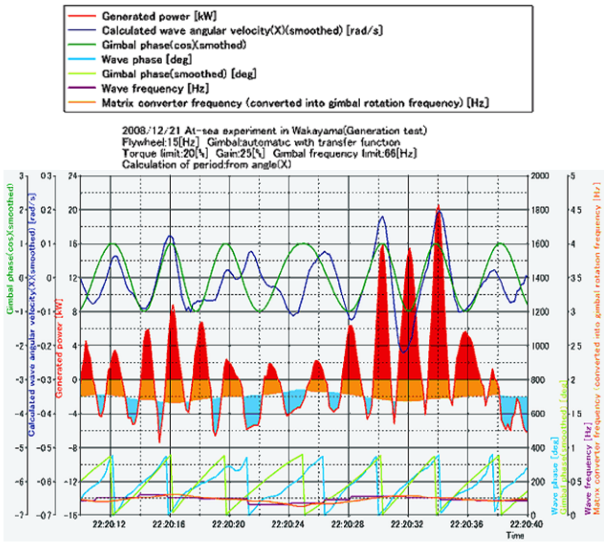


Figure 9: No.3 prototype typical test results

7 Conclusions

The development of gyro wave power generation system has been continued for 8 years. The latest prototype 45kW system has been tested and gave many important information. This system can supply the moderate quantity power application for many kind of distributed electric applications such as small islands, fisherman's ports, and also megawatt electric source for conventional electric supply by group setting of this system. The development will be continued to complete 100kW class system as target standard units.

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