Dynamics and Power Absorption of a Self-reacting Wave Energy Converter with Mechanical Motion Rectifier

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Abstract: A self-reacting wave energy converter which consists of a floating buoy and a submerged body is studied in this paper. The energy is extracted through the relative motion of the floating buoy and submerged body. The power takeoff system is a ball screw system with a mechanical motion rectifier gearbox (which is called the MMR system). The design of the proposed wave energy converter is presented and the model of the proposed system is established based on its mechanisms. A time domain method is adopted to investigate the dynamics and power absorption for the proposed wave energy converter. The effect of equivalent mass on the optimal power and corresponding optimal power takeoff damping are studied in regular waves. Due to the disengagement in the MMR system, the equivalent mass helps to increase the power absorption at small wave periods. The effect of uncertainty of the drag coefficient on the power absorption of the MMR system is also investigated.

Keywords: Wave Energy Converter, Power Takeoff, Mechanical Motion Rectifier

1. Introduction

The self-reacting wave energy converter has been investigated significantly in recent years [1, 2]. The power takeoff system used in the self-reacting wave energy converter can be a hydraulic system [1] or mechanical system [2]. In this paper, a self-reacting wave energy converter with a mechanical motion rectifier (MMR) is proposed and investigated. The MMR can convert the bidirectional input rotation into unidirectional output rotation by using two one-way bearings in the gear system. It has been applied in several projects [3-5] for energy harvesting and proved to be effective.

The first objective of this paper is to present the design of a self-reacting wave energy converter with a MMR. The second objective is to establish the model of the proposed MMR wave energy converter by considering essential nonlinearities in the system.

The rest of this paper is organized as follows, in Section 2, the design of a self-reacting wave energy converter with mechanical power takeoff system is presented. The model of the MMR and a self-reacting wave energy converter oscillating in heave with the proposed power takeoff system is established in Section 3 and 4. The power absorption of the proposed MMR system under regular wave excitation is studied in Section 5. The conclusions are given in Section 6.

2. Design of a Self-reacting Wave Energy Converter with Mechanical Power Takeoff

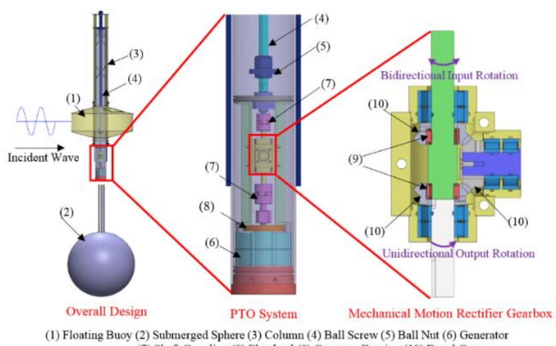

Figure 1. Configuration of the proposed self-reacting wave energy converter with mechanical power takeoff system

Figure 1 shows the configuration of the proposed self-reacting wave energy converter with the MMR. The key components are listed in the figure as well. The energy is extracted from the relative motion of these two bodies. A ball screw is used in this system to convert the relative linear motion into bidirectional rotation of the screw. The MMR gearbox is connected to the lower end of the screw and converts the bidirectional input rotation of the screw into unidirectional rotation of the generator. The mechanism of the MMR gearbox is also presented in Figure 1. Two one-way bearings are installed in opposite directions on the input and output shaft, each of which allows the motion transfer in one direction. In this way, the birdirection motion of the input shaft is converted into unidirectional rotation of the output shaft.

3. Modeling of a Mechanical Motion Rectifier based Power Takeoff System

The schematic of the proposed power takeoff system with a mechanical motion rectifier gearbox is shown in Figure 2. The ball nuts in Figure 2 moves back and forth along the screw and drives the screw in a bidirectional rotation under external excitation$F$. Through the engagement and disengagement of the two one-way bearings in the MMR gearbox, the output shaft rotates in one direction. Thus, the equation of motion of the MMR power takeoff system can be concluded as following.

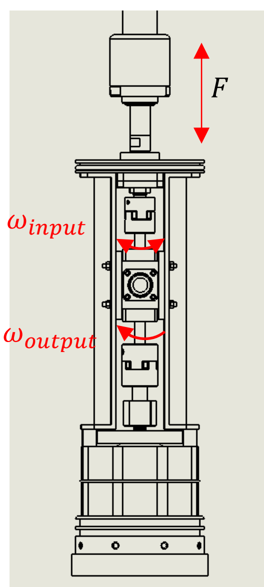

Figure 2. Schematic of the power takeoff system with mechanical motion rectifier

When $\omega_{output} = \dot{x}_{nut} n_g$(the rotation speed of output shaft ω_{output} is equal to the rotation speed of input shaft $\dot{x}_{nut} n_g$), the system is engaged and the equation of motion can be expressed as,

$$(m_{nut} + m_e)\ddot{x}_{nut} = F - c_e \dot{x}_{nut} \qquad (1)$$

When $\omega_{output} > \dot{x}_{nut} n_g$ (the rotation speed of output shaft ω_{output} is larger than the rotation speed of input shaft $\dot{x}_{nut} n_g$), the system is disengaged and the rotational generator is decoupled with the driving ball screw system. Therefore, the equation of motion of disengaged system consists of two decoupled equations as following,

$$\begin{cases} m_{nut}\ddot{x}_{nut} = F \\ m_e \dot{\omega}_{output} + c_e \omega_{output} = 0 \end{cases} \qquad (2)$$

where, in Eq. (1) and (2), m_e is the equivalent mass and c_e is equivalent damping of the MMR system, which are defined with the following equation,

$$\begin{cases} m_e = (J_{fw} + J_{ge}) n_g^2 \\ c_e = \frac{k_t k_e n_g^2}{(R_i + R_e)} \end{cases} \qquad (3)$$

where,

- m_n is the mass of the nut.
- x_{nut} is the displacement of the nut.
- ω_{output} is the output rotational speed of the shaft.
- J_{fw} and J_{ge} are the moment of inertia of the flywheel and generator, respectively. One should notice that the moment of inertia for the shafts and gears are neglected since they are small comparing with J_{fw} and J_{ge} in reality.
- n_g is the gear ratio of the ball screw system, the gear ratio of the MMR gearbox is 1.
- k_t and k_e are generator constant.
- R_i and R_e are the internal and external resistance of the generator.

4. Modeling of a Self-Reacting Wave Energy Converter with the Mechanical Motion Rectifier

The equations of motion of the proposed self-reacting wave energy converter oscillating in heave can be written as following,

$$m_1 \ddot{x}_1 = f_e^1 + f_r^1 + f_h^1 + f_{PTO} + f_d^1 + f_m^1 \qquad (4)$$
$$m_2 \ddot{x}_2 = f_e^2 + f_r^2 + f_h^2 - f_{PTO} + f_d^2 + f_m^2 \qquad (5)$$

where,

- m_1 and m_2 are the mass of the floating and submerged body respectively.

- f_e^i, f_r^i, f_h^i are the hydrodynamics forces on the floating and submerged body obtained from linear wave theory. Since the power takeoff system is piecewise as we described. A time domain wave force is used here.
- f_{PTO} is the power takeoff force applied by the MMR.
- f_d^i is the quadratic drag force applied on the floating and submerged body.
- f_m^i is the mooring force applied on the floating and submerged body, respectively.

The model of the MMR has been built in Section. 2. Here, the power take off force from the MMR is considered as a piecewise linear force as following,

$$f_{PTO} = \begin{cases} -m_e(\ddot{x}_1 - \ddot{x}_2) - c_{pto}(\dot{x}_1 - \dot{x}_2) & Engagement \\ 0 & Disengagement \end{cases} \quad (6)$$

where,

- m_e is the equivalent rotation mass obtained with Eq.(3). One should notice that the mass of ball nut is neglected here since it is small. As a result, the power takeoff force is zero for disengagement case
- c_{pto} is the power takeoff damping induced by the rotating generator, which can be calculated with Eq. (3) .

Details about other forces, including the wave force, drag damping and mooring force, can be found in [6].

5. Simulation and Power Takeoff System Optimization

In this section the simulation results of the proposed self-reacting wave energy converter with the MMR are presented under regular wave excitation. The frequency dependent hydrodynamic parameters are calculated using the commercial software WAMIT [7]. The meshed plot of the proposed system is shown in Figure 3. The water depth is 50m. The dynamic of the system, Eqs. (4) and (5), were numerically solved in Matlab. The system parameters are listed in Figure 3.

Figure 4 shows the time domain simulation of the proposed self-reacting wave energy converter with both the MMR and non-MMR system. The input rotational speed of the MMR system is different from the output rotational speed when disengagement happens, as shown in the bottom figure with blue and red curve.

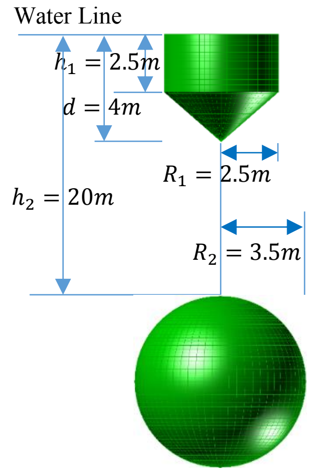

Figure 3. Dimension and mesh of the self-reacting wave energy converter used for WAMIT

As one can find in Section 3, the power takeoff system has two parameters for the MMR system. The equivalent mass in Eq. (3) is a parameter determined by the system mass and gear ratio. The equivalent mass can be tuned by adding a flywheel or changing the gear ratio of the system (ball screw or gearbox), which is very hard to implement once the system is operational. The equivalent damping, however, can be tuned by selecting different external resistors. Therefore, in this part, the optimal power and corresponding optimal damping are studied for the MMR system under regular wave excitation.

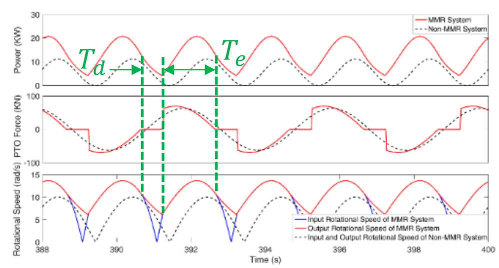

Figure 4. Simulation results of a self-reacting wave energy converter for MMR system and Non-MMR system under regular wave excitation. T_d and T_e are the disengagement and engagement periods.

The modified constrained complex method [8] is used here to find the optimal power and corresponding optimal damping. The damping is optimized in the interval of $[0, 2 * 10^6 N * s/m]$. Figure 5 shows the optimal power of a self-reacting wave energy converter with the MMR system under regular wave excitation. One can find that there are two peaks for the optimal output power. One is around 4s, which is close to the natural frequency of the floating buoy ($\omega_1 = \sqrt{\frac{k_{s1}}{m_1+A_{11}}} = 1.57 rad/s$, and the corresponding period is $T_1 = \frac{1}{\omega_1} = 4s$.). Therefore, the motion of the floating buoy is very large around 4s. The other peak power happens around 8s, which is the damped natural frequency of the two-body system. When the equivalent mass increases from 0 to $5 * 10^4 kg$, the optimal power between the two peaks increases as well. The optimal power around 8s does not change with equivalent mass.

In conclusion, due to the disengagement mechanism of the MMR system, the equivalent mass helps to increase the power absorption at small wave periods. The peak period of the MMR system is not sensitive to the variation of equivalent mass.

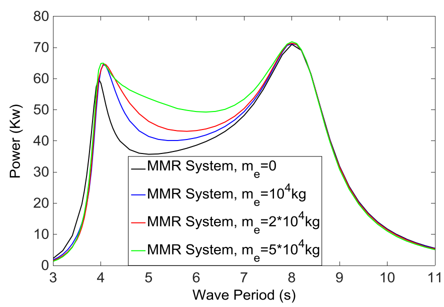

Figure 5. Optimum power of the MMR system with various designs of equivalent mass m_e under regular wave excitation. The wave height is 2m. c_{d2} is 0.5.

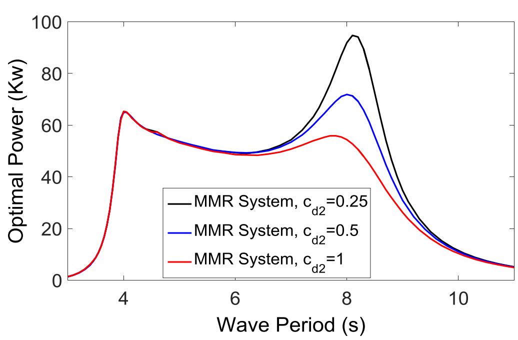

Figure 6. Optimum power of the MMR system with various selection of drag coefficient c_{d2} under regular wave excitation. The wave height is 2m.

In practice, it is difficult to determine an accurate drag coefficient. Therefore, various drag coefficients, c_{d2}, were selected in Figure 6 to investigate the effect of the drag coefficient on the system response and power absorption. It is found that with increased drag damping, the optimal power and corresponding damping around 8s for MMR system decreases dramatically while they keep almost the same at other periods. As a result, one can conclude that the uncertainty of the drag coefficient for both the MMR and non-MMR systems only affects the optimal power and optimal PTO damping around 8s in regular waves, while they are almost the same for other wave periods.

6. Conclusion

A self-reacting two-body wave energy converter with mechanical power takeoff system is studied in this paper. The power takeoff system is designed based on a mechanical motion rectifier. The dynamic model of the wave energy converter is established and studied under regular and irregular wave excitation.

It is found that due to the disengagement of the power takeoff system, the equivalent mass in the MMR system can help to increase the power absorption at small wave periods and maintains the same performance at large wave periods. The drag damping has a bad effect on the power absorption of the MMR system. The peak power around 8s decreases dramatically with the increase of drag coefficient c_{d2} while the power at other frequencies is remains the same.

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