WAVE ENERGY CONVERTER WITH MECHANICAL MOTION RECTIFIER

[1, 2] Changwei Liang, [2]Xiaofan Li, [2]Lin Xu [1]Junxiao Ai and [2]Lei Zuo
[1] Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA, 24061, USA
[2] Department of Mechanical Engineering, Stony Brook University, Stony Brook, NY 11794, USA
Email: leizuo@vt.edu

ABSTRACT

In this paper, the designs of two oscillating wave energy converters (WEC), using a mechanical motion rectifier (MMR) as the power takeoff system (PTO), are presented. The mechanical motion rectifier transfers the bidirectional input buoy motion into unidirectional generator rotation. The first design is a single body point absorber oscillating in heave, and the mechanical motion rectifier is designed as a conventional rack pinion system with two one-way bearings. The second design is a two-body self-reacting WEC, and the MMR is realized with a ball screw and a gearbox which rectifies the bidirectional input motion into unidirectional output rotation. The preliminary lab test for the rack pinion based PTO and the ocean test for the single body WEC are also presented.

Key Words: Wave Energy Converter, Mechanical Motion Rectifier, One-way Bearing

INTRODUCTION

The total useful wave energy around the world is estimated to be 2-8 TW (10^{12}W). To harvest a small portion of it can make a significant contribution to the worlds high energy demand. The first attempt of harvesting energy from ocean waves can date back to 1799 [1]. Hundreds of concepts have been designed and prototyped since then [2-6]. The research and development of wave energy converters (WEC) has been very active in recent years. It is estimated that there are more than one hundred ongoing WEC projects in different stages around the world [7]. Generally, WECs can be categorized into three main categories: oscillating water columns, oscillating bodies and overtopping devices based on the working principle [7]. One of the most important mechanisms in the design of WECs is the power takeoff system (PTO), which transfers the mechanical energy extracted from waves to electricity. As Falcao [7] pointed out, the PTO "is possibly the single most important element in wave energy technology, and underlies many (possibly most) of the failures to date".

There are three types of PTOs that have been widely used in different projects in the past decades. The first type of PTO is the air turbine, which is widely used in the oscillating water column. One of the most famous and widely used air turbines is the wells turbine [8, 9]. Invented in the 1970s, it is able to rectify the bidirectional flow motion into one directional blades rotation. Another popular PTO is the hydraulic system, which has the advantage of transferring the large force or moment exerted on the buoy into electrical energy. In addition, a gas accumulator can be included in the hydraulic system to store the kinetic energy and smooth the irregular output power. However, the losses accrued during fluid transmission greatly reduce the efficiency of the PTO. The third type of PTO that has been used in the WEC is the electro-magnetic system, which usually consists of a moving translator and a stator. The system requires a large physical dimension when it is used in the WEC. This makes the magnet heavy and unwieldy, decreasing the efficiency of the overall system.

In this paper, In this paper we introduce the mechanical motion rectifier (MMR) as the PTO design for the WEC. The bidirectional input motion can be converted into unidirectional output rotation by using two one-way bearings in the conventional rack pinion or ball screw system. In addition, a flywheel is easy to integrate in the system and helps to store the kinetic energy and smooth the irregular output power, in the same function as the gas accumulator used in hydraulic system. The first prototype is a single body point absorber oscillating in heave, and the MMR is achieved using a conventional rack pinion system

MMR. The second design is a two-body self-reacting WEC, and the MMR is achieved with a ball screw and a gearbox which rectifies the bidirectional input motion into unidirectional output rotation. The preliminary lab test for the rack pinion based PTO and the ocean test for the single body WEC are also presented.

The rest of the paper is organized as follows. Section 1 is the introduction of the MMR. Section 2 presents the design and prototype of the single body WEC. Section 3 shows the lab and ocean test for the single body WEC. Section 4 shows the design of the two-body self-reacting WEC using a ball screw. The conclusion and future work are presented in Section 5.

MECHANICAL MOTION RECTIFIER

The mechanical motion rectifier (MMR) is a mechanism which converts bidirectional input motion into unidirectional output rotation by using two one-way bearings as shown in Figure [1].

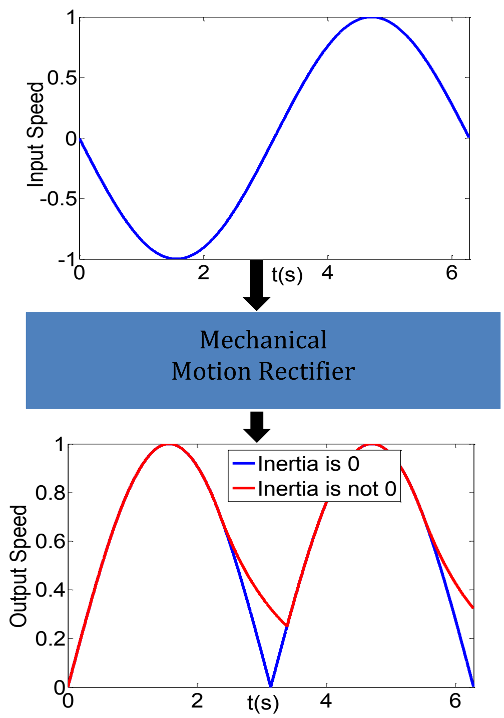

Figure 1. Working principle of mechanical motion rectifier. The bidirectional input motion is converted into unidirectional output rotation through two one-way bearing.

The key mechanism of mechanical motion rectifier is using two one-way bearings to rectify the bidirectional motion into unidirectional rotation through the engagement and disengagement of two one-way bearings. It was first proposed in [10] to harvest energy from the vibration of railway tracks. The authors found that the efficiency of the MMR system is higher than the non-MMR system. Li et. al [11] later designed an MMR based regenerative shock absorber. They found that the efficiency of the MMR system is much higher than the conventional regenerative shock absorbers in oscillatory motion. The working principle of the MMR is shown in Figure 1.

The dynamics of the MMR is piecewise linear due to the engagement and disengagement of one-way bearings. When the MMR system is used in a vibration system for energy harvesting, the reaction force from the MMR and electricity load can be written as a piecewise force as following,

$$F_{MMR} = \begin{cases} m_e\ddot{x} + c_e\dot{x} & engagement \\ 0 & disengagement \end{cases}$$

where, m_e is the equivalent mass due to the rotational inertia in the MMR system; c_e is the equivalent damping due to the electricity load. The details about the modeling of the MMR system can be found in [12, 13].

DESIGN AND EXPERIMENTAL RESULTS OF A SINGLE BODY OSCILLATING WAVE ENERGY CONVERTER WITH A RACK PINION BASED MECHANICAL MOTION RECTIFIER

A single body wave energy converter with mechanical motion rectifier has been designed and fabricated by Liang et. al [12] in 2014. The overall design is presented in Figures 2 and 3. The buoy is floating on the surface of the wave and oscillates under the wave excitation. The shaft is connected with the racks and is fixed on the seabed. The oscillation of the buoy is converted into the bidirectional rotation of the pinion.

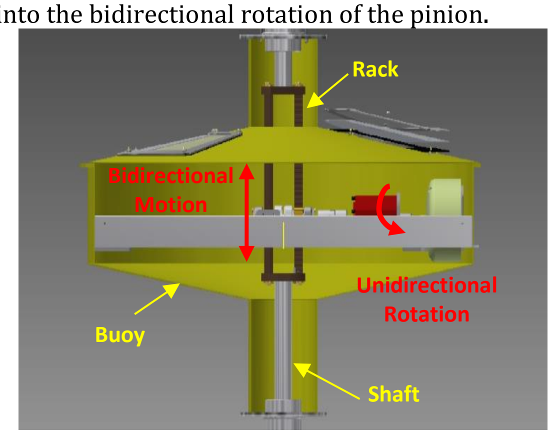

Figure 2. Overall design of single body wave energy converter with rack pinion based MMR.

Two one-way bearings are mounted between the pinions and output shaft in such a way that at most one one-way bearing is engaged and drives the output shaft. When the rotation speed of the output shaft is larger than the rotation speed of the pinions, both one-way clutches get disengaged. The detailed design can be found in [12]. The prototype for the ocean test can be seen in Figure 4.

Figures 5 and 6 show the lab and ocean test results of the MMR. One can find that the output power and voltage of the generator is always larger than zero due to the disengagement of the MMR system. This indicates that a larger power output is possible with the design of the MMR. The largest power in the ocean test was 200W, shown in Figure 6. The details about the lab and ocean test of the single body system can be found in [12].

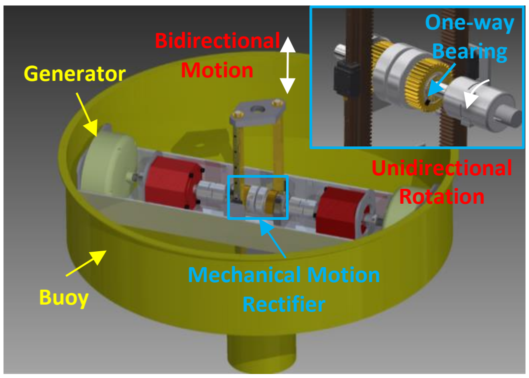

Figure 3. Detail design of single body wave energy converter with rack pinion based MMR.

Figure 4. Prototype of single body wave energy converter with MMR.

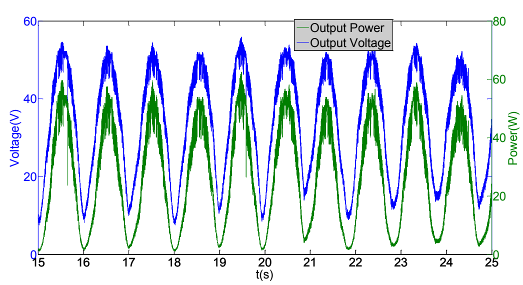

Figure 5. Output power and voltage of MMR in the lab test.

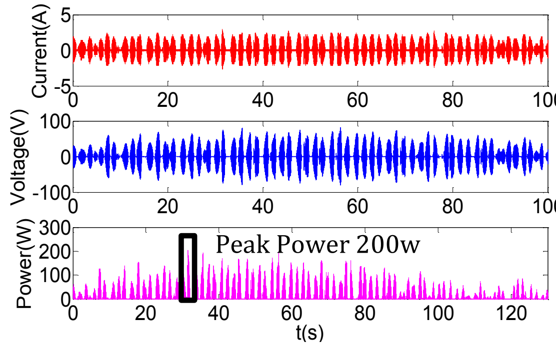

Figure 6. Ocean test of the single body wave energy converter with MMR.

DESIGN OF TWO-BODY SELF-REACTING WAVE ENERGY CONVERTER WITH BALL SCREW BASED MECHANICAL MOTION RECTIFIER

The lab and ocean tests for the single body WEC have verified that the MMR is able to harvest energy from ocean waves. However, the experimental results in Figure 6 are not satisfying, since the power output is not large enough. One of the main causes for the reduced power is that the mechanical damping in the conventional rack pinion system is very large, which significantly decreases the output power in the generator. As a result, a new design of the WEC is proposed, shown in Figure 7. The new design is a two-body WEC and the energy is harvested through the relative motion of these two bodies.

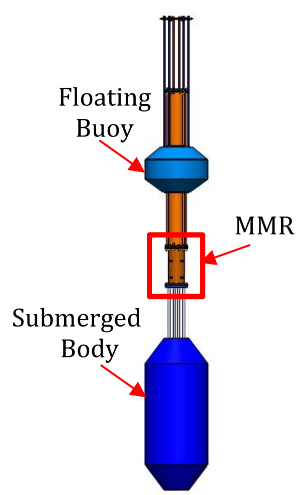

Figure 7. Overview of two-body wave energy converter with ball screw based mechanical motion rectifier.

The MMR is realized with the ball screw and gearbox shown in Figures 8 and 9. The screw is fixed within the floating body, while the ball nut is connected to the submerged body. In this way, the relative motion of the floating and submerged body is converted into the relative motion between ball nut and screw. The design of the ball nut is illustrated in Figure 8.

In Figure 8, the plate at the very top is connected with the nut converter through two connect rods which transfers oscillation of the buoy to the nut converter. The ball nut converts the oscillation into the bidirectional rotation of the screw. The two rods are used to guide the oscillation with two linear guides and hold the reaction torque generated in the rotation of the screw.

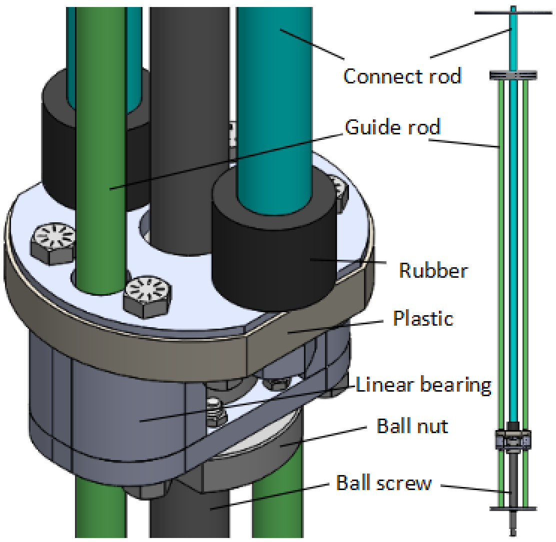

Figure 8. Design of nut converter

Another key design in this system is the gearbox, which converts the bidirectional screw rotation into unidirectional rotation of the generator. As illustrated in Figure 9, the input shaft of the gearbox is connected with the ball screw by a coupling. Two one-way bearings are mounted with the top and bottom bevel gear. When the input shaft rotates in the clockwise direction, the top one-way bearing engages and the bottom one-way bearing disengages. Therefore, the top gear drives the generator in counter-clockwise direction through two side gears. When the input shaft rotates in the counter-clockwise direction, the one-way bearing on top disengages and the one on the bottom engages. As a result, bidirectional input motion is converted into unidirectional rotation of the generator.

This new design is different from the single body design in the following two aspects. First, the overall design is composed of a floating buoy and a submerged body. Second, the MMR is realized with a ball screw and a gearbox. This design is believed to have the advantages in the following aspects. Firstly, the dynamics of the two-body system are different from the single body system. By adding an additional body underneath, it is possible to create resonance with the incident wave frequency [14-17]. Secondly, the energy is extracted through the relative motion of the two bodies. This makes the mooring to be easier than the single body system, especially in deep water. Thirdly, the ball screw used in this prototype has smaller mechanical damping and a longer life cycle.

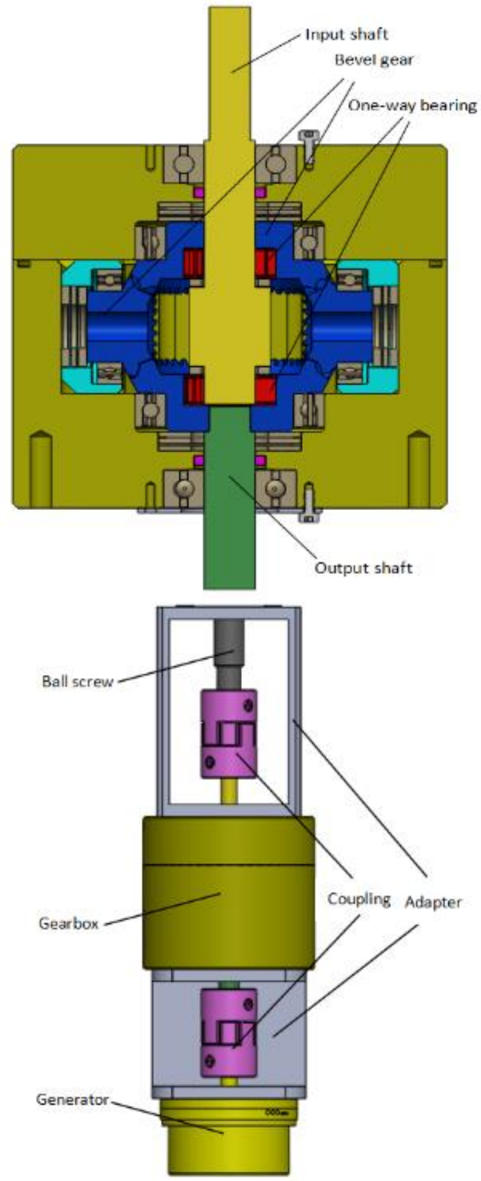

Figure.9 Design of the gearbox

CONCLUSION AND FUTURE WORK

In this paper, the design for two types of wave energy converters are presented. The first one is a single body system oscillating in heave with a rack pinion based mechanical motion rectifier. A 500W prototype was fabricated and tested. The concept of using mechanical motion rectifier to harvest energy from ocean waves is verified. Based on the single body design, an improved design is proposed. The improved design is a two-body self-reacting wave energy converter, and the energy is extracted through the relative motion of the two bodies. This design is believed to have advantage on the dynamics and mooring with smaller mechanical damping and longer life cycle. Future work includes system optimization, control, as well as lab and ocean testing of the new design.

ACKNOWLEDGEMENT

The authors would gratefully acknowledge financial support from Nation Science Foundation (NSF 1530122), EPA P3 program (SU835532).

REFERENCE

[1]. Ross D. Power from sea waves. Oxford: Oxford University Press; 1995.
[2]. Waters, R, Stålberg, M, Danielsson, O, Svensson, O, etc. Experimental results from sea trials of an offshore wave energy system. Applied Physics Letters, 2007; 90(3), 034105.
[3]. Budar, K and Falnes, J. A resonant point absorber of ocean-wave power. Nature, 1975; 256(5517), 478-479.
[4]. Engström, J., Eriksson, M., Isberg, J. and Leijon, M. Wave energy converter with enhanced amplitude response at frequencies coinciding with Swedish west coast sea states by use of a supplementary submerged body. Journal of Applied Physics, 2009;106(6), 064512.
[5]. Ocean Power Technologies. URL: http://www.oceanpowertechnologies.com/, last accessed data 2015.
[6]. Dick, W. 2005 U.S. Patent No. 6,857,266. Washington, DC: U.S. Patent and Trademark Office.
[7] Falcao AF de O. Wave energy utilization: A review of the technologies. Renewable and Sustainable Energy Reviews 2010;14:899-918.
[8] Wells AA. Fluid driven rotary transducer. British Patent Spec No. 1595700;1976.
[9] Whittaker TJT, Wells AA. Experiences with hydropneumatic wave power device. In: Proceedings of Wave and Tidal Symposium, Canterbury, UK; 1978.
[10] Wang J, Lin T, Zuo L. High efficiency electromagnetic energy harvester for railroad application. InASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference 2013. American Society of Mechanical Engineers.
[11] Li Z, Zuo L, Kuang J, Luhrs G. Energy-harvesting shock absorber with a mechanical motion rectifier. Smart Materials and Structures. 2013;22:025008.
[12] Liang C, Ai J, Zuo L. Design, Fabrication, Simulation and Testing of a Novel Ocean Wave Energy Converter. In: ASME 2015 International Manufacturing Science and Engineering Conference 2015. American Society of Mechanical Engineers.
[13] Ai J, Lee H, Liang C, Zuo L. Ocean Wave Energy Harvester with a Novel Power Takeoff Mechanism. InASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers.
[14] Budal, K. and Falnes, J. Interacting point absorbers with controlled motion. Power from sea waves, 1980;381-399.
[15] Evans, D. V.. A theory for wave-power absorption by oscillating bodies. Journal of Fluid Mechanics, 1976;77(01), 1-25.
[16] Mei, C. C. Power extraction from water waves. Journal of Ship Research, 1976;20, 63-66.
[17] Falnes, J. Wave-energy conversion through relative motion between two single-mode oscillating bodies. Journal of Offshore Mechanics and Arctic Engineering, 1999; 121(1), 32-38.
[18] Falnes J. Ocean waves and oscillating systems: linear interactions including wave-energy extraction. Cambridge University Press, 2002.