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ANALYSIS OF ELECTROMAGNETIC FORCE OF THE LINEAR GENERATOR IN POINT ABSORBER WAVE ENERGY CONVERTERS

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Key words: linear generator, electromagnetic force, point absorber wave energy converters, electromechanical coupling.

ABSTRACT

In recent decades energy shortage and environmental pollution have increasingly become challenges faced by the world. New innovation technology to harness renewable energy such as wave energy is considered to be the key to solve this problem. Point absorber wave energy converter (WEC) is one of the most effective means to utilize wave energy. Several different types of power take off (PTO) devices have been used in the design of point absorber WEC amongst which linear generator has the advantages of direct drive, structural simplicity, high-efficiency and so on. This paper studies the electromagnetic force of the linear generator, and the responses of point absorber WEC with line generators. An analytical model is built to simulate the electromagnetic force of a linear generator. Finite element method (FEM) and empirical equation are used to calculate the electromagnetic force, magnetic flux and vector field of magnetic induction. Comparison between the results from FEM and the analytical method shows great agreement. By using analytical model of electromagnetic force of linear generator, the motion equations of the WEC are developed and the dynamic responses of the whole WEC system are obtained. This work is helpful for designing WEC and understanding of the motion mechanism.

I. INTRODUCTION

Compared with other forms of renewable energy, such as wind or solar energy, ocean wave energy is more energy-concentrated and constant, therefore, it has high potential to be harnessed with proper technologies.

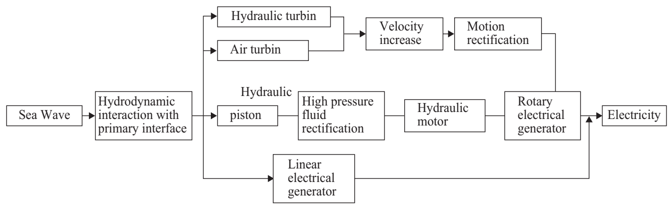

Fig. 1. The scheme of types of power take-off for WEC.

According to WECs' design (e.g., horizontal extension and orientation), WECs can be classified into different types. A point absorber means a WES with a relatively small horizontal dimension compared against the typical wavelength. While if the horizontal dimension of the WEC is comparable, or even larger than, a prevailing wavelength, the WEC is called attenuator or terminator. A point absorber, if placed in the path of the incident wave, is able to collect energy from all directions. As such , it is regarded as one type of the most effective devices for harnessing wave energy. Typically, a point absorber is designed as either a single-body device generating energy by reacting against a fixed seabed frame, or a multiple-body device harnessing energy from the relative movement between two adjacent bodies (Cruz, 2007; Falnes, 2007). According to energy conversion mechanism, there are a large number of types of PTO system that can be used in WECs, such as mechanical, hydraulic, pneumatic or directly electrical PTOs, as shown in Fig. 1.

Traditional point absorber WECs often use high speed rotary machines, such as turbines or hydraulic machines, to extract energy from ocean waves. In this case, the structure is very complicated, and a transmission gear box is needed. Linear generators have been proposed recently as alternatives to the above mentioned PTO devices. The obvious advantage of a linear generator is that the structure of the PTO device is greatly simplified, and it can attenuate the energy loss due to mechanical transmission. In this setting, the vertical buoy motion, caused by ocean waves, provides piston movement relative to the stator coils. Springs connecting the bottom of the translator to the foundation serve as a restoring force and energy storage.

There has been considerable effort on developing Perma-

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nent Magnetic Linear Generator (PMLG) for WECs. Cruz (2007), Scruggs and Jacob (2009) reviewed various types of PTOs used in WECs, and recommended the Linear Generator as a preferred choice of PTOs. Lockett (1996), Li and Yu (2012), Shi et al. (2014) reported dynamic models of point absorber wave energy converter in which the PTO was simplified to be a damping unit. Pirisi et al. (2009) and Parthasarathy (2012) studied the electrical and magnetic characteristics of Linear Generator by using FEM and simulated the flux density and voltage current of linear PM generator. In order to simplify the calculation and uncover the relationship between magnetic force and other parameters, analytical model was presented by Thorburn (2006) and Ekströma et al. (2015). The empirical equations to calculate the magnetic force were obtained in linear generators of WECs (Eriksson et al., 2004; Polinder et al., 2004; Leijon et al., 2006). Bozzi et al. (2013) modeled a point absorber for energy conversion in Italian seas with linear generator. Antonio (2008) employed phase control method for higher energy absorbing efficiency.

In this paper an analytical model is derived to describe the linear generator used for point absorber of wave energy converters. The electromagnetic forces in the linear generator are calculated by empirical equations. To verify the validity of the calculation, finite element analysis is performed by using software Ansys Maxwell. Based on the analytical model, the whole dynamic model of point absorber WEC with linear generator is obtained, and coupling between point absorber and linear generator is also analyzed.

II. LINEAR GENERATOR FOR POINT ABSORBER OF WAVE ENERGY CONVERTER

1. Linear Generator as Power Take-off

The point absorber wave energy converter is modeled as a single body system with one degree of freedom (DOF) along the heave direction. Its scheme is illustrated in Fig. 2. It mainly includes a buoy, a cable and a linear generator PTO device. As mentioned before, this direct PTO can reduce the complexity of the mechanical system and help to convert the kinetic energy into electrical energy efficiently, reliably and commercially. Basically, the PTO is contained in a cylindrical air-filled chamber. The waves move the buoy and the lid of this chamber in vertical direction relative to the bottom part, which is fixed to the sea-bottom. The details of a typical linear generator is shown in Fig. 3. In this system, the buoy heaves with the wave motion and pulls the translator back and forth so that electrical current will be generated in the coil of the stator. In this process, the kinetic energy is transferred to useful electrical energy while the electromagnetic force will be generated to resist the motion of the translator.

In general, the electromagnetic force can be considered as a damping force and usually calculated by:

$$F_M(t) = c\dot{z}(t) \tag{1}$$

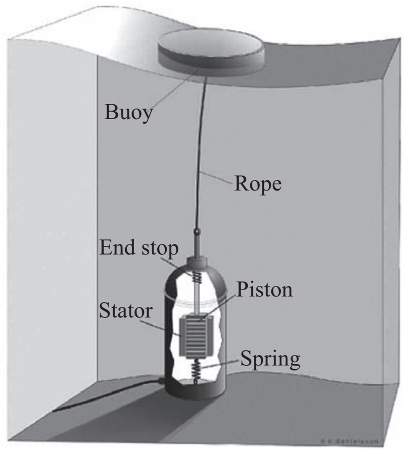

Fig. 2. Scheme of single-body point absorber WEC.

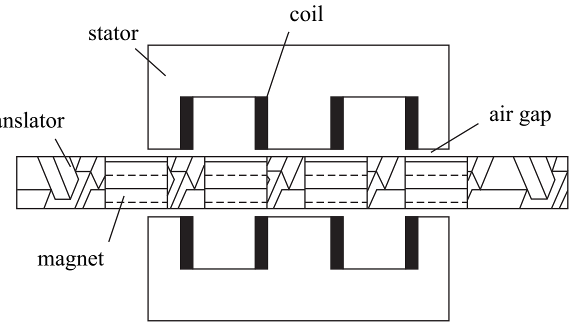

Fig. 3. Model of linear generator.

where c is the generator damping coefficient.

Eq. (1) is a simplified model for electromagnetic force of linear generator and represents the basic relationship between the electromagnetic force and the moving velocity of the translator. However, this representation is deemed too rough, and a more comprehensive description is needed in order to design and analyze a more efficient linear generator to be used in a point absorber.

2. The Electromagnetic Force by FEM

According to the scheme given in Fig. 3, a 3D FEM model of the linear generator is developed as shown in Fig. 4. In this model, the magnet is considered as permanent magnet, and the frame of the translator as aluminum. Silicon steel sheet combines the stator, and the coil material is set to be copper. The main parameters used in the simulation are listed in Table 1. It is assumed that the motion of translator is reciprocal with a velocity of 0.5 m/s and a period of 0.05 s.

The model is built using Ansys Maxwell and its meshes are shown in Fig. 5. The vector field of the magnetic induction is shown in Fig. 6.

The electromagnetic force obtained from the FEM simulation is shown in Fig. 7. It can be clearly seen that the maximum electromagnetic force is about 14.81N (see Fig. 7), and the curve looks like a sinusoid. The electromagnetic force

Table 1. Main structural parameters of linear generator.

Name of Parameters	Units	value
pole width w_p	mm	50
magnetic field in a tooth B_t	T	0.75
width of a stator tooth w_t	mm	10
width of the stator stack d	mm	50
outer resistance R_{out}	Ω	30
air gap	mm	1
load angle δ	rad	0
number of poles p		3
number of cables in slot c		50
number of slots per pole and phase q		1

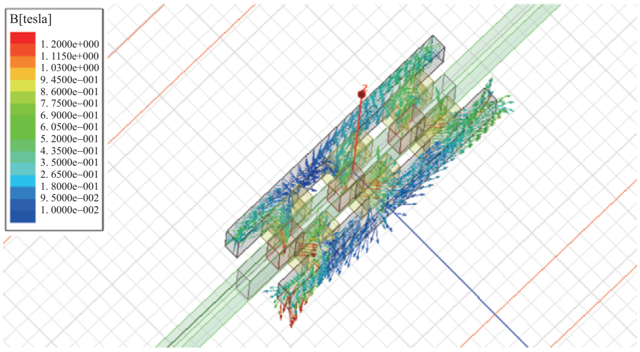

Fig. 6. Magnetic flux of magnetic induction. The arrows present the direction of magnetic vectors.

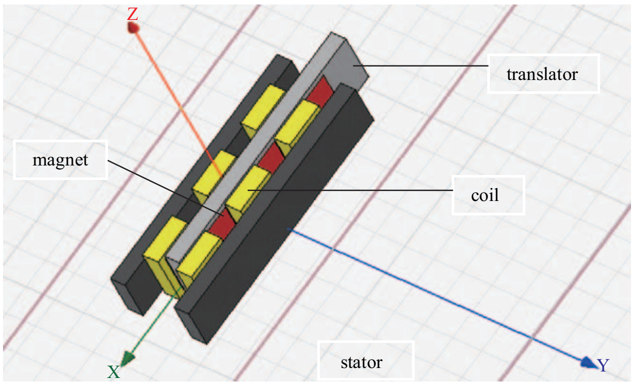

Fig. 4. The 3D model of linear generator.

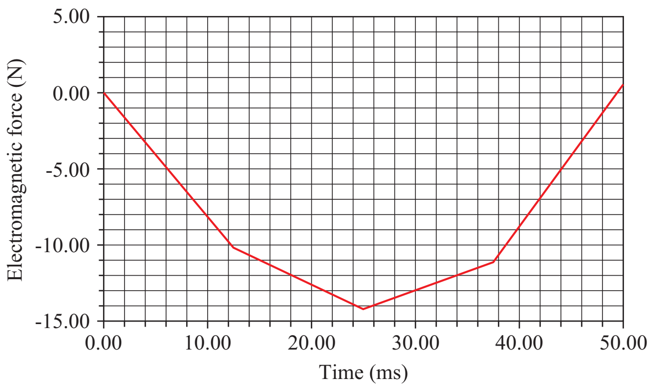

Fig. 7. The electromagnetic force in linear generator by FEM.

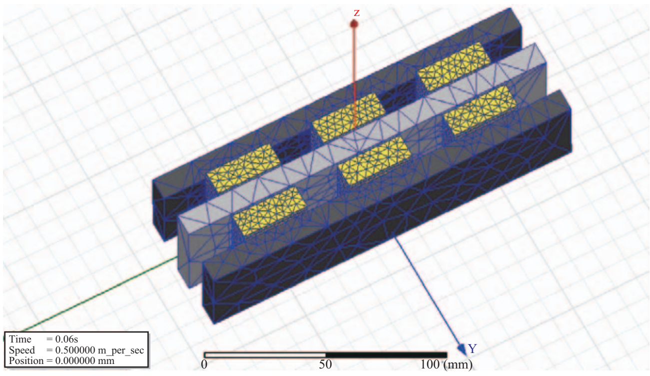

Fig. 5. Meshes of linear generator model.

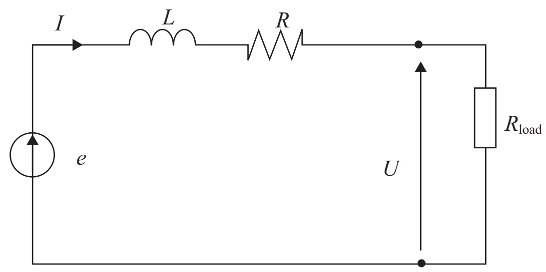

Fig. 8. Equivalent circuit of for linear generator.

resists the motion of transition, and its direction is opposite to the moving direction of the translator.

3. The Electromagnetic Force from Analytical Model

The electromagnetic force can also be obtained by the analytical model based on Faraday's Law and Maxell's equations which govern the magnetic induction in the stator-translator structure. The simplified analytical model presented by Thorburn and Leijon (2007) is used to calculate the voltage generated in the stator $e(t)$. The empirical equation for $e(t)$ is given as

$$e(t) = \frac{2\pi \cdot B_t \cdot w_t \cdot d \cdot p \cdot q \cdot c}{w_p} \cdot \dot{z}(t) \cdot \sin\left(\frac{2\pi}{w_p} \cdot z(t) - \delta\right) \quad (2)$$

where w_p is the pole width, B_t is the magnetic field in a tooth, w_t is the width of a stator tooth, d is the width of the w_p stator stack, p is the total number of poles, q is the number of slots per pole and phase, c is the number of cables in a slot and δ is the load angle.

Through the equivalent electric circuit (see Fig. 8), the voltage $U(t)$ at the terminals for a single phase is

$$U(t) = e(t) - RI(t) - L\frac{dI(t)}{dt} \quad (3)$$

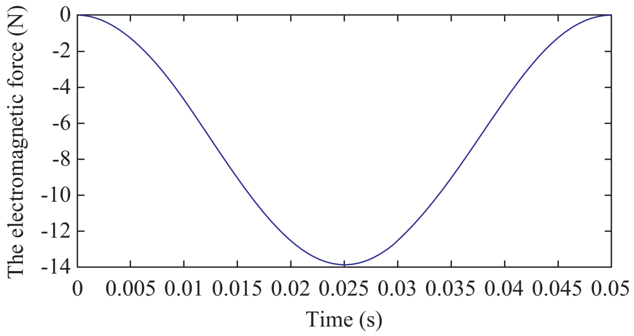

Fig. 9. Electromagnetic force in line generator by analytical model.

where R is the circuit resistance, L is the circuit inductance. The relationship between the current $U(t)$ and $I(t)$ at the terminals of a single phase generator is

$$I(t) = \frac{U(t)}{R_{load}} \tag{4}$$

where R_{load} is the load resistance.

The output power of the linear generator $P(t)$ is calculated by:

$$P(t) = U(t)I(t) \tag{5}$$

According to Eqs. (3) and (4), the electromagnetic force can be written as:

$$F_M(t) = \frac{U(t)\cdot I(t)}{\dot{z}(t)\cdot\mu} \tag{6}$$

where μ is the generator efficiency.

For linear generator with multiple-phase, the whole electromagnetic force F_{MA} is given by

$$F_{MA} = \frac{\sum_{i=1}^{n} U_i(t)I_i(t)}{\dot{z}(t)\mu} \tag{7}$$

where n is the number of phases of the linear generator.

We find that the difference between $U(t)$ and $e(t)$ is quite small in our model. In order to simplify the calculation, $U(t)$ is approximated with $e(t)$ in subsequent analysis.

Following the above analysis, the equation of electromagnetic force of a single-phase linear generator can be given as:

$$F_M(t) = \frac{\left(\frac{2\pi\cdot B_t\cdot w_t\cdot d\cdot p\cdot q\cdot c}{w_p}\right)^2\cdot\dot{z}(t)\cdot\sin^2\left(\frac{2\pi}{w_p}\cdot z(t)-\delta\right)}{R_{load}\cdot\mu} \tag{8}$$

The electromagnetic force calculated with Eq. (8) is shown in Fig. 9. In Fig. 9 the maximum value of the electromagnetic force is about 14N, and the shape of curve is a sinusoid. This indicates that the results from this analytical model agree well with the ones from the finite element simulation.

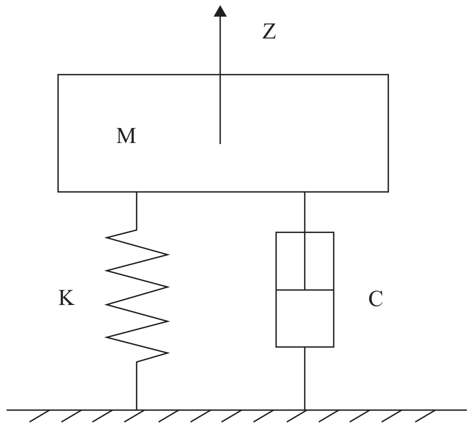

Fig. 10. Scheme of model of point absorber wave energy converter with linear generator.

III. ELECTROMECHANICAL COUPLING MODEL OF POINT ABSORBER WAVE ENERGY CONVERTER

The point absorber wave energy converter with a linear generator can be modeled as a vibration system as shown in Fig. 10. There is relative motion between buoy and the fixed component in the vertical direction (heave mode). The model of this system can be described as (Lockett, 1996)

$$(M+m)\ddot{z}(t) + C\dot{z}(t) + F_k(t) + F_M(t) = F_e(t) \tag{9}$$

where $z(t)$, $\dot{z}(t)$ and $\ddot{z}(t)$ are the displacement, velocity and acceleration of buoy in the vertical direction respectively. M is the mass of the buoy, m is the added mass of the buoy. C is the damping coefficient, $F_M(t)$ is electromagnetic force, $F_k(t)$ is restore force on buoy, $F_e(t)$ is the excitation force and considered as a harmonic rules.

The excitation force on the heaving buoy can be calculated by

$$F_e(t) = AF_1\sin(\omega_0 t + \varphi_0) \tag{10}$$

where A is the amplitude of wave, F_1 is the wave force coefficient, ω_0 is the frequency of regular wave, φ_0 is the phase of the regular wave.

The restore force of the spring system $F_k(t)$ is modeled as:

$$F_k(t) = kz(t) = \rho g A_w z(t) \tag{11}$$

where k is the stiffness of the spring, ρ is the density of the water, A_w is the main mass water plane area, g is the gravity acceleration.

Table 2. The parameters of cylindrical buoy.

Parameters	Units	Numerical value
Radius r	m	1.5
High h_b	m	3.0
density ρ	kg/m^3	1025
wave period	s	8.0
Wave height	m	1.0
Mass M	kg	2700

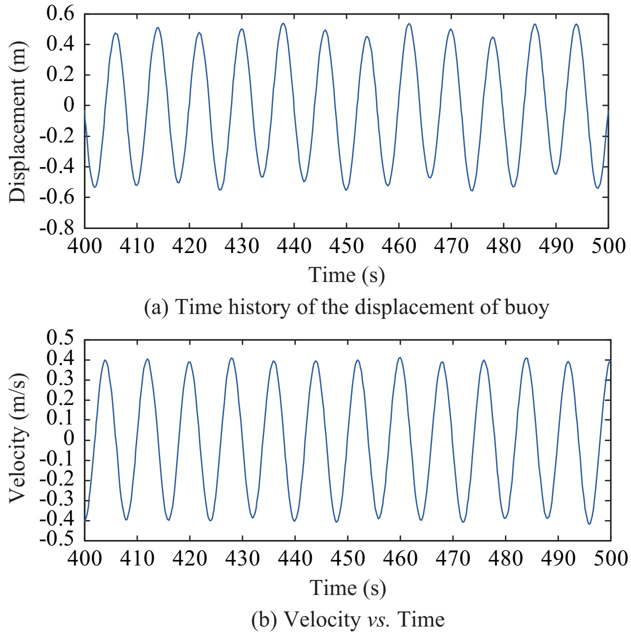

Fig. 11. The response of floater of point absorber WEC.

The electromagnetic force can be obtained by Eq. (8). By substituting Eq. (8) into (9), the dynamic model of a point absorber WEC system with linear generator as the PTO can be described as:

$$(M+m)\ddot{z}(t)+C\dot{z}(t)+F_k(t)+\frac{\left(\frac{2\pi\cdot B_t\cdot w_t\cdot d\cdot p\cdot q\cdot c}{w_p}\right)^2\cdot\dot{z}(t)\cdot\sin^2\left(\frac{2\pi}{w_p}\cdot z(t)-\delta\right)}{R_{lord}\cdot\mu}=F_e(t) \quad (12)$$

Eq. (12) is a nonlinear equation. In this model, the shape of buoy is considered to be cylindrical. The main parameters of the point absorber are shown in Table 2. The added mass, damping coefficient and wave force coefficient can be obtained by the AQWA software.

The simulation results of the dynamic equation of point absorber WEC with linear generator as shown in Fig. 11(a) and Fig. 11(b). It can be observed through Fig. 11(a), the amplitude of the buoy is about 0.5 m and the oscillation period of buoy is about 7.3 s. The amplitude of the buoy will be almost as large as that of the wave amplitude. From Fig. 11(b), the velocity curve of buoy is similar to sinusoid with a period of 7.3 s and ta magnitude of 0.4 m/s.

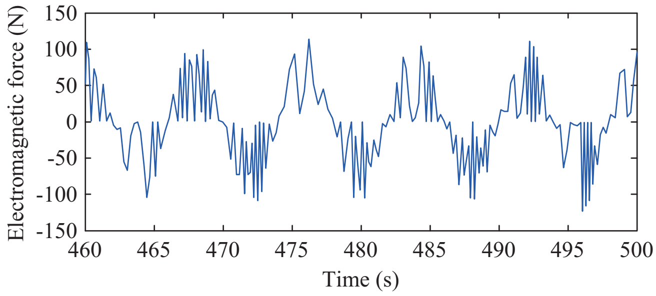

Fig. 12. The electromagnetic force *vs.* time.

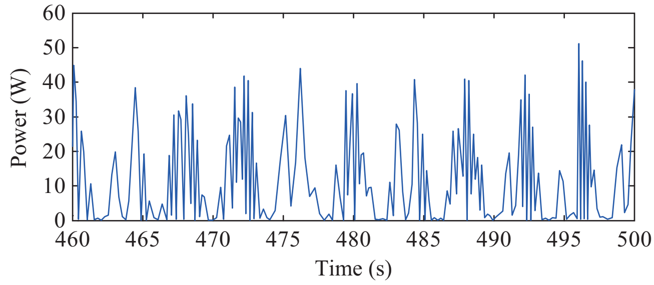

Fig. 13. Power in linear generator *vs.* time.

Following Eq. (12), the electromagnetic force is calculated by the dynamics analysis of point absorber system and shown in Fig. 12.

In Fig. 12 the maximum value of electromagnetic force is about 103N and the force curve is not as regular as the response of the buoy. To some degree it depends on the property of nonlinearity of Eq. (12).

Once the electromagnetic force is obtained, the power of the linear generator can be estimated, as shown in Fig. 13.

From Fig. 13, it can be seen that the maximum power of the linear generator is about 47.9W with an average power of about 20W. It can be seen the power is not continuous when only a single-phase of linear generator is considered.

IV. CONCLUSION

This paper studied the electromagnetic force of linear generator and the dynamic response of a whole model of point absorber WEC with a linear generator PTO. With an analytical model of the electromagnetic force is obtained. By comparing against results from FEM, great agreement is observed. The responses of the system are obtained as well by numerically solving the dynamic equation. Further with the dynamic simulation, the kinematic parameters, electromagnetic force and the power can be obtained. The model and method developed in this paper are useful for estimating the performance of WEC with a linear generator PTO.

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