NUMERICAL SIMULATION OF A WAVE ENERGY CONVERTER USING LINEAR GENERATOR

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Abstract: *This paper presents results of numerical simulation for a wave energy converter using linear permanent magnet generator. Using a linear permanent generator has the advantages of simple structure, minimizing the mechanical loose… On the basic mechanics model, a system of equations describing the operation of the device under linear potential wave was obtained. The magnetic field in generator was calculated by FlexPDE software. The system of movement equations was numerically solved with Matlab. Various calculations were performed with the different parameters of wave conditions and device's structures to determine the device's configuration for a 300W output power under wave condition in the South-Central offshore of Vietnam. The results also show potential of developing the wave energy conversion to meet the energy demand in some coastal and island regions of Vietnam.*

Keywords: *Wave energy convertor, linear electrical generator, permanent magnet generators.*

1. Introduction

1.1. Ocean wave energy

In terms of fossil energy resource depletion and sustainable development, the use of renewable energy, including wave energy is inevitable. The global power potential represented by waves is estimated to be 1–15 TW [1]. Technically, the potential available in Sweden is estimated to 5–10 TWh annually which can be compared to Sweden's total electric energy consumption during one year, 144 TWh [1].

In Vietnam, according to the latest studies, the total wave power in the coast zone is about 58677.02 MW while the total electric power generation capacity of Vietnam in 2010 was 12200.00 MW [2, 3]. The region has great potential for wave energy in Vietnam is South-Central offshore. The annual average wave energy flux for this region is over 30kW/m and reaches the maximum value of about 100 kW/m in December. This is a good energy resource to meet the energy demand of the development.

1.2 Wave energy conversion technologies

Up to day, different types of wave energy conversion principles are illustrated, which have carefully been documented and presented as in Fig. 1 [4]. So far most researchers have concentrated on the hydrodynamic aspects of different converters. The two best known concepts are the IPS buoy [5] and the AquaBouy [6, 7, 8]. These devices all require an intermediate mechanical structure to transform the kinetic energy of the buoy to that compatible with the conventional turning generator, such as pump and turbine systems. However, the complexity in structure increases mechanical energy loss, and it is very hard to get the generators and related accessories available to fit the device's characteristics. They cause reliability problems when operating in extreme marine environment conditions and this is the biggest barrier to the success of the project to manufacture wave energy converter in real field conditions.

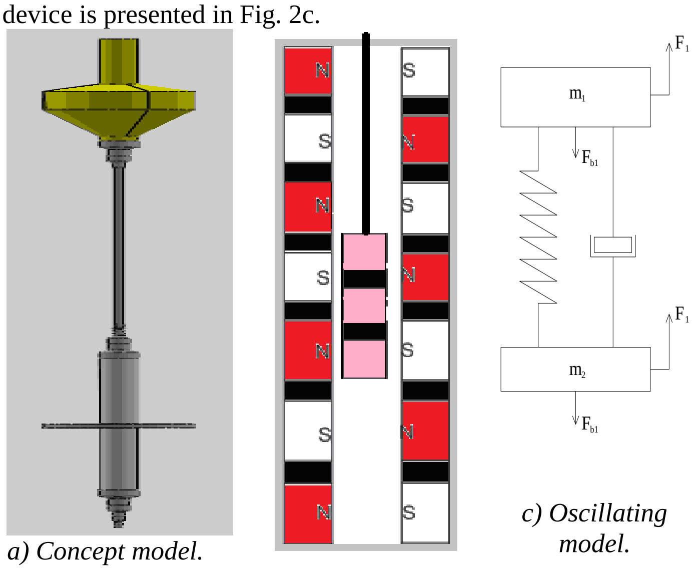
Recently, a number of different working principles to convert wave energy using linear generator have been presented and described [10]. Particularly, the direct conversion using point absorbed and three-phase synchronous three-slide linear generator have been simulated for 10kW units [10]. This structure has the advantage of simple, without many intermediate structures, less mechanical energy loss. Permanent magnet generator helps more dependable operation in hard conditions of the marine environment [6-10].

For starting develop wave energy convertor that is suitable with wave conditions and using purposes in Vietnam, this study deals with a 300W wave energy convertor. This device consists of a buoy connects directly with a linear permanent magnet generator placed at the sea bottom. The generator consists of a two-slide piston with surface mounted permanent magnets. The piston is connected to a buoy by a robe. Stator is situated outside piston with symmetric winding. Reciprocal movements of the piston induce currents in stator winding (Fig. 2a).

2. Concept model and modeling

2.1 Concept model

The concept and operation of the device are described in Fig. 2a. The piston is covered with rows of permanent magnets of alternating polarity. The magnet rows are separated with aluminum spacers. The stator is made of laminated electrical non-oriented steel sheets and isolated copper conductors. The conductors are wound in slots (holes) in the stator steel and forms closed loops or coils. When the buoy oscillates in heave mode under wave forces, it makes piston move relative to the stator. Reciprocate movements of the piston induce currents in stator winding. The current in turn affects the piston with Lorentz force opposite to the direction of motion. The oscillating model of the device is presented in Fig. 2c.



a) Concept model.

b) stator and "rotor" of generator.

c) Oscillating model.

Fig 1: Device's model.

2.2. Governing equations

- Linear wave theory

Ocean waves are very complex. In this study, the analysis is carried out for the linear wave theory only. Then the wave equation has the form:

$$\eta(t) = \eta_a \cos(\omega t - kx)\,. \qquad (1)$$

In which, $\eta(t)$ is the surface water displacement related to still water level, η_a is the wave amplitude, ω is angular frequency, k is wave number.

- Buoy's motion

We select a point-absorbed system of mass m and model its response to monochromatic wave extinction. The dynamic equation of motion for a heaving structure is [12]

$$m_b\,\ddot{s}(t) + S_b s(t) = F_{\mathrm{w},b}(t) + F_{\mathrm{f},b}(t) + F_u(t) + F_c(t) + F_m$$
$$m_b\,\ddot{s}(t) = F_{\mathrm{w},p}(t) + F_{\mathrm{f},p}(t) - F_u(t) - F_c(t) - F_m + F_{drag}(t) \qquad (2)$$

where s_b is the vertical distances of displacement from equilibrium of the buoy, m_{b1} is the mass of the buoy, $F_{e,b}(t)$ is the excitation force, $F_{r,b}(t)$ is radiation force, $F_{b,b}(t)$ is the net buoyancy force, $F_{b,drag}$ is the drag force, $F_{b,f}$ is the friction loss force, $F_{b,u}$ is the electromagnetic load force from generator.

These equations can be reorganised as follows.

$$m_b + m_{r,11}(\infty))\dot{u}_b(t) + m_{r,12}(\infty)\dot{u}_p(t) = g_1(t)$$
$$m_{r,21}(\infty)\dot{u}_b(t) + (m_p + m_{r,22}(\infty))\dot{u}_p(t) = g_2(t) \qquad (3)$$

When the expressions for the radiation forces given in equation (3) have been used, and the following functions have been introduced to increase the readability.

$$g_1(t) = F_{e,b}(t) - k_{11}(t)u_b(t) - k_{12}(t)u_p(t) - R_{f,b}u_b(t) - S_b s_b(t) + F_u(t) + F_c(t) + F_m$$
$$g_2(t) = F_{e,p}(t) - k_{21}(t)u_b(t) - k_{22}(t)u_p(t) - R_{f,p}u_p(t) - F_u(t) - F_c(t) - F_m + F_{drag}(t) \qquad (4)$$

By further manipulation the equations of motion can be written as the following system of equations:

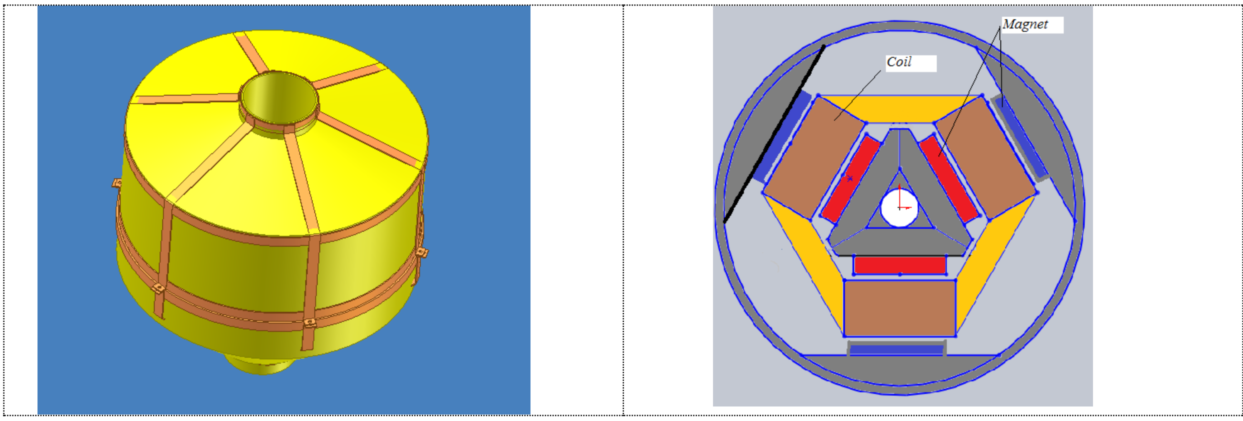


Fig. 2 The concept device's model.

$$\begin{aligned}
\dot{s}_b(t) &= u_b(t) \\
\dot{u}_b(t) &= C_{11}g_1(t) + C_{12}g_2(t) \\
\ddot{s}_b(t) &= u_p(t) \\
\dot{u}_p(t) &= C_{21}g_1(t) + C_{22}g_2(t)
\end{aligned} \qquad (5)$$

which are also called state equations. The following constants have been introduced

$$\begin{aligned}
C_{11} &= (m_b + m_{r,11}(\infty))^{-1}\left(1 - \frac{m_{r,12}(\infty)m_{r,21}(\infty)}{(m_b + m_{r,11}(\infty))(m_p + m_{r,22}(\infty))}\right)^{-1} \\
C_{12} &= -\frac{m_{r,12}(\infty)}{(m_b + m_{r,11}(\infty))(m_p + m_{r,22}(\infty))}\left(1 - \frac{m_{r,12}(\infty)m_{r,21}(\infty)}{(m_b + m_{r,11}(\infty))(m_p + m_{r,22}(\infty))}\right)^{-1} \\
C_{21} &= -\frac{m_{r,21}(\infty)}{(m_b + m_{r,11}(\infty))(m_p + m_{r,22}(\infty))}\left(1 - \frac{m_{r,12}(\infty)m_{r,21}(\infty)}{(m_b + m_{r,11}(\infty))(m_p + m_{r,22}(\infty))}\right)^{-1} \\
C_{11} &= (m_p + m_{r,22}(\infty))^{-1}\left(1 - \frac{m_{r,12}(\infty)m_{r,21}(\infty)}{(m_b + m_{r,11}(\infty))(m_p + m_{r,22}(\infty))}\right)^{-1}
\end{aligned} \qquad (6)$$

11 For a buoy of cylinder shape with the half sphere at the end, the expression for the forces has the forms [12]:

$$F_{e,b}(t) = \exp(-kl)\kappa_{33}\rho g S_{wb}\eta_a \cos(\omega t) \qquad (7)$$

$$F_{r,b} = -m_{33}\ddot{s}_b(t) - R_{33}\dot{s}_b(t) \qquad (8)$$

$$F_{b,b} = -S_{b,b}s_b(t) \qquad (9)$$

$$F_{b,f} + F_{b,v} = -(R_{b,f} + R_{b,v})\dot{s}_b(t) - 0.5C_B\rho A_B|\dot{s}_b(t)|\dot{s}_b(t) \qquad (10)$$

In which, $m_{b_1} = (2\pi/3)r^3\rho\mu_{33}$ is added mass, ρ is water density, μ_{33} is added mass coefficient, $R_{33} = \exp(-2kl)\omega\rho(2\pi/3)a^3\varepsilon_{33}$, ε_{33} is damping coefficient, κ_{33} is non-dimentionalised excitation force, $S_{b,b} = \pi\rho g r^2$ is buoyancy stiffness, $R_{b,f}$ is friction resistance coefficient, $R_{b,v}$ is viscosity resistance coefficient, $R_{b,v} = 0.5C_B\rho A_B|\dot{s}_b(t)|$ is drag resistance, $m_{b_2} = \frac{\pi r^2}{4}l\rho\mu_{b_2}$ [11].

where mr,ij(∞) (i = 1,2, j = 1,2) are the elements of the added mass matrix of the WEC, at infinite frequency, ub(t) and up(t) are the vertical velocities of the two bodies, $\dot{u}_b(t)$ and $\dot{u}_p(t)$ are the vertical accelerations and kij(t) (i= 1,2, j= 1,2) are the radiation force kernels. An example of radiation force kernels, for the geometry shown in figure 1, is given in figure 3. Note that, in equation (3), the upper integration limits are t because the radiation force kernels, contrary to the excitation force kernels, are causal impulse response functions, that is kij(t) = 0 for t<0. Further, we have k12(t)= k12(t), due to the symmetry of the radiation resistance matrix. The integration kernels have been obtained from the frequency domain expressions for the hydrodynamic parameters of the body, which have been computed by a method previously described by the author, using linear hydrodynamic theory and assuming an ideal incompressible fluid19.The calculation is described in more detail in Appendix A. Note that, since the kernels are computed by linear hydrodynamic theory, these expressions are valid only for small excursions. How large the error becomes when the excursion is large, depends on the geometry of the device and of the steepness of the incident wave.

The drag force is expressed as follows (12)

$$F_{draf}\ (t) = -\frac{C_D}{2}\rho A_D \left|u_b\ (t)\right| u_b\ (t) \qquad (12)$$

- *Electromagnetic field*

In general, the electromagnetic field in the generator is described by Maxwell's equations. In this study, magnetic field of permanent magnets is calculated by a stationary mode by using the equations as follow:

$$\nabla \times H = J + \frac{dD}{dt}\ , \qquad (13)$$

$$B = \mu H\ , \qquad (14)$$

Where H is the magnetic field, B is the magnetic flux density. J_{pm} is a factious current density that models the permanent magnets, μ is magnetic permeability.

The above equation needs more some initial and boundary conditions. For the generator in this study, restricting the field problem to two dimensions of magnetic field of permanent magnet, an expression for the field can be derived by using the magnetic potential vector which only z-component, A_z**,** being non-zero**.** The equation for this component has the form

$$\nabla.(\frac{\nabla A_z}{\mu}) = J_{pm} \qquad (15)$$

- *Circuit theory*

In this study, a simplest load is a purely resistive load as in Fig. 3. In this figure, θ is internal EMF of the generator from the coils (armature winding), R_g and L_g are resistance and inductance of the coils respectively, R_L is resistance of the load, I is current in the circuit.

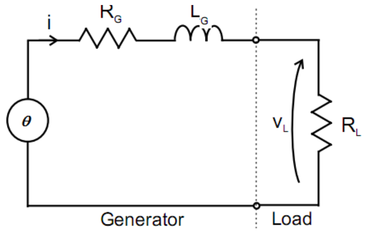


Fig. 3 Generator connected to a resistive load

The terminal voltage V_L, for the circuit can be written as,

$$R_L I = \theta - L_G \frac{dI}{dt} - R_G I \qquad (16)$$

The electromotive force in each coil, θ for this linear generator can be written as

$$\theta = -(-1)^{\left(fix\frac{x(t)}{2a}+1\right)} nlB_n bv(t) \qquad (17)$$

The output power of device is calculated by: $P = I^2 R_L$ (18)

Electromagnetic (Lorentz) force acting on piston by one coil, $F_{b,u}(t)$ is

$$F_{b,u}(t) = nlbB_n I \qquad (19)$$

In which, n is loop number of wire in a unit length of a coil, l is length of a coil, B_n is magnetic flux at air cap, $x(t)$ and $v(t)$ are displacement and velocity of piston respectively, a and b are the dimensions of cross section of the coil.

2.2 Tools and program development

The system of equations (1-13) are used to solve for obtaining the state variables of the device such as buoy's displacement, buoy's velocity, current, electromotive force, output power... depending on the device's and wave's parameters.

From the flow chat we can see that, the steady state magnetic field problem is solved once by FEM method in FlexPDE software. The output is magnetic flux field, B. This result is then used to calculate magnetic flux at air cap, B_n for transient time domain problem, (Eqs. 2 and 10). The transient time domain model is then solved with time progressive by semi-implicit Runge-Kutta method in Matlab.

3. Results and discussions

The program after the test was used to simulate, explore basic characteristics of the device with a capacity of about 300W. The wave period and height are based on the observation data in the South-Central offshore of Vietnam. The basic parameters are presented in Table 1.

Table 1: Parameters of device

Parameter	Value	Unit
Coil dimension	0.1x0.03x0.03	m
Magnet dimension	0.1x0.03x0.03	m
Generator diameter	0.8	m
Number of coil	24	
Number of magnet	152	
Magnet’s magnetization, B0	1.4	T
Buoy radius	0.8	m
Buoy length	0.8	m
Buoy mass	200	kg

With a wave of 2m height and 7.0s period, the simulation results are presented on figures 5-10. Fig. 5 is the displacement of the buoy and wave. Fig. 6 is the velocity of buoy vs. time. Fig. 7 shows the excitation and Lorentz forces. The figures 8-10 are the electromotive force, output power and cumulative power from device vs. time.

The simulation results were compared with the experimental results of M. Eriksson [11] (Fig. 11) and shows the compatibility in quality.

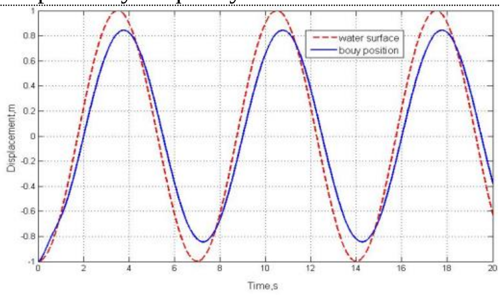


Fig. 5 Displacement of wave and buoy

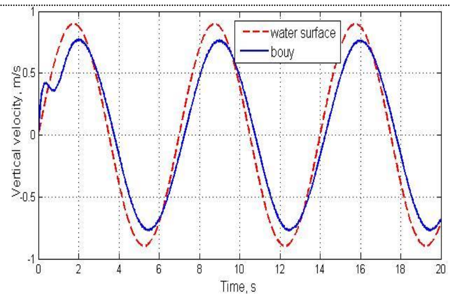


Fig. 6 Vertical velocity of buoy and water surface.

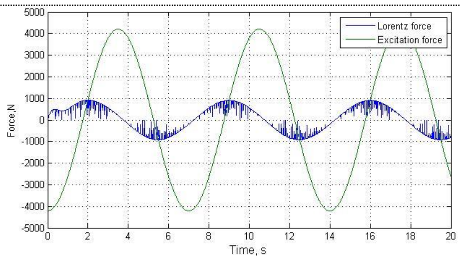


Fig. 7 Excitation and Lorentz force.

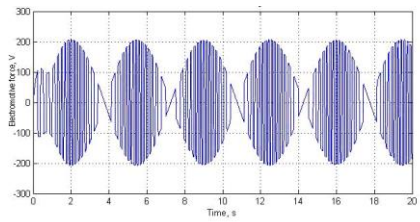


Fig. 8 Electromotive force of generator.

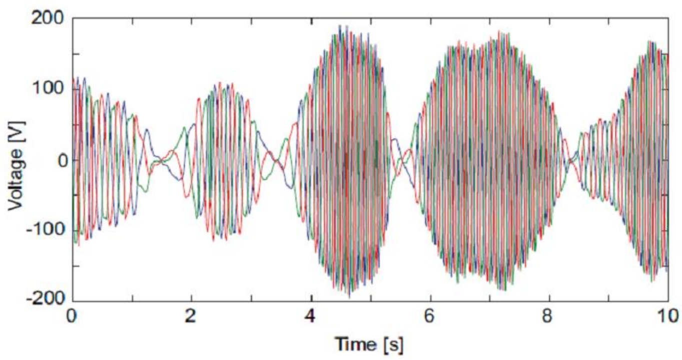


Fig. 9 Output voltages in experiment of M. Ericksson [11]

The average absorbed power of the device under different wave conditions are presented in Table 2. From there results, we can see that the output power are linear with the wave heigth.

Table 2. Output power vs. wave conditions

Wave height (m)	period (s)	P TB (w)
0.7	5.7	57.84
0.8	5.8	72.97
1.0	6.2	100.95
1.4	6.6	175.18
1.6	7.0	205.42
1.8	7.4	234.43
2.0	7.8	263.56
2.4	8.3	336.07
2.6	8.6	366.22
3.0	9.1	434.78

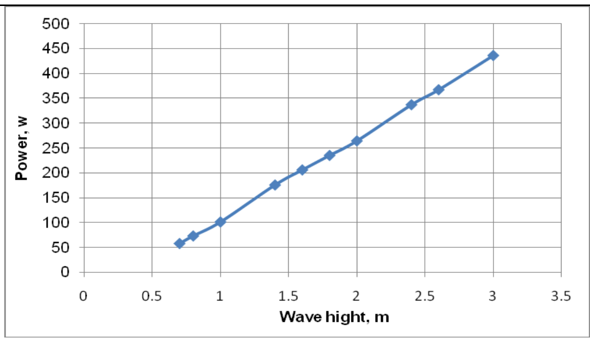


Fig. 10 Average output power vs. wave high

4. Conclusion

Wave energy data of Vietnam was analyzed. From the previous investigation on potential use of marine energy resource of Vietnam, it shows that the South-Central offshore has advantages of wave energy exploitation than the others. This region has a high energy demand, especially for social-economic development in the coastal zone and islands while other conventional energy sources can not meet the requirement. Therefore the South-Central sea is the appropriate area for research and development equipment to convert wave energy.

A simple configuration device including a buoy directly connected to a generator was modelled by a system of two ordinary differential equations. The first equation describes the motion of the buoy; the second equation describes the electromotive force of the generator. The system of equations was solved by Runge-Kutta method in Matlab. The magnetic flux of the permanent magnets in the generator was obtained by solving the Maxwell equations with FlexPDE software.

A device with output power of about 300W was investigated. The simulation results were generally consistent with the experimental results of M. Eriksson [11]. The model was used to investigate the dependency of the device output power on the device parameters and wave condition. These results can be used for designing, manufacturing prototype device in the laboratory and field experiment.

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