

## Analysis and Experiments of the Linear Electrical Generator in Wave Energy Farm utilizing Resonance Power Buoy System

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In this research, the linear electrical generator in wave energy farm utilizing resonance power buoy system is studied. The mechanical resonance characteristics of the buoy and the wave are analyzed to maximize the kinetic energy in a relatively small wave energy area where WRPS is operated. In this research, we chose an analog model of the linear electrical generator of which size is one-hundredth of an actual size of it in WPRS (Wave energy farm utilizing Resonance Power buoy System) prior to verifying the characteristics of actual model of linear electrical generator in WPRS. In addition, the finite element analysis is conducted using commercial electromagnetic analysis software named MAXWELL to examine the electric characteristic of linear generator. Finally, for the verification of dynamic and electric characteristics of linear generator, the prototype was manufactured and the experiments to measure the displacement and the output electric power were performed.

**Keywords :** buoy, linear generator, wave kinetic energy, resonance

### 1. Introduction

The importance of renewable energy has led to the preliminary development of a technology that converts wave energy to electric energy. Wave energy is an abundant, available energy source that can move over long distances without large energy losses. Waves are caused by winds blowing over the surface of the ocean. In many areas of the world, winds blow with enough consistency and force to provide continuous waves. Ocean waves carry tremendous energy. Wave power devices extract energy directly from the surface motion of ocean waves or from the pressure fluctuations below the surface of the waves. Wave power devices are generally categorized as the method to capture the energy of the waves such as float type, tube type, turbine type and movable body type.

Movable body type devices use the linear kinetic motion or rotational kinetic motion of the wave directly. The movable body type using rotational motion requires a complex and expensive dual structure to convert the reciprocating linear motion of a wave into rotational motion for power generation. In addition, the system efficiency is

significantly reduced because of the energy losses due to mechanical friction. On the other hand, the linear electrical generator can overcome the drawbacks of rotational motion as it can use linear kinetic motion of the wave straightly without any mechanical mechanism to convert the motion. Therefore, wave power generation system, which uses the linear electrical generator, has been studied in recent years [1-3]. As part of the recent research, we have been researching on WRPS (Wave energy farm utilizing Resonance Power buoy System). WRPS basically consists of a buoy, linear electrical generator, suction pile

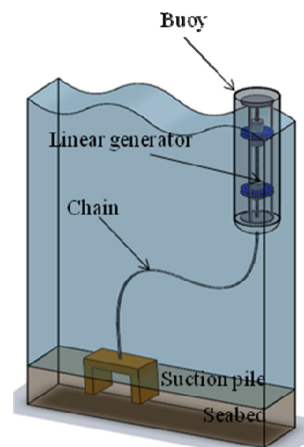


Fig. 1. (Color online) Schematic diagram of WRPS.

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and chain, and operates in depths of about 30m shown in Fig. 1.

The key technology of the WRPS magnifies the heaving motion to maximize the kinetic wave energy through the resonance between the frequency of the wave and that of the designed buoy. In result, amplified kinetic energy of the buoy leads to efficient production of electricity. Therefore, WRPS can produce sufficient electricity even with a relatively small wave energy area is required. The WRPS has height of [5m], diameter of [1m], and the size of the linear electrical generator in WRPS is 1[m] high, 0.2[m] width. The target output power of this WRPS is 2[Kw].

In this study, we chose an analog model of the linear electrical generator of which size is one-hundredth of an actual size of it in WRPS prior to verifying the characteristics of actual model of linear electrical generator in WRPS. Also, we analyzed dynamic and electric characteristics of the analog model of the linear electrical generator. The mathematical vibration model was created and analyzed to investigate the dynamic characteristic of the linear electrical generator. In addition, FEA (finite element analysis) was performed using commercial electromagnetic analysis software named MAXWELL to investigate its electric characteristic. Lastly, the experiments to measure the displacement and the output electric power were conducted for the verification.

## 2. The Linear Electrical Generator for WRPS

### 2.1. The structure and the operation principle of the linear generator for WRPS

Fig. 2 shows the schematic diagram of the linear generator in WRPS. The parts of the linear generator can be largely divided into moving parts and stator. Moving parts

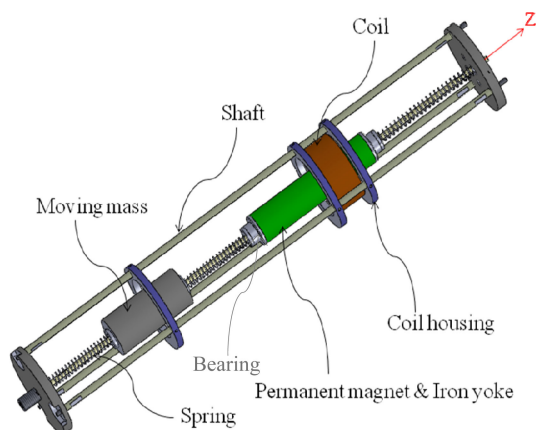


Fig. 2. (Color online) Schematic diagram of the proposed linear generator in WRPS.

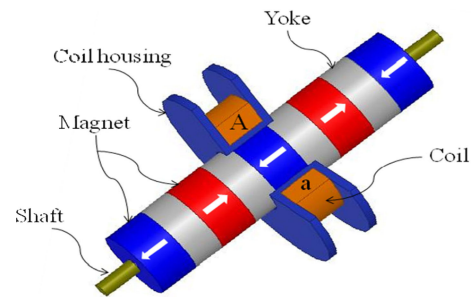


Fig. 3. (Color online) A detailed view of the slider and the stator.

consist of two moving masses; one, called the slider for electricity production, and the other one facilitates the vertical vibration between the slider and itself. Three compression springs and bearing enable the linear generator to vibrate up and down smoothly. Stator consists of solenoid coil and coil housing which is attached to the shaft.

Fig. 3 shows a detailed view of the slider and the stator in the linear electrical generator.

The part that actually generates the electricity consists of two main parts; the slider and the stator. The slider includes permanent magnets and steel bars. The permanent magnets are mounted between steel bars, called pole shoes, with the poles face to face. The pole shoes are made of steel and serves as conductors of the magnetic flux. The stator consists of coil windings and the coil housing, which is nonmagnetic material.

As shown in Fig. 3, the permanent magnets are axially magnetized and mounted alternately on the shaft. The magnetic flux generated by the permanent magnet flows in the opposite direction for each segment.

The electromotive force (emf) is generated at the stator coils terminals as the slider vibrates up and down by the heaving motion of the buoy. The electromotive force is calculated by Faraday's law and can be expressed by the following Eq. (1)

$$emf = -N \frac{d\phi}{dz} \frac{dz}{dt} \quad (1)$$

where  $N$  is the number of turns per coil,  $\phi$  is the flux passing in each turn in real time  $t$ ,  $dz/dt$  is the slider speed, and  $z$  is the distance along  $z$ -direction. So, the electromotive force is proportional to the speed of the slider, the number of coil turns and the amount of flux, which interlinks to the solenoid [4].

## 3. Dynamic Characteristics Analysis and Experiments

### 3.1. Mathematical vibration model and analysis

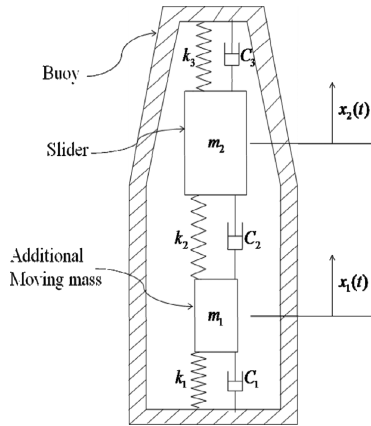


Fig. 4. Vibration model of the linear electrical generator.

Fig. 4 shows the mathematical vibration model of the linear electrical generator. The linear electrical generator in WRPS is a Two Degree of Freedom spring-mass system. The moving motion of this system is completely described by the coordinates  $x_1(t)$  and  $x_2(t)$ , which define the positions of  $m_1$  and  $m_2$  at any time  $t$  from their respective equilibrium positions. The application of Newton’s second law of motion to the system gives the matrix below (2)

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F\}$$

$$[M] = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}, [K] = \begin{bmatrix} k_1+k_2 & -k_2 \\ -k_2 & k_2+k_3 \end{bmatrix}, [C] = \begin{bmatrix} c_1+c_2 & -c_2 \\ -c_2 & c_2+c_3 \end{bmatrix}$$

$$[F] = \begin{Bmatrix} k_1 Y \\ k_3 Y \end{Bmatrix}, Y = y \sin\left(\frac{2\pi}{T}t\right) \quad (2)$$

In Eq. (2),  $[F]$  is the external force generated by wave energy, which causes the heaving motion of the buoy.

Table 1 shows the design specification of the system for vibration analysis.

To characterize the dynamic performance of the proposed design, mathematical equation is determined and cal-

Table 1. The design specification of the system.

	Symbol	Value [unit]
Additional moving mass	$m_1$	2.08 [kg]
Slider	$m_2$	3.02 [kg]
Spring 1	$k_1$	650 [N/m]
Spring 2	$k_2$	200 [N/m]
Spring 3	$k_3$	38 [N/m]
Damper 1	$c_1$	0.1 [N-s/m]
Damper 2	$c_2$	25 [N-s/m]
Damper 3	$c_3$	10 [N-s/m]
Amplitude of sinusoidal wave	$Y$	0.6 [m]
Period of wave	$T$	0.5 [sec]

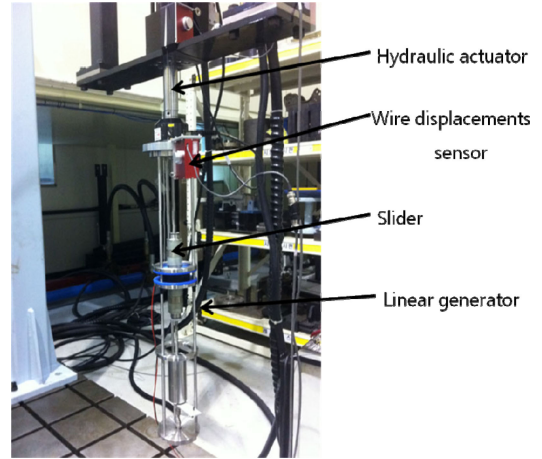


Fig. 5. (Color online) Prototypes of linear generator and experimental apparatus.

culated by using MATLAB program ode23.

### 3.2. Prototype and Vibration experiments

In order to verify the results of vibration analysis using MATLAB, the prototype of linear generator was made and experiment which uses wire displacements sensor was performed. Fig. 5 shows prototypes of linear generator and experimental apparatus for experiments.

The experiments apparatus consist of hydraulic actuator to depict wave motion, wire displacements sensor to check vibratory motion of slider and linear generator. As the linear generator and its slider vibrate up and down by sinusoidal vibration signal produced by hydraulic actuator, the wire displacements sensor measures the vibratory motion of slider and sends the signal to laptop which can visualize the time responding signal. Fig. 6 shows results of the vibration characteristics.

The ratio of the amplitude of the response  $x$  to that of the base motion  $y$  called displacement transmissibility is

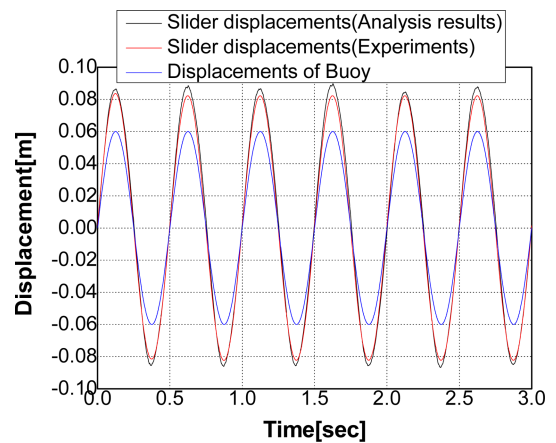


Fig. 6. (Color online) Results of the vibration analysis.

about 1.4, which means that even relatively small amplitude of wave can create sufficient motion of the slider for power production.

In the results, the displacement of the slider is shown as approximately  $\pm 82$  [mm]. The results prove that the strokes of the slider are sufficient to produce electricity, because the required strokes of the slider are about  $\pm 100$ [mm] for power generation considering the fact that the whole size of the proposed linear generator is limited and already determined.

### 4. Electric Characteristics Analysis and Experiments

#### 4.1. Simulation of the linear electrical generator

To examine the electrical performance of the proposed linear electrical generator, finite element analysis was performed by using the commercial electromagnetic software, MAXWELL. As the proposed linear generator is cylindrical shape, when it comes to an analysis model, a 2-D half cross section model has an advantage over an entire full model in respect to reducing analysis time. Therefore, we use the 2-D half cross section model using triangle elements for FEA in cylindrical coordinates. Fig. 7 shows entire model and 2-D model in cylindrical coordinates for simulation.

Table 2 shows the specification for FEA.

Fig. 8. shows the input velocity and displacement of the slider.

This FEA results reveals the behavior of the generator when the slider is moving at non-constant speed, and gives information on the voltages when the slider is moving with the movement of the ocean waves. In this simulation, input velocity of the slider, which refers to the results of the vibration experiments in chapter 3.2, is a

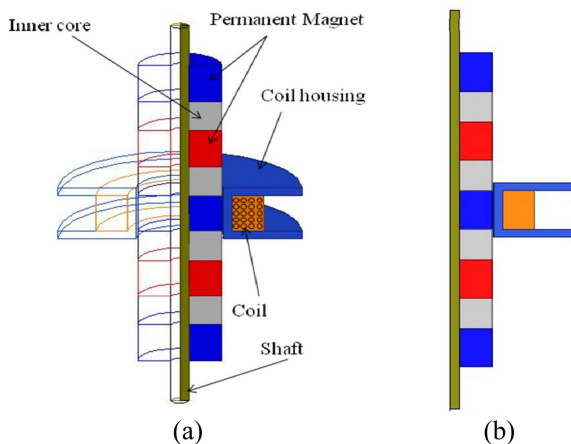


Fig. 7. (Color online) (a) Cross section view of analysis model (b) 2-D analysis model for simulation.

Table 2. The design specification for simulation.

	Variables	Value [unit]
Moving parts	PM height	25 [mm]
	PM width	19 [mm]
	Shaft width	10 [mm]
	Pole pitch	45[mm]
	Residual flux density	1.1 [T]
Stationary parts	Coil width	18 [mm]
	Coil height	25 [mm]
	Coil turns	1000 [turns]
	Air gap	6 [mm]

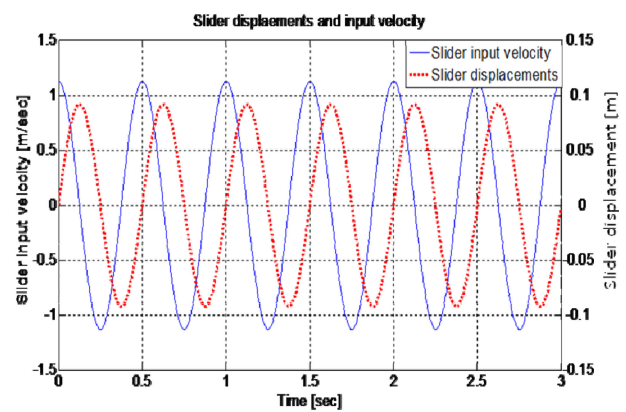


Fig. 8. (Color online) The input velocity and displacement of the slider.

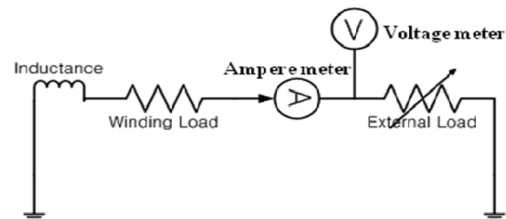


Fig. 9. Equivalent circuit for load analysis.

cosinusoidal wave of maximum amplitude of 1.1304[m/sec], and the slider follows the motion of a sinusoidal wave of amplitude 0.082[m] and period 0.5 seconds.

The output characteristics of the linear electrical generator are calculated by load analysis using equivalent circuit shown in Fig. 9. The linear electrical generator is connected to an external load [5].

#### 4.2. Experimental verification

For more exact verification for electric characteristics of linear generator, the additional experimental equipments were set up. Fig. 10 shows the schematic diagram of additional experiments.

As the hydraulic actuator is driven by power supplier



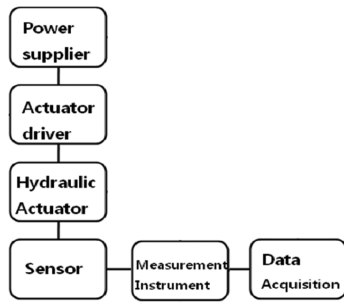


Fig. 10. The additional experiments process.

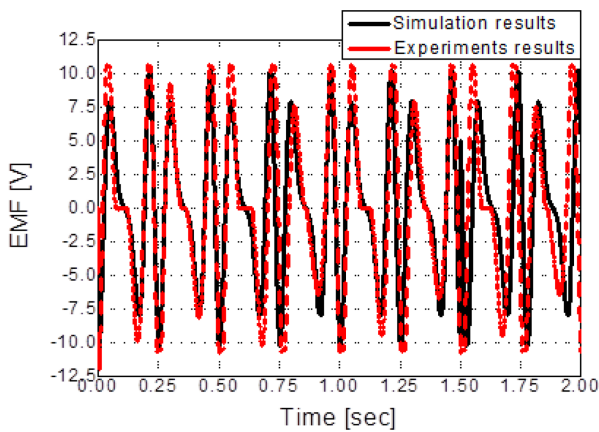


Fig. 11. (Color online) Results of simulation and experiments.

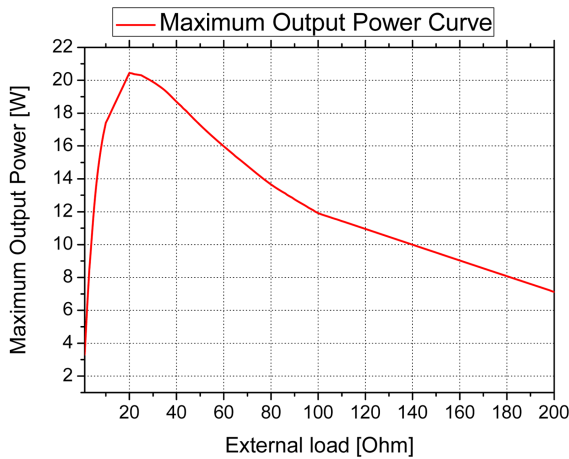


Fig. 12. (Color online) The maximum output power versus varying external loads.

and actuator driver, the linear generator vibrates up and down and the electro motive force produced by generator can be measured by Lab View software. Fig. 11 shows the results of FEA and experiments. The results reveal

that there is less error between the results of analysis and those of experiments and it can produce maximum voltage of 10[V]. Fig. 12 shows the maximum output power curve due to the varying external loads. As the results, we can find that the linear generator can produce maximum output voltage of 20[W].

#### 4. Conclusions

In this study, we analyzed the characteristics of the analog model of the linear electrical generator in WRPS. In order to characterize the dynamic performance of the linear electrical generator, mechanical vibration model was created. Also, dynamic characteristic of the linear electrical generator was calculated and verified through vibration experiment. This result proved that the displacement of the slider was sufficient to produce electricity and was amplified by 40% by mechanical resonance effect. This is because the excitation caused by wave motion cannot provide sufficient slider’s motion for power generation without mechanical resonance effect. Also, the FEA results showed that the linear electrical generator with a maximum voltage of 10[V] can be constructed, when the slider follows the motion of a sinusoidal wave of amplitude 0.082[m] and period 0.5 seconds. The experiments result about electric characteristics shows that there is less error between the results of analysis and those of experiments and it can produce maximum voltage of 10[V] and output power of 20[W]. Through experiments, the possibility of electricity generation is verified.

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