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Numerical Study of a Permanent Magnet Linear Generator for Ship Motion Energy Conversion

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Abstract. In order to harvest kinetic energy of a ship moving in waves, a permanent magnet linear generator is designed and simulated in the present study. For the sake of simplicity, only heave motion which will be considered in this preliminary study. The dimension of the generator is designed based on the dimension of the ship. Moreover, in order to designed an optimal design of rotor and stator, the average vertical displacement of heave motion is needed. For this purpose, a numerical method called New Strip Method (NSM) is employed to compute the motions of the ship. With NSM, the ship hull is divided into several strips and the hydrodynamics forces are computed on each strip. Moreover, because the ship is assumed to be slender, the total forces are obtained by integrating the force on each strip. After the motions can be determined, the optimal design of the generator is designed and simulated. The performance of the generator in terms of force, magnetic flux, losses, current and induced voltage which are the primary parameters of the linear generator performance, are evaluated using a finite element analysis software named Maxwell. From the study, a linear generator for converting heave motions is designed so that the produced power from the designed generator can be determined.

INTRODUCTION

It is known that ocean contains abundant renewable and clean energy resources such as wind, waves, solar, tidal, current, thermal, and salinity gradient energy resources. Besides their renewable and cleanliness characteristics, these energies are also can be converted continuously and available in most of the places on earth. Therefore, they have a significant amount of potential to be harvested and could make an important contribution to the supply of energy especially to communities located close to the sea. Amongst the ocean energy forms, significant advantages and opportunities have been identified when extracting waves energy form. Several advantages of the waves energy are longer available period and more stable and predictable power. Moreover, waves energy also has higher density than other energy forms which enables the device to extract more energy from a smaller volume and lower costs [1]. Therefore, researching and developing a method to extract and harvest waves energy is also significantly important to be conducted.

Methods to convert waves energy vary from simple methods to very complex ones. Most of the device can be classified into 2 (two) categories which are turbine-type and buoy-type [2]. Both methods have operational prototypes, and some of which have demonstrated the potential to be commercialized. Besides converting directly using above both methods, waves energy can also be converted indirectly from structure floating or operating in the ocean for example extracting the kinetic energy of operating ships in waves. In this case, a generator is installed aboard the ship which would convert the ship motions into electricity. It is known that a ship in waves has 6 (six) degree of freedom. However, converting all mode of motions will require a complex device. Therefore, in the present study only heave

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motion which will be considered. The heave motion is only a translational motion so it is possible to convert it using a simple linear generator.

In order to design a linear generator which can extract and harvest energy from the ship motions, the information about ship motion displacement is necessary. For that purpose, a numerical method called new strip method (NSM) developed by Kashwagi [3], is employed. NSM is a numerical method based on potential flow theory which assumes that the ship hull is slender so that it could be divided into a certain number elements or strips. The forces and moments are calculated on each strip so that the total forces and moments are obtained by integrating the forces and moments on each strip. After the motion displacement of the ship can be obtained, the linear generator is designed. In the present study, a software package called Ansoft Maxwell will be used. From the design, the expected power produced from the ship motion displacement can be predicted.

NEW STRIP METHOD

In order to determine the main dimension and parameters of the generator, the motions of the ship are necessary to be determined in the beginning. For that purpose, new strip method (NSM) is employed. The NSM is based on potential flow theory which assumes that the ship is long enough to be considered as slender. With this assumption, the ship could be divided into a certain number of strips. The strips are considered to be independent and have no interaction. Moreover, the forces and moments are computed on each strip so the total forces and moments are obtained by integrating the forces and moments on each strip.

Therefore, in order to solve the problem, a ship is assumed to advance with constant velocity U and oscillating with circular frequency ω in deep water. Moreover, a regular incident wave is also assumed to be incoming with angle β degree with respect to the ship advancing direction as shown in the following figure [4].

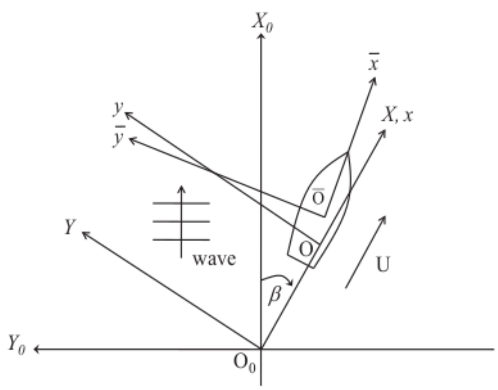


Figure 1. NSM Problem definition

In NSM, the symmetric mode of motions (surge, heave and pitch) are computed independently. Therefore, these longitudinal motions are computed by solving the following simultaneous equation [5].

$$\sum_{j=1,3,5}\left[-\omega^2\left(M_{ij}+A_{ij}\right)+i\omega_e B_{ij}+C_{ij}\right]X_j = E_i \quad \text{for } i=1,3,5 \tag{1}$$

Where ω_e represents the encountered frequency, M is the mass matrix, and C_{ij} is the restoring-force matrix. E_i is the wave-exciting force in i-th direction, A_{ij} and B_{ij} are the added mass and damping coefficients matrixes, respectively. X_j is the j-th mode of ship motions that we sought where j=1 for surge, j=3 for heave, and j=5 for pitch.

MAGNETIC MODEL

The present study will analyze and design the linear generator using a software package called Ansoft Maxwell. Maxwell is premier electromagnetic field simulation software for engineers tasked with designing and analyzing 3-D and 2-D electromagnetic and electromechanical devices such as motors, actuators, transformers, sensors and coils. Maxwell uses the accurate finite element method to solve static, frequency-domain and time-varying electromagnetic and electric fields. A key benefit of Maxwell is its automated solution process where users are only required to specify geometry, material properties and the desired output. From this point, Maxwell will automatically generate an appropriate, efficient and accurate mesh for solving the problem [6].

Maxwell software use finite element method as the main numerical method of its solver. The finite element method is a numerical technique for solving engineering problems involving differential equations applied over regions constrained by boundary conditions. The governing equations and boundary conditions for most problems can easily be determined, but it is usually difficult or impossible to find a closed-form, analytic solution. The finite element method provides an accurate numerical solution for such problems by dividing the model into small, interconnected elements and solving the governing equations for each small element. The elements are joined by ensuring the boundaries of each element are compatible with those of its neighbors and with the overall boundary conditions of the model. The entire solution can then be found by assembling all of the individual elements [7].

In Maxwell software, the finite element method is used to find the magnetic fields inside the linear generator in a magnetostatic case. Magnetostatic analysis is governed by Maxwell's equations which could be derived from the following basic Gauss's and Ampere's laws [8]:

$$\nabla \bullet \mathbf{B} = 0 \tag{2}$$

$$\nabla \times \mathbf{H} = \mathbf{J} \tag{3}$$

where **B** is the magnetic flux density vector, **H** the magnetic field intensity vector, and **J** the total current density vector. The curl of the magnetic vector potential which also satisfies Eq. (2), is defined as:

$$\mathbf{B} = \nabla \times \mathbf{A} \tag{4}$$

where **A** is the magnetic vector potential. By replacing Eq. (4) in (3), we obtain:

$$\nabla \bullet \nabla \times \mathbf{A} = \mu \mathbf{J} \tag{5}$$

Where μ = magnetic permeability. In addition to Maxwell's equations, the constitutive relation that describes the relation between flux density vector and magnetic material is given as [9]:

$$\mathbf{B} = \mu \mathbf{H} \tag{6}$$

By using the magnetic vector potential (**A**) in Eq. 4 along with the constitutive equation given in Eq. (6), Eq. (1) to be rewritten in terms of the magnetic vector potential as

$$\nabla \bullet \nabla \times \mathbf{A} = 0 \tag{7}$$

To insure the uniqueness of the magnetic vector potential formulation, the Coulomb gauge condition is described by [10].

$$\nabla \bullet \mathbf{A} = 0 \tag{8}$$

The Coulomb gauge coupled with the vector identity $\nabla \times \nabla \times \mathbf{A} = \nabla(\nabla \cdot \mathbf{A}) - \nabla^2 \mathbf{A}$ can be applied to Eq. (5) to obtain a vector Poisson equation as follows

$$\nabla^2 \mathbf{A} = -\mu \mathbf{J} \tag{9}$$

From Eq. (9), the model would be defined and load is applied to obtain a set of elemental differential equation which must be solved for each element of the model. Then, these elemental differential equations are assembled into a matrix equation representing the behavior of the entire system, the boundary conditions for finding magnetic flux and flux density in a magnetic field are imposed, and the solution for magnetic forces or torques related to the magnetic field is generated. In generating the solution, Maxwell software uses finite element method as described previously.

MAXWELL PROGRAM MODELLING

As described previously, the present study will use Ansoft Maxwell to design and simulate the performance of a linear generator. The general procedure of performing simulation in Ansoft Maxwell are as follows [11]:

1. Choose the type of electromagnetic analysis to be performed.
2. Draw the geometry of the model using the drawing space provided by the 3D Modeler menu and Draw menu command.
3. Assign the material properties to all solid objects in the model. Define new materials if needed materials are not provided in the default library.
4. Specify the field sources (excitations) and boundary condition to obtain a unique solution.
5. Define additional global parameters that are needed to compute such as torque, force, flux, inductance/capacitance, losses, etc.
6. Define mesh operations for special applications
7. Specify solution option by entering parameters that affect how the solution is computed.
8. Start to compute solution for the appropriate field quantities.
9. When the solution is available, post processing is performed such as plotting field quantities and calculating expressions.

These steps must be chosen in the sequence in which they appear. For example, a geometric model must be first created before material characteristics are specified for objects. A check mark appears on the menu next to each step which has been completed. The steps above can also be summarized in the following figure:

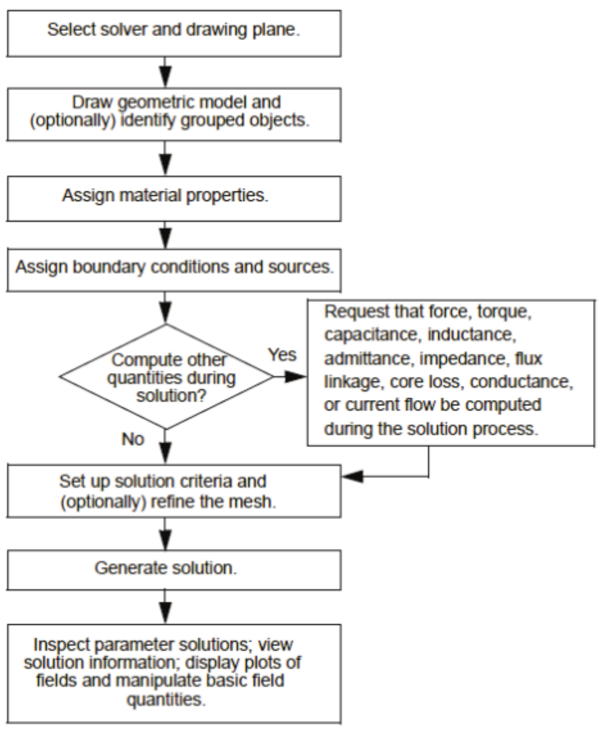


Figure 2. Flowchart of Ansoft Maxwell simulation procedure [12]

SHIP PARTICULARS AND MOTIONS

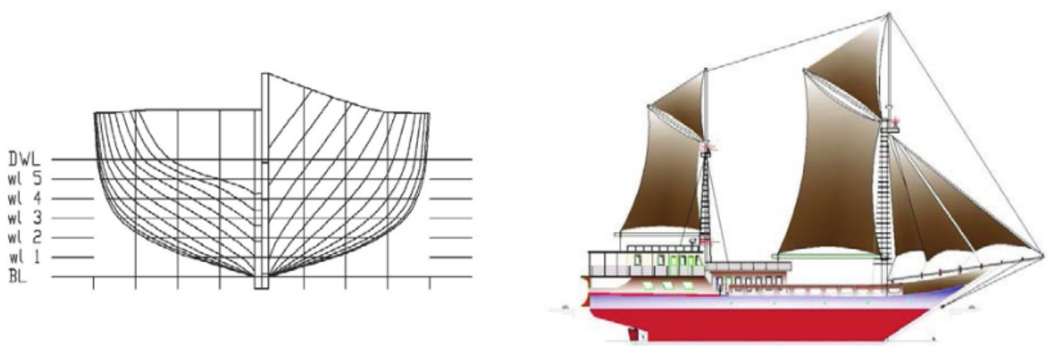
Ship Data

In order to predict the power produced by the designed generator, the data of ship and its motions are necessary. The data are taken from previous research by Mahmuddin [4]. The ship data computed in the previous research was a traditional type ship called Phinisi ship. The ship name is MV. Jacuzzi Bathups. The ship main dimensions are shown in the following table.

Table 1. Particulars of MV. Jacuzzi Bathups [4]

Parameter	Length (m)
Length overall (LOA)	45.20
Length waterline (LWL)	37.50
Length between peak (LBP)	28.70
Breadth (B)	10.00
Height (H)	3.85
Draught (T)	2.76

The ship body plan and its two-dimensional view are shown in the following figure:



(a) (b)

Figure 3. Body plan and 2D view of MV. Jacuzzi Bathups [4]

Ship Motions

By using New Strip Method (NSM), the previous study could predict the ship motions. 2 (two) Froude number cases are computed which are *Fn*=0.1 and 0.2. In both cases, the computations are performed for varying wavelength (***L***). The motions amplitude especially for heave motion is nondimensionalized by the incoming wave amplitude (ζ_a). Because the considered case was head waves case, only 3 degree of motions for each case which appear in graph as shown below

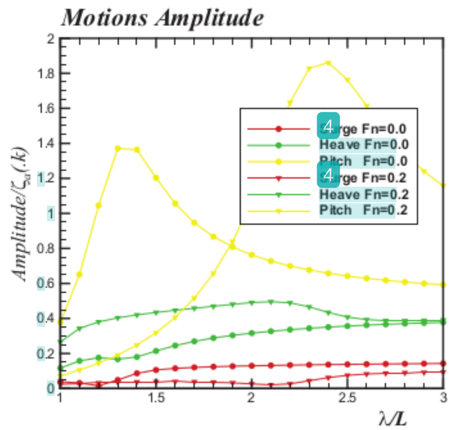


Figure 4. Motion amplitude for Fn=0.0 and Fn=0.2 [4]

In order to know the maximum displacement of the generator, the wave amplitude needs to be known. The average wave amplitude in the present study is assumed to be 0.125 m [13]. Therefore, the maximum displacement for heave motion equals to 1.0 m.

DESIGN AND SIMULATIONS

The designed linear generator in the present study will consist of a stator made from coils and a rotor made from a permanent magnet. Moreover, based on the ship dimension shown in Table 1 and heave motion amplitude shown in Fig. 4, the main dimension and parameters of the linear generator are determined which is shown in the following table

Table 2. Main dimension and parameters of the linear generator

Description	Value	Description	Value
Stator height	1000 mm	Rotor height	400 mm
Stator inner diameter	440 mm	Rotor diameter	435 mm
Stator thickness	40 mm	Rotor material	NdFe35
Stator material	copper	Rotor speed	1500 mm/s

By using Ansoft Maxwell software package, a linear generator which consists of a rotor and stator is designed using the input design and data shown in Table 2. The design is shown in the following figure.

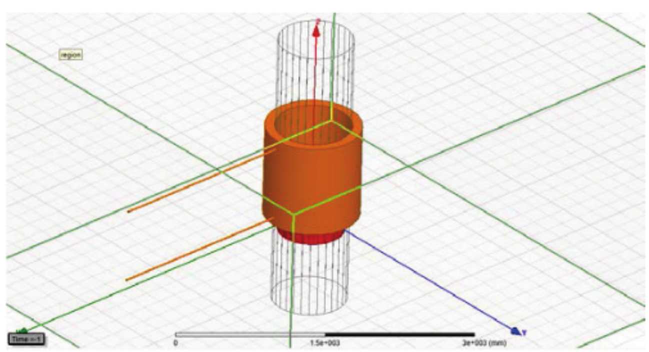


Figure 5. Generator stator and rotor

After the design and its parameters are determined. The simulation can be performed. The simulation result in terms of current are shown in the following figure.

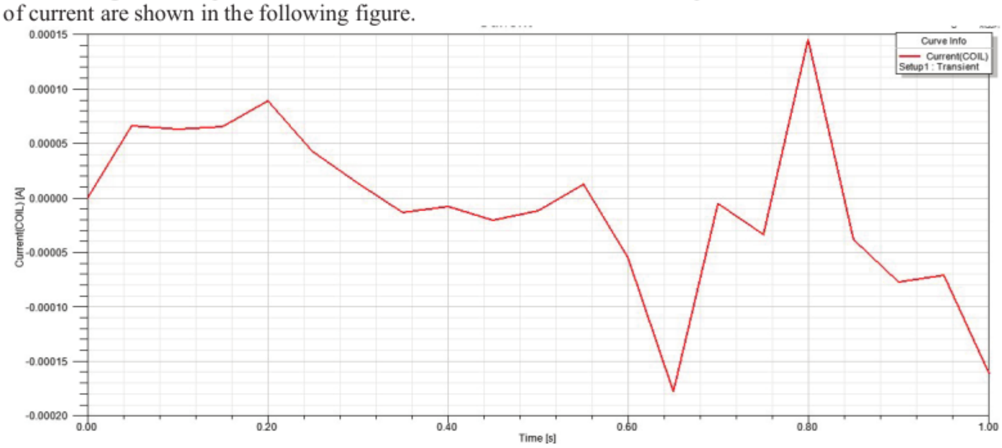


Figure 6. Current of the generator

Fig. 6 shows the current produced by the designed generator for varying time. It can be seen that the current has increasing tendency at the beginning of simulation but then it tends to reduce for longer time period. This is because the magnet has moved from the center of the coil to the end. The performance of the generator in terms of voltage is shown in the following figure.

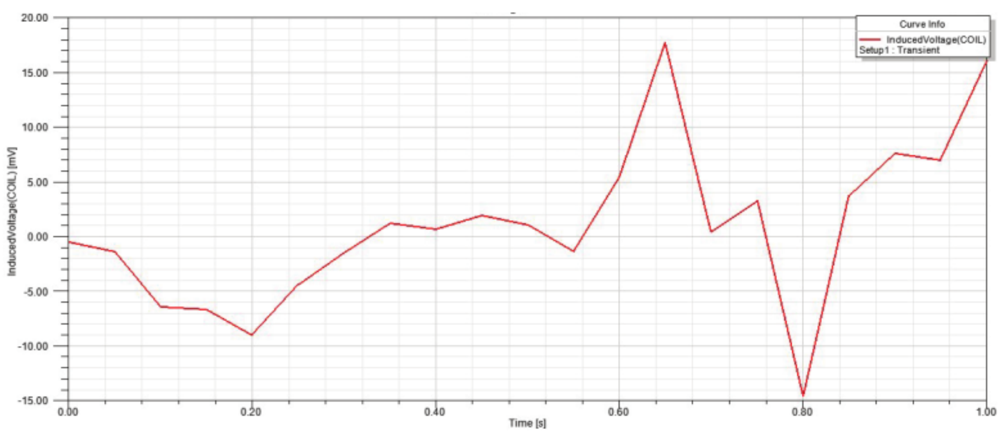


Figure 7. Voltage of the generator

From Fig. 7 above, we can see that voltage has reversed tendency as compared to current tendency shown in Fig. 6. It can also be seen that the highest voltage is produced when time equals to 0.72, which is around 18 mV while the lowest voltage occurs when the time equals to 0.8 which is -15 mV. The current and voltage results shown above are computed when the rotor is moving for one stroke. Therefore, from these results, the power produced by the designed linear generator can be predicted by considering the number of times the rotor oscillates.

SUMMARY

In the present study, a linear generator which is supposed to be used to harvest energy from ship motions, are designed. Only heave motion which is considered. The Ansoft Maxwell software package is used as the main tool for designing. Only the basic component of a linear generator which are rotor and stator, considered in the present study.

Moreover, the data from ship motions obtained from the previous research are used to determine the generator excitation and other parameters. The voltage and current produced from the designed generator are predicted and analyzed.

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