Experimental and Numerical Investigation of Magnetohydrodynamic Generator for Wave Energy

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The performance characteristics of a Liquid Metal Magnetohydrodynamic (LMMHD) generator, with a low melting point alloy U47 as the working liquid for wave energy conversion, were investigated numerically and experimentally in this paper. The numerical results show that a leakage current and an eddy current are in the regions of the electrodes’ ends. The experimental results of the open circuit agree well with those from the simulations, indicating that the model is right. The maximum output power of 1.1 kW was measured with a load resistance of 45 μΩ and a magnetic flux density of 0.9 T.

INTRODUCTION

Beyond all doubt, ocean wave energy will become an important clean and renewable energy in the near future. The global wave energy (including that on the open ocean) is in the order of $10^{13}$ W, a quantity that is comparable with the world’s present power consumption (Falnes, 2007). China has abundant ocean wave energy reserves with a theoretical value of 12.84 million kilowatts (Wang and Lu, 2009). Many different wave energy conversion devices have been proposed to utilize wave energy for human purposes. In recent years, they have become more specific. Traditionally, high-speed rotating generators are used for wave energy conversion, which require an intermediate system to convert the slow linear/rotation motion of the wave energy absorber into a high speed rotating one. Hydraulic systems or turbines are used for this purpose, which increase the complexity and cost and at the same time decrease the reliability and efficiency of the system (Eriksson et al., 2005). Therefore, direct wave energy conversion systems with a linear permanent generator or a Liquid Metal Magnetohydrodynamic (LMMHD) generator were developed.

An LMMHD Wave Energy Conversion (WEC) system makes use of a reciprocating LMMHD generator, whose speed-torque characteristics excellently match the mechanical impedance of an ocean wave, so there is no intermediate step. It is highly efficient and can be a very compact device with a very high power density, and it is expected to be one of the best ways to directly convert ocean wave energy into electricity. The LMMHD wave energy conversion technology has been researched at the Institute of Electrical Engineering, Chinese Academy of Sciences (IEECAS) since 2005. A demonstration LMMHD wave energy conversion device was designed, manufactured, and set up in 2008 (Peng, 2008). A series of experiments were carried out, and the output electrical power of 200 W was obtained (Li, 2010). Then a 2 kW LMMHD generator was developed in 2012. Many experiments with different loads under simulation conditions were carried out. In this paper, first, the concept of the LMMHD wave energy generation system is described; second, the experimental system is described and the experimental method is presented; third, the numerical simulation is followed; finally, the performance characteristics of the generator under different experimental conditions are analyzed emphatically and compared with those from the numerical simulation.

LMMHD WAVE ENERGY GENERATION SYSTEM

Liquid Metal MHD Generator

As shown in Fig. 1, the liquid metal with a low density, low viscosity, and high conductivity, such as U47, is forced to flow back and forth within a flow channel in response to an external force such as the wave force. A vertical magnetic field is established across the flow channel by a permanent or superconducting magnet. According to Faraday’s law of electromagnetic induction, an Electromotive Force (EMF) is generated between the electrodes. There is an electrical current with a load, and thus electric power is produced.

Oscillating Float Type LMMHD WEC System

Figure 2 shows a kind of liquid metal MHD wave energy conversion system with an oscillating float. The floaters are on the surface of the ocean and moves up and down with the waves to extract the wave energy. The floaters is connected to the LMMHD generator with a shaft and forces the liquid metal to flow up and down within the magnetic field inside the LMMHD generator. Compared to the traditional rotating wave generation system, there is no rotating part or intermediate system, which not only obviously improves the system’s power efficiency and reliability, but also reduces its cost and simplifies the installation. Furthermore, it can work in the low sea condition.

EXPERIMENTAL STUDY

Description of the Experimental System

The experimental system is composed of a liquid metal MHD generator, a wave simulation system, and connection pipes, as shown in Fig. 3. The wave simulation system includes a master cylinder, a slave cylinder, and a hydraulic station (system), which simulates the wave’s reciprocating motion and provides a reciprocation stroke of less than 1 m. In the simulation system, the working liquid is the hydraulic oil L-HM 46. The hydraulic station drives the master cylinder’s piston and then drives the piston in the slave cylinder to do a vertical and reciprocating motion by the hydraulic transmission.
The LMMHD generator mainly includes two piston accumulators, an integrated generating channel, and a permanent magnet. The two piston accumulators and generating channel are connected space through which the liquid metal U47 flows. The two piston accumulators are connected to the slave cylinder. Shaftless pistons coaxial with the piston accumulators make the oil and liquid metal separate. The integrated generating channel is through the air of the magnet. Figure 4 shows a photo of the developed liquid metal MHD generator. Figure 5 shows a photo of the integrated generating channel that is made of polyoxymethylene (POM). Its effective cross-sectional area is $50 \times 6 \text{ mm}^2$ with the effective length of 160 mm in the flow direction. It has rectangular to circular transition sections at both ends in order to connect with the piston accumulator. The electrodes are made of copper and are symmetrically embedded in both sides of the channel.
The permanent magnet adopts a split structure, and the permanent material is embedded in the pits of the generating channel’s outer surface. The permanent magnet has a rectangular air gap that is 50 mm in the magnetic field’s direction. The permanent magnet produces a 0.9 T magnetic field perpendicular to both the flow direction and the electrical magnetic field. The measured distribution of the magnetic flux density along the flow direction (Z-direction) is shown in Fig. 6. From \( Z = -60 \text{ mm} \) to \( Z = 80 \text{ mm} \), the magnetic flux density distributes almost evenly with the value of above 0.9 T. In the end regions, the magnetic flux density varies sharply with very large gradients.

**Experimental Method**

Before the installation of the magnet, the hydrodynamic experiment of the device was carried out first. The flow pressure drop with different velocities of the working liquid and at different times was measured. After the installation of the magnet, the open-circuit experiments were conducted first. Then the performance parameters with different loads were measured.

A Banner laser displacement sensor (model LT3NU) with a measuring range of 0.3 to 5 m was used to measure the differential displacement of the piston (see Fig. 7). Two pressure transducers located on the sidewalls, up and down the generator, were used to measure the pressure drop across the generator. Another two pressure transducers located on the sidewalls, up and down the slave cylinder, were used to measure the pressure drop across the slave cylinder. An Omega pressure transducer (model PX309-500G1) with a pressure range of 0 to 340 kPa and an accuracy of 2% was used to measure the differential pressure of the device (see Fig. 8). A PAS current transducer (model HDIE-C45) with a range of 0 to 10000 A and an accuracy of 1% was used to record the current of the load (see Fig. 9). A PAS voltage transducer (model JUI-C51) with a range of 0 to 2 V and an accuracy of 1% was used to measure the voltage of the load (see Fig. 10). All the digital signals from the sensors were acquired by a ZTIC data logger (model EM9636B). Figure 11 shows the schematic diagram of the data acquisition, and Fig. 12 shows the interface of the data collection system. The piston’s speed of the slave cylinder was calculated as:

\[
V = \frac{S_n - S_{n-1}}{\Delta t}
\]

where \( S_n \) is the distance at \( t_n \), \( S_{n-1} \) is the distance at \( t_{n-1} \), and \( \Delta t = t_n - t_{n-1} \). \( V \) is changed by adjusting the output power of the hydraulic station.
### NUMERICAL SIMULATION

#### Simulation Conditions

Figure 13 shows the calculation region for numerical analyses. The size of the generating channel is as described in Fig. 5. There is a magnetic field in the effective zone. Table 1 shows the system parameters. To facilitate a comparison between the simulation and experimental results, the inlet velocity of the channel was imported via a velocity data file, which was obtained from the experiment.

The output electrical parameters of the channel are listed as follows:

- The output voltage:
  \[ U = B u_{\text{MHD}} b k \]  
  (2)

- The output current:
  \[ I = \sigma B u_{\text{MHD}} a l (1 - k) \]  
  (3)

- The output power:
  \[ P = \sigma B^2 u_{\text{MHD}}^2 a b l k (1 - k) \]  
  (4)

where \( B \) is the magnetic flux density, \( u_{\text{MHD}} \) is the velocity in the channel, \( a \) is the width of the electrodes, \( b \) is the distance between the electrodes, \( l \) is the effective length of the generating channel, \( \sigma \) is the conductivity of the liquid metal, and \( k \) is the load factor of the system.

#### Numerical Method

In an LMMHD generator, the flow field and electromagnetic field are coupled with each other in the generating channel. The fluid flow abides by time-dependent, incompressible Navier-Stokes equations including the MHD effects. The governing equations for the electromagnetic field consist of Maxwell’s equations and Ohm’s law. The continuity equation, momentum equations, Ohm’s law, and Maxwell’s equations can be written, respectively, as:

- Continuity equation:
  \[ \nabla \cdot \vec{u} = 0 \]  
  (5)

- Momentum equation:
  \[ \frac{\partial \vec{u}}{\partial t} + \rho \vec{u} \cdot \nabla \vec{u} = -\frac{1}{\rho} \nabla p + \mu \nabla^2 \vec{u} + \vec{j} \times \vec{B} \]  
  (6)

- Ohm’s law:
  \[ \vec{j} = \sigma (\vec{E} + \vec{u} \times \vec{B}) \]  
  (7)

- Maxwell’s equations:
  \[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \]  
  (8)

where \( \vec{u} \) is the velocity, \( \rho \) denotes the density, \( p \) is the pressure, \( \mu \) is the viscosity, \( \vec{j} \) and \( \vec{B} \) denote the current density and magnetic flux density, respectively, and \( \sigma \) is the conductivity of the liquid metal, and \( \vec{E} \) is the electrical field intensity.

The MHD model in the Fluent software was used to calculate the flow field, induced magnetic field, and induced current of the LMMHD generator. The Magnetic Induction Method (MIM) was adopted, and the external magnetic field (shown in Fig. 6) was imported via a magnetic data file. The electromagnetic variables, such as the induced magnetic flux vector, induced electric current density vector, induced electric field vector, and Lorentz force vector, were obtained.

### RESULTS AND DISCUSSIONS

Figures 14 and 15 show the distribution of the flow and electromagnetic fields in the generating channel. Because of the electromagnetic force, the velocity is not distributed evenly. Therefore, the potential in the channel is not distributed evenly. As described in Fig. 14, a small eddy exists at the inlet and outlet of the channel, which will cause a leakage current. Figure 15 shows that at the normal time, the potential distributes evenly and the most current can go through the load resistance. The eddy current generated due to the uneven distribution of potential in the channel leads to a lower efficiency of conversation than that at the normal time.
Pressure Drop Without the Magnetic Field

There are two incompatible fluids in the device system; one is the liquid metal U47 and the other is the hydraulic oil L-HM 46. The pressure drop of the liquid metal can be obtained from the pressures at the two ends of the generating channel:

$$\Delta p_c = p_{1c} - p_{2c}$$

where $p_{1c}$, $p_{2c}$ = the pressures at the two ends of the generating channel.

The pressure drop of the oil can be obtained from the pressures at the two ends of the slave cylinder:

$$\Delta p_s = p_{1s} - p_{2s}$$

where $p_{1s}$, $p_{2s}$ = the pressures at the two ends of the slave cylinder.

The experimental data were collected from the pressure and optical displacement sensors. The pressure drops in the channel and slave piston were also compared and analyzed with the results from the calculations, as shown in Fig. 17.

Figure 16 shows the piston’s displacement and velocity of the slave cylinder varying with time. It can be seen that both the displacement and velocity vary sinusoidally with time and there is a phase lag between them. The maximum displacement is 0.3 m, and the maximum velocity is about 0.5 m/s. From Fig. 17, it can be seen that the pressure drops; $\Delta p_c$ and $\Delta p_s$ vary with time periodically, and $\Delta p_s$ is larger than $\Delta p_c$. It can also be seen that the results from the calculations and experiment agree well.

Performance Characteristics of the Open Circuit

In the open-circuit experiment, the voltage data were collected in addition to the pressure and displacement. The results are shown in Figs. 18, 19, and 20. It can be seen that the piston’s displacement and velocity of the slave cylinder, the pressure drops in the channel and slave piston, and the voltage vary with time periodically, and are compared with the results from the calculations. It can also be seen that the results from the calculations and experiment match well.

Performance Characteristics with Loads

In the load experiment, six different loads (45 $\mu\Omega$, 53 $\mu\Omega$, 78 $\mu\Omega$, 113 $\mu\Omega$, 166 $\mu\Omega$, and 192 $\mu\Omega$) were used. The experimental
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Fig. 21 Piston velocity and displacement in load condition

Fig. 22 Pressure drop performance in load condition

results with 45 $\mu\Omega$ are shown in Figs. 21 to 25. It can be seen that the output voltage, current, and power vary sinusoidally with time. The period of the output voltage and current is 2 s and that of the output power is 1 s because the output power is the product of the output voltage and current. It can also be seen that the maximum output voltage is about 0.33 V and the maximum output current is about 3250 A, which shows that the LMMHD generator has the characteristics of low voltage and high current. Under this condition, the peak output power of 1100 W was measured.

CONCLUSIONS

An LMMHD generator with U47 as the working liquid was developed, and experiments under simulation conditions were carried out. From the experimental and numerical results, the following conclusions were obtained:

1. The LMMHD generator experiment device generates AC electricity and the output voltage. The current and power vary sinusoidally with time under a simulated wave condition.

2. Except for the output power, the other performance parameters have the same period as that of the simulated wave. The period of the output power is half the period of the simulated wave.

3. The simulated pressure drops and open-circuit voltage are matched well with those from the experiments without the magnetic field or loads.

4. Under a simulation condition with a period of 2 s and a stroke of 300 mm, the maximum output power of 1.1 kW was measured with a load resistance of 45 $\mu\Omega$ and a magnetic flux density of 0.9 T.

The 10 kW sea pilot device is being developed. The sea trial will be carried out in the near future.
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