Design of a Wave Powered Combination Electric Generator Based on the Liquid Metal MHD

(Sun Yue, Master, School of Energy Science and Engineering, Harbin Institute of Technology, Harbin, 150001)

Highlights

>This system includes two parts of power generation, a buoy-swing plate system and a hanged plate-pendulum system.

>With these two part, this system can make full use of wave energy, include wave energy and vibration energy.

>This system simplifies the process of Mechanical transmission, so that it can decrease the mechanical loss.

>This system provides a more effective method of power generation, reduce the cost. It can provide electricity to industrial production and scientific research so that it can take significant economic results.

Design of a Wave Powered Combination Electric Generator Based on the Liquid Metal MHD

(School of Energy Science and Engineering, Harbin Institute of Technology, Harbin, 150001)

Abstract: The aim of this paper is to develop an innovative method for electric power conversion of the ocean wave energy. The wave energy is a kind of new clean energy, while its feature of low density and instability made it cannot be used efficiently. The efficiency of the existing wave energy plant is no more than 20% mostly. A combined magneto hydrodynamics-based wave energy converter (CMHDWEC**)** is proposed to enhance the electric power generation from wave fluctuations. In the CMHDWEC design, the working media of this system is magnetic fluid, such as mercury, and the generating terminal is the MHD channel. This device absorbs wave energy through a plate-pendulum hanged on the girder, and converts the wave energy into electric power using the MHD channel. Design concept and the working principle were firstly demonstrated. Then the key technologies of main components system are carried out for an adequate explanation of the proposed system. Finally, numerical simulations using were performed to verify the effectiveness of the system. From the simulation results，the electric power generated can achieve to 20kW when the system is run under the steady-state operating conditions.

Key words: Wave energy, Combination, Converter, MHD channel, Numerical simulation

Nomenclature

B	Complex magnetic field (T)
b,h,l	The width, height and length of MHD channel (mm)
c	Specific heat capacity of the magnetic fluid (J/kg·K)
J	Density of induced currents (A/m2)
k	The external load factor
P_{o1}	Output Power of MHD channel with one wheel drive (W)
P_{o2}	Output power of the buoy-swing magnetic fluid system (W)
R_l, R_g	External resistance and internal resistance of MHD channel (Ω)
V	Velocity of the magnetic fluid (m/s)
λ	Thermal conductivity of the magnetic fluid (W/(m·K))
ν	Kinematic viscosity of the magnetic fluid (St)
ρ	Density of the magnetic fluid (Kg/m3)

σ	Conductivity of the magnetic fluid (S)
Φ_V	Viscous dissipation (J)
Φ_{JH}	The Joule heat (J)
ω	Flow frequency of the magnetic fluid (rad/s)

1 Introduction

Energy saving and emission reduction is a common topic in current world, and renewable energy is becoming increasingly important due to the expected exhaustion in the current energy resources[1], more and more people have been paying their attention to explore and utilize sustainable energy. Among the new energy, ocean energy occupied the quite essential position because of the tremendous storage on the earth, and the wave energy has been regarded as one of the most promising renewable technologies. Compared with other sustainable technologies, wave energy is more dependable, and the power at a given site is available up to 90 percent of the time, while solar and wind availability tend to be available just 20-30 percent of the time[2]. The waves are produced by wind directly, being considered as an indirect form of solar energy therefore [3]. The possibility of converting wave energy into other usable energies has inspired numerous inventors for a long time: thousands of patents had been registered by 1980 and the number is increasing rapidly [4]. Interestingly, the earliest patent was filed in France in 1799 by a father and a son named Girard [5]. And it can be seen that the final product of the most devices developed or considered is electrical energy from the patents registered so far.

Experiencing decades of development, the four main types of energy harvest and storage methods have been applied in wave energy generation (WEG). The first type of devices is based on oscillating water column (OWC), which is most widely used in current research and utilization. This WEG method depends on the air column and the pressure difference generated by waves. The rotational motion of air turbine rotor caused by the compressed air makes it possible to store amounts of energy as kinetic energy or convert mechanical energy into electrical energy through generator connected to turbine [6]. The second type is overtopping method, whose working principle is in much the same way as a hydroelectric dam and stores energy as potential energy in a water reservoir[7], such as Wave Dragon constructed in Denmark. Incoming waves surged up into a reservoir placed above the mean water level through two wing reflectors towards a doubly-curved ramp which is used to focus the waves [8]. The third type is oscillating wave surge converter, which is more efficient for ocean waves of low frequencies and large forces, with a pendulum hanging on a girder or fixing on the seabed, and the pendulum swings within a certain angle range to drive the electrical generator through some devices, such as hydraulic pump. And the last type is point absorber method, whose horizontal size is much smaller than the wavelength. The strength that point absorbers possess is they can effectively convert the vertical motion of ocean waves in linear and rotational motion for driving the electrical generators by means of a power take off (PTO) system [9].

Last few decades, most of the existing technologies are complex, expensive devices with the low efficiency, and in most cases they can't be scaled down or use offshore and on shorelines [10]. The pendulum type are regarded as one of the three commercial power stations, many organizations or inventors focusing their attention on that how to make it more effective in converting waves into electrical energy under several conditions. In addition, a new method using magnetic fluid instead of solid metal to generate electricity has been applied in some conditions, Carsten M. invented the Double-duct Liquid Metal Magneto hydrodynamic (MHD) Engine in 1995[11], and some other studies found it a satisfying method to generate electric energy using MHD. Then in this paper, the pendulum was combined with floating-swing body and the MHD channel to convert the mechanical energy of liquid metal by wave energy into reciprocally electrical energy.

The remaining of this paper organized as follows: Section 2 described the *CMHDWEC* design concepts and in detail, including the structures of four parts. Section 3 simulated the main process of the system, such as the mechanical transmission and the liquid metal flow in the magnetic field. Section 4 discussed the benefit of the proposed system, and the conclusions were conducted in last section.

2 CMHDWEC design concept

2.1 General concept of CMHDWEC

The system configuration is depicted in Figure 1. The proposed CMHDWEC system includes four main components: a hanged plate-pendulum system, a mechanical transmission system, a MHD system and a buoy-swing magnetic fluid system.

The plate-pendulum is hanged in the water chamber, which is used as a reflector of incident waves, and the slotted rockers fixed to the plate drive the wheel run synchronously. Then the pushers connected to the wheels are mounted in the channel and the channel is full of magnetic fluid. Besides, the buoy-swing magnetic fluid system is floated above the water.

2.2 CMHDWEC working principle

The design principle of the proposed system is to convert the ocean wave energy in high efficiency by using MHD channel. The plate will move reciprocating within a range of angles under the shock of incident waves, and the rockers will swing with the plate synchronously. Meanwhile, the rockers will drive the wheels rotate incompletely. With the effect of the mechanical transmission system, the pushers mounted in the MHD channel will make the liquid metal flow in the magnetic field, accompanying the cutting magnetic induction line. In the other hand, the buoy-swing magnetic fluid system in the water chamber will move ups and downs, and then the magnetic fluid will flow spontaneously in the channel due to the gravity. According to the physical facts, the energy of reflected waves is strong enough so that we can make full use of it. The strength of the combination is both fluctuant and vibrational energy can be utilized.

2.3 CMHDWEC key technologies

2.3.1 Hanged plate-pendulum system

As the key part of the energy capture unit in CMHDWEC system, the hanged plate-pendulum is used to collect the horizontal wave energy. Considering the marine reality, the designers gave four types of plate to choose, that are: rectangle, inverted cone, cone and serrated, and they were depicted in Figure 2. Compare the deflection angle of the four types; the rectangle type can swing within the range of -33°~-8°, the inverted cone is -63°~-15°, the cone is -80°~59°, and the serrated is -31°~-3°.

Obviously, only the cone can get the forward angle, and the others are always negative angle. Because of the structure limit and the best effect of energy absorption, the cone type is chosen to be the main wave absorber.

2.3.2 Mechanical transmission system

To ensure the uniformity of the motion of plate, we restrict the deflection angle varying from -30° to +30°. The *wheel-connecting rod-pusher* structure is adopted as the main mechanical transmission system. The wheel is double layers structure, and the layers are connected with three cylinders. The rockers are hanged on the rollers extended from wheels. When rockers swing back and forth between -30°and +30° with plate synchronously, a linear relative displacement in the rockers' groove of the rollers will occur, followed by the reciprocating rotation of wheel and the reciprocating linear displacement of pusher to drive the liquid metal flow.

2.3.3 MHD system

From the explanation above, the plate-pendulum system and the mechanical transmission system can convert the wave fluctuant and vibrational energy into the kinetic energy of liquid metal, shown as the behavior of liquid metal flowing in the magnetic field. When the flow direction is perpendicular to the magnetic field, it will generate the electromotive on the electrode; the schematic is shown in Figure 3.

The liquid metal is filling in the piston cylinder, the force from the transmission system push the piston to do the reciprocating motion, and the liquid metal flows reciprocating in MHD channel as well to cut the magnetic induction line. To improve the power density of generating electricity, the area of the cross-section of the cylinder is much larger than that of MHD channel; therefore, the liquid metal will flow the generating channel with the velocity several times than the velocity of the piston.

2.3.4 Buoy-swing magnetic fluid system

Buoy-swing magnetic fluid system is a relatively independent unit, if it occurs the change of water level in chamber or wave fluctuations, the system can be used as a small electric generator. Generally, the system is installed on the back wall of chamber with hinges, and the buffer devices are added to weaken the impact of the wave. The best advantage is that the device can use wave energy spontaneously without any mechanical transmission system, and the high energy conversion ratio thereafter. The structure diagram and the operation process are shown in Figure 4 and Figure 5 separately.

3 Simulations and Results

3.1 Mechanical transmission systems

According to the model of ocean wave, particles of water are conducted with a simple harmonic motion. The superposition of incident waves and the reflected waves by chamber wall causes a harmonic torque to plate-pendulum. Then the plate makes a sense to the wheel, followed by the motion of connecting rods and pushers. Next, we use the SIMMECHANICS module of MATLAB to simulate the process of mechanical transmission, including the wheel, connecting rod and the pusher of piston cylinder .etc. Considering the energy dissipation process of magnetic fluid flow and the pressure change of fluid, add the corresponding damping to the simulation system, as Figure 6 shown. Give the sinusoidal signal like the motion of ocean wave as input, and then get the velocity variation of the pusher, shown in Figure 7.

From the results, we can see that with the effect of mechanical transmission system, the pusher of the piston can get the approximate sinusoidal motion with the peak velocity v=0.4m/s and the cycle period T=5s, which provides a regular propulsion to the latter motion of the magnetic fluid.

3.2 MHD assessment

In this system，mercury is chose to be the magnetic fluid. If we neglected the compression，we can establish equations of MHD:

Continuum equation:

$$\nabla \cdot V = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial V}{\partial t} + (V \cdot \nabla) \cdot V + \frac{1}{\rho} \nabla p = \nu \nabla^2 V + g + \frac{1}{\rho} (J \times B) \tag{2}$$

Energy equation:

$$\rho c \frac{DT}{Dt} = \nabla \cdot (\lambda \nabla T) + \Phi_V + \Phi_{JH} \tag{3}$$

Where: V is the velocity of the magnetic fluid (m/s); ρ, ν, c, λ is the density (Kg/m^3)，kinematic viscosity (St)，specific heat capacity (J/(kg·K)) and thermal conductivity（W/(m·K)）of the magnetic fluid; J is the density of induced currents（A/m^2）; B is the complex magnetic field（T）; Φ_V is the viscous dissipation（J）;Φ_{JH} is the Joule heat (J). When simulate this flow with the MHD module of FLUENT based on these equation，and get results as Figure 8.

Looking at simulation results above，we find that it will conduct symmetry induced currents and magnetic field within the channel when out of load. The velocity of the mercury close to the wall will be faster due to the Lorentz force. All of this channel can provide output current around 10^4A.

3.3 The performance of generating unit

The principle of electricity generation with magnetic fluid is electromagnetic induction, with which we analyze the performance of LMMHD unit.

Velocity of the magnetic fluid:

$$v = v_{max} \sin \omega t = v_{max} \sin\left(\frac{2\pi t}{T}\right) \tag{4}$$

Voltage, Currents and Power of the magnetic fluid:

$$U = Bvbk = Bv_{max} bk \sin(\omega t) \tag{5}$$

$$I = \sigma Bvhl(1-k) = \sigma Bv_{max} hl(1-k)\sin(\omega t) \tag{6}$$

$$P = 2UI = 2\sigma B^2 v_{max}^2 bhl(1-k)^2 \sin^2(\omega t) \tag{7}$$

Where : ω is the flow frequency of the magnetic fluid (m); σ is the conductivity of the magnetic fluid (S); b, h, l are the width, height and the length of the magnetic fluid channel (m); $k = R_l / (R_g + R_l)$ is the external load factor; R_l, R_g are the external resistance and the internal resistance of the magnetic fluid channel (Ω).

Based on the equations above, the output power under different load factor and the output power variation with time are shown in Figure 9 and Figure 10 respectively. From these analysis, we find that the power will be maximum when *k*=0.5 and *v*=6m/s, and the output power of the magnetic fluid channel with one wheel drives is $P_{o1} = 7.5\text{KW}$ .According the design condition, the output power of the buoy-swing magnetic fluid system is $P_{o2} = 1.5\text{KW}$. Compare with the existing power generation driven by hydraulic pump, this system can increase the output power around 30%.

Besides，the starting torque of this system is smaller than the existing system obviously. So，it will be more dominance in small wave condition.

4 Discussions

The system doesn’t have the economic benefit, but the environmental benefit. According to the analysis above, if we combine two MHD channels and three buoy-swing magnetic fluid systems as a generator to convert ocean wave, it will get about 19.5 kW output, i.e. 614952MJ per year. Calculate with the parameters of existing common coal-powered plants (the efficiency is about 40%, the calorific value of standard coal is 29307kJ/kg, the combustion efficiency is 0.9, and the average carbon emission factor is 0.8), and the generator can reduce the amount of CO_2 emission 68.389t, SO_2 emission 1t, and NO_x emission about 0.5t.

Besides, the design has wide ranges of potential applications due to its many advantages.

(1) This design is based on the specific ocean wave model，and it can be used in coastal area to generate the electric energy.

(2) As for the coastwise, especially the small island, this system can provide the demand of electricity in their daily life. It can also be used to provide energy for the large lighthouses.

(3) After the efficient electricity output，it can also be used to hydrogen manufacturing，sea water desalination and heating.

(4) In this design，the floating magnetic fluid swing system can also apply to the deep ocean area, whose wave energy has high density.

5 Conclusions

In this paper, the combined magneto hydrodynamics-based wave energy converter is proposed, and the key technologies are demonstrated. Some simple simulations are done to validate the effectiveness of the system. According to the analysis, the system obtains the wave energy with the plate-pendulum. The buoy-swing magnetic fluid system can fit the motion characteristics of waves well. Besides, this system generates electricity with the principle of the magnetic fluid to cut the magnetic induction line. In addition，it can be easy to manufacture and have the advantage of low-cost，high stability and easily service. Furthermore，this system has high effect with less energy conversion process，small damp power and less energy dissipation.

Acknowledgment

This work is supported by the National Natural Science Foundation (91216123, 50930007) and Innovative Research Groups of the National Natural Science Foundation of China (Grant No. 51121004).

Reference

[1] Ahn k. k, Truong D.Q, Hoang H. T, Jong I. Y. An innovative design of wave energy converter. Renewable Energy, 2012; 42: 186-194.

[2] Robin P, Rod M, Fujita. Renewable energy from the ocean. Marine Policy, 2002; 26: 471-479.

[3] António F. D. O. F. Wave energy utilization: A review of the technologies. Renewable and Sustainable Energy Reviews, 2010; 14: 899-918.

[4] McCormick M. E. Ocean wave energy conversion. New York: Wiley, 1981.

[5] Ross D. Power from sea waves. Oxford: Oxford University Press, 1995.

[6] Leijon M, Bernhoff H, Agren O, Isberg J, Sunberg J, Berg M, er al. Multiphysics simulation of wave energy extraction by a point absorber in heave. Appl Ocean Res, 2004; 26(1-2): 61-72.

[7] Tedd J, Kofoed J. P. Measurements of overtopping flow time series on the wave dragon wave energy converter. Renewable Energy, 2009; 34 (3): 711-715.

[8] Stefano P, Jens Peter K, Madsen E. F. Experimental update of the overtopping model used for the wave dragon wave energy converter. Energies, 2013; 6, 1961-1992.

[9] Silvia B, Miquel A. M, Alessandro A, Giusrppe P, Renata A. Modeling of a point absorber for energy conversion in italian seas, Energy, 2013; 6:

3033-3051.

[10] Carsten M, Haaland. Double-duct liquid metalmagnetohydrodynamicengine, United States Patent; 1995, Patent No.5473205.

[11] Carsten M. Haaland. Double-duct liquid metalmagnetohydrodynamicengine, United States Patent; 1995, Patent No. 5637935.

[12] Madhavan S, Doiphode P. M, Chaturvedi S. Modeling of shock-wave generation in water by electrical discharges, IEEE Transactions on Plasma Science, 2000; 28(5): 1552-1557.

[13] Bowman A. W, Lisauskas J. B, Kovacs S. Sufficient ventricular end-systolic potential energy is stored to power diastolic untwist and mechanical suction-initiated Doppler E-wave generation, Journal of the American College of Cardiology, 2000; 35(2): 185A-185A.

[14] Leubner M. P. Wave induced suprathermal tail generation of electron velocity space distributions. Planetary and Space Science, 2000; 48(2-3): 133-141.

[15] Leubner M. P. Wave-powered relativistic electron generation in nonuniform magnetic fields. Highly Energetic Physical Processes and Mechanisms for Emission From Astrophysical Plasmas, 2000; 195: 315-316.

[16] Jeannie L. Waves generation of electric power to make hydrogen.

Hydrogen Energy Progress XIII , Vol S 1 and 2 , Proceedings ; 2000: 446-454.

[17] kebuchi T, Takatsu N, Koterayama W. A study on motions in waves and performance of wave energy absorption of an autonomous biogeochemical monitoring platform. Proceeding of the Ninth (1999) International Offshore and Polar Engineering Conference , Vol III , 1999, 1999; 635-642.

[18] Xu H. M, Day S. M , Minster J. B. H, Model for nonlinear wave propagation derived from rock hysteresis measurements. Journal of Geophysical Research-Solid Earth, 1998; 103(B12): 29915-29929.

[19] Wu Z. Q, Tong W. G , Absorbance detection of amino acids by laser wave mixing in microbore liquid chromatography. Journal of Chromatography A , 1998; 805(1-2): 63-69.

[20] Wanan S, Raymond A, Tony L, Physical modelling of wave energy converters. Ocean Engineering, 2014; 84:29-36.

[21] Gordon R, Integrating wave energy into the power grid: Simulation and forecasting . Ocean Engineering, 2013; 73:168-178.

[22] Zheng C. W, Pan J, Li J. X, Assessing the China Sea wind energy and wave energy resources from 1988 to 2009. Ocean Engineering , 2013; 65:39-48.

[23]Lin Y. G, Le T, Zhang D. H, Li W, A study on dual-stroke pendulum wave energy conversion technology based on a water/oil integrated transmission system. Ocean Engineering ,2013; 67:27-34.

[24] Falcão A. F. de O, Pereira P. E. R, Henriques J. C. C, Gato L. M. C, Hydrodynamic simulation of a floating wave energy converter by a U-tube rig for power take-off testing. Ocean Engineering, 2010; 37(14-15): 1253-1260.

[25] Adriana M. F, Nuno F, Finite depth effects on the wave energy resource and the energy captured by a point absorber. Ocean Engineering, 2013; 67:13-26.

[26] Tofany N, Ahmad M. F, Kartono A, Mamat M, Lokman H. M, Numerical modeling of the hydrodynamics of standing wave and scouring in front of impermeable breakwaters with different steepnesses. Ocean Engineering, 2014; 88: 255-270.

Figure captions

Fig.1. Configuration of the system

Fig.2. Four type of plant

Fig.3. The schematic of MHD system

Fig.4. The structure diagram of buoy-swing magnetic fluid system

Fig.5. The operation process of buoy-swing magnetic fluid system

Fig.6. Simulation of transmission system

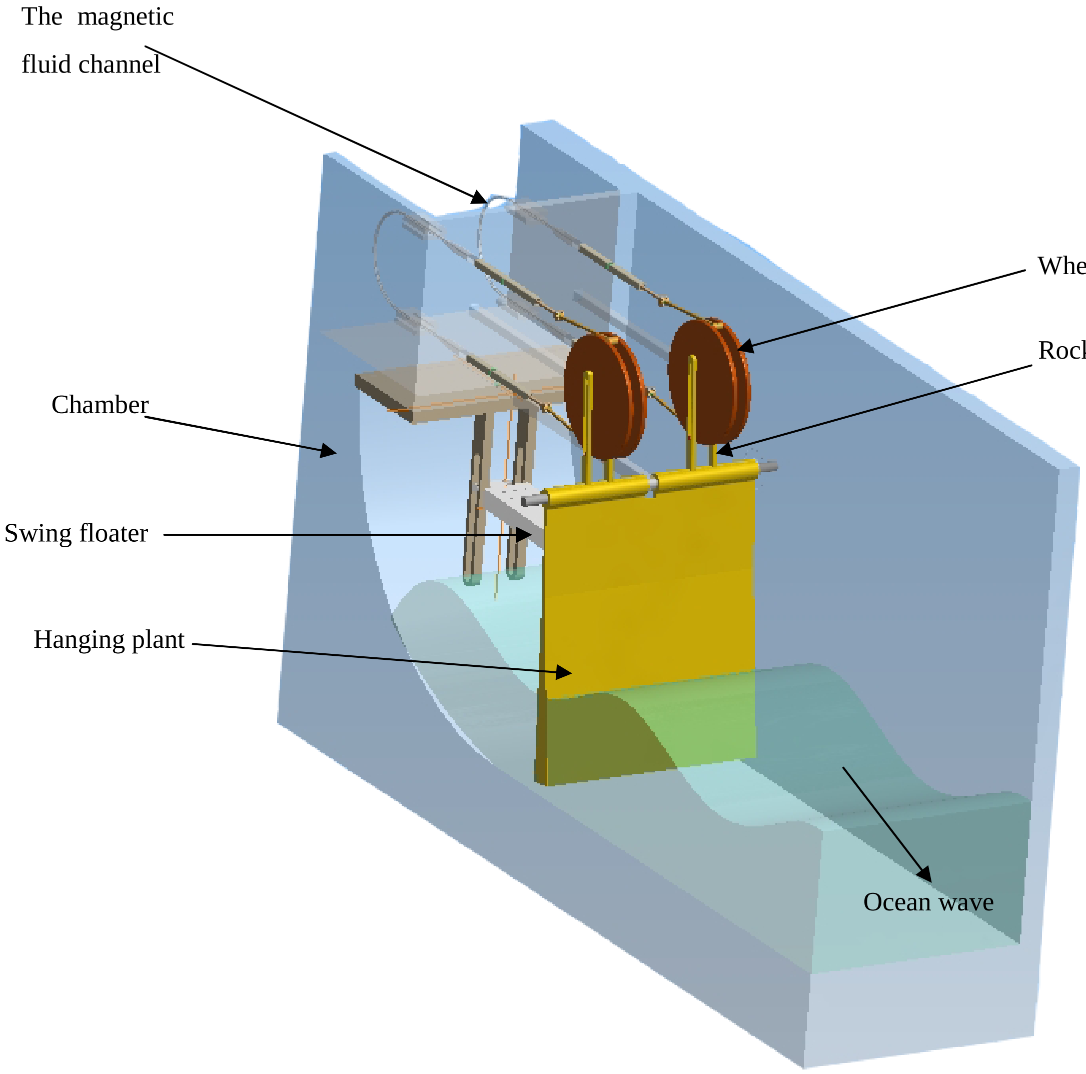
Fig.7. Result of simulation

Fig.8. Simulation of MHD

Fig.9. Output power in different load factor

Fig.10. Output power variation with time

Figure 1



The magnetic fluid channel
Wheels
Rocker
Chamber
Swing floater
Hanging plant
Ocean wave

Figure 2

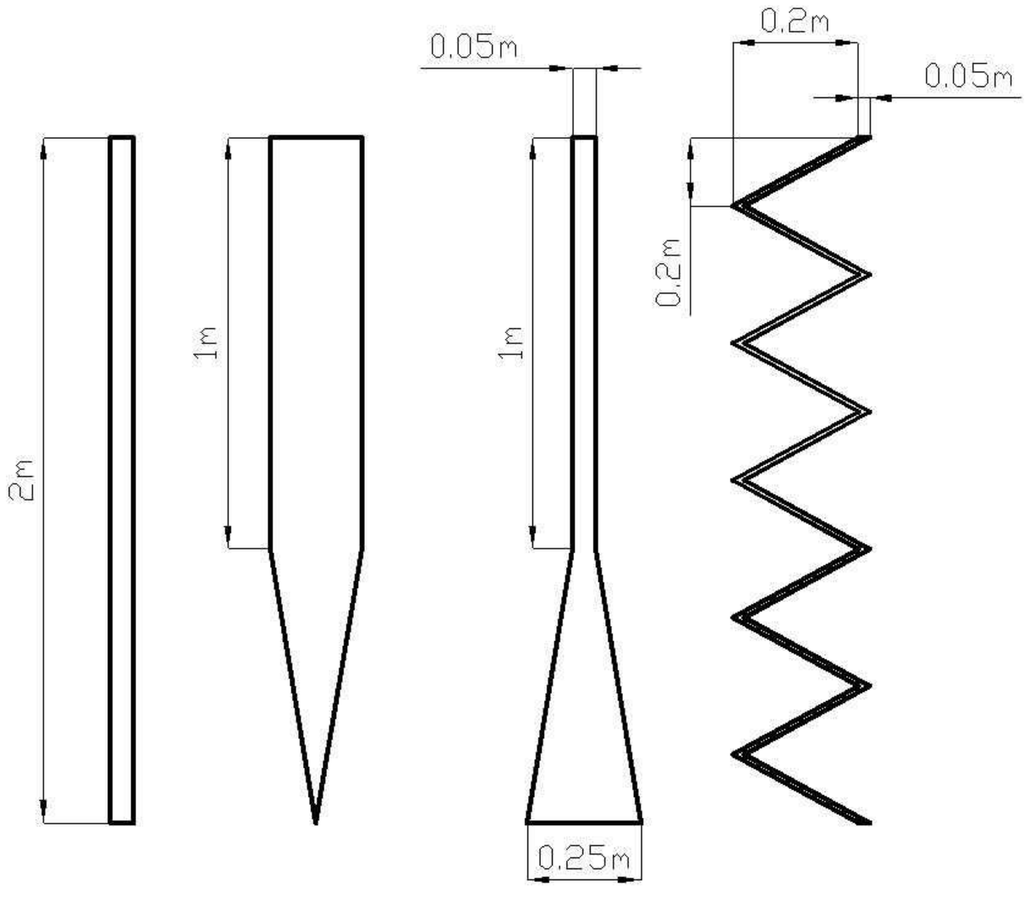


Figure 3

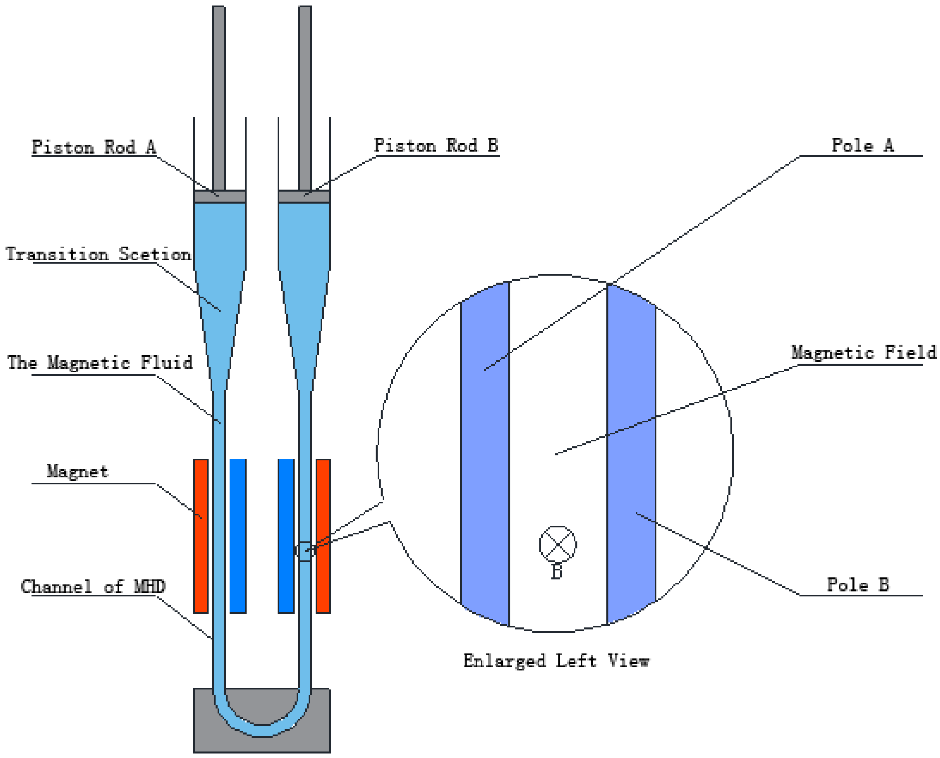

Piston Rod A
Piston Rod B
Pole A
Transition Scetion
The Magnetic Fluid
Magnetic Field
Magnet
Channel of MHD
B
Pole B
Enlarged Left View

Figure 4

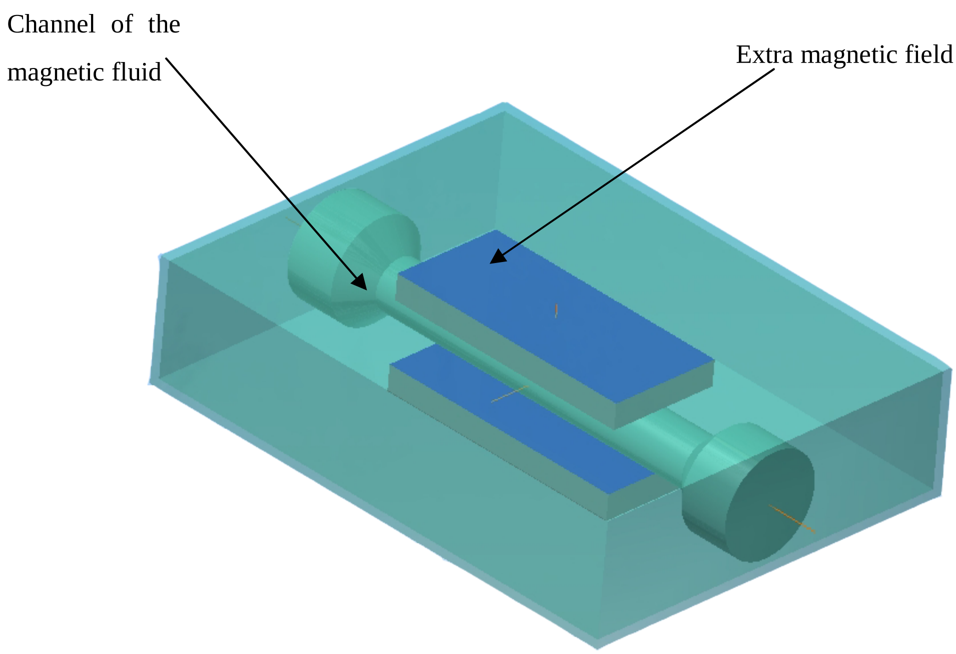


Figure 5

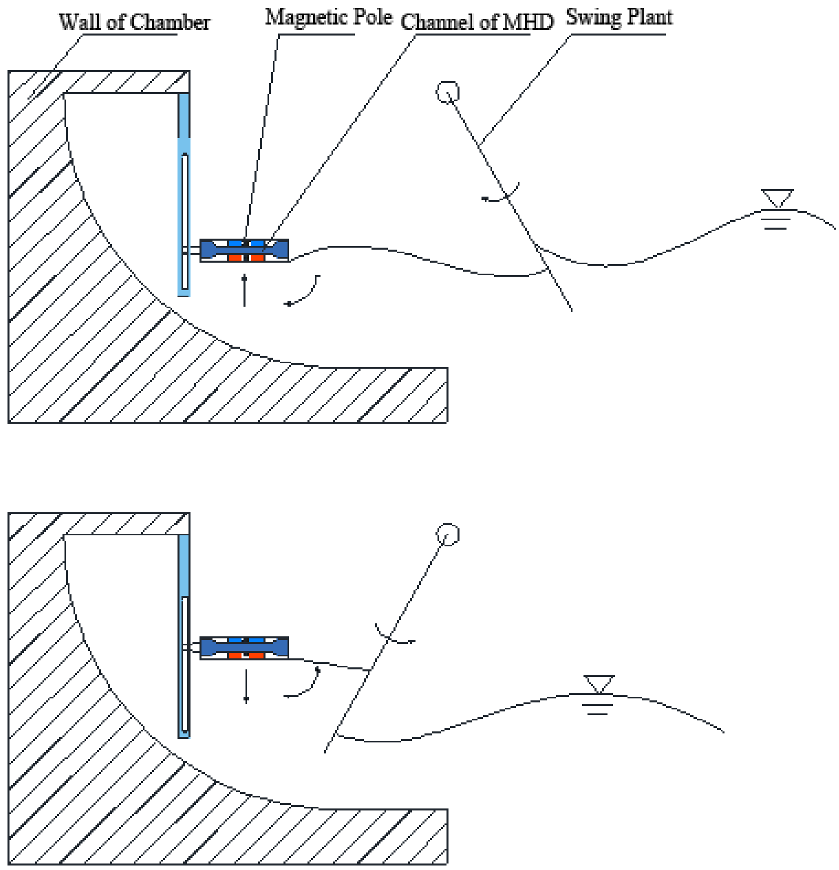


Figure 6

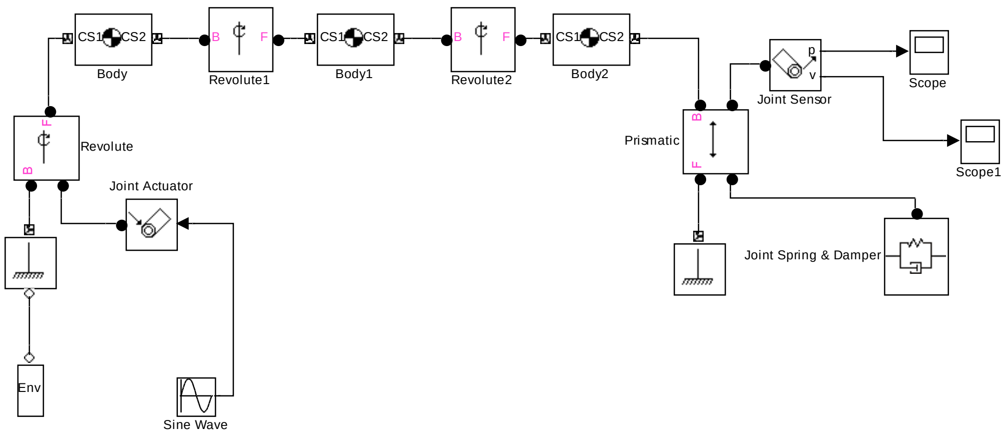

CS1
CS2
Body
B
F
Revolute1
CS1
CS2
Body1
B
F
Revolute2
CS1
CS2
Body2
p
v
Joint Sensor
Scope
Scope1
F
B
Revolute
Joint Actuator
B
F
Prismatic
Joint Spring & Damper
Env
Sine Wave

Figure 7

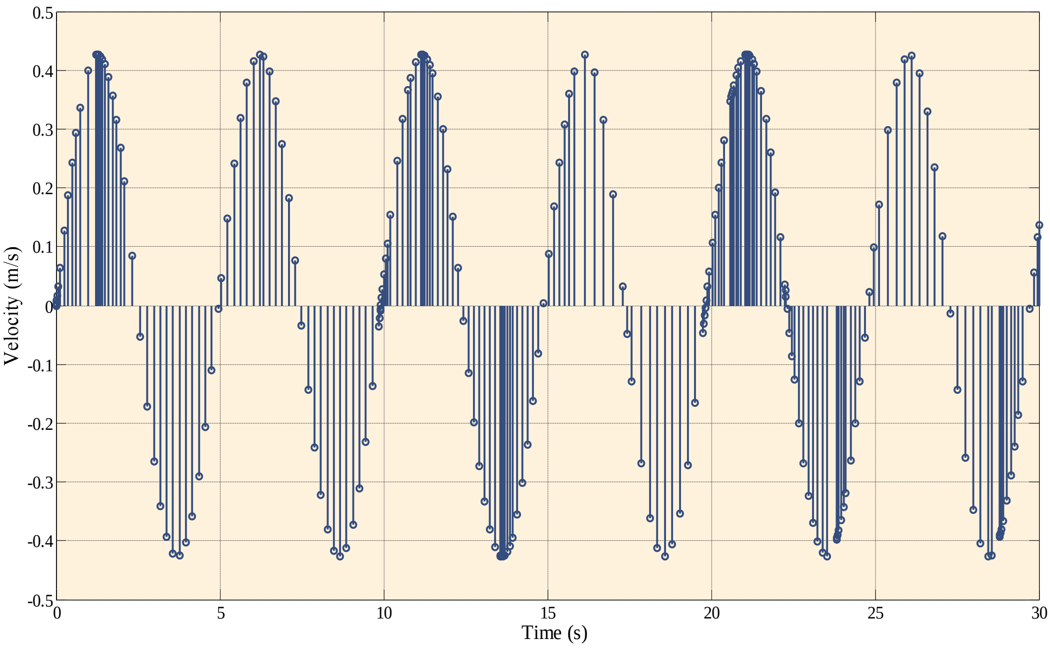
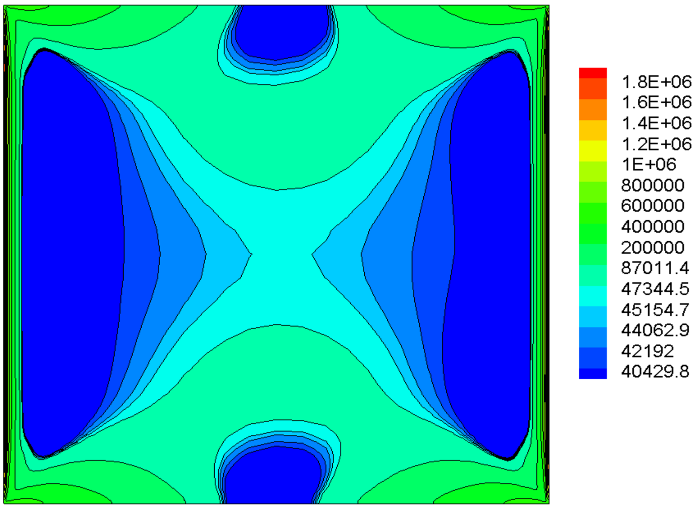
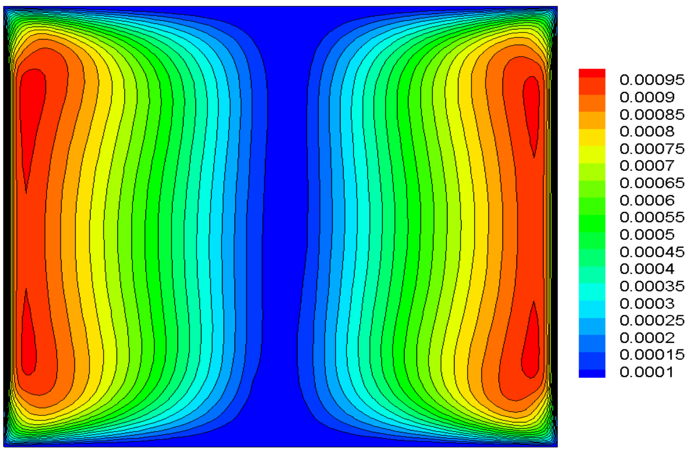


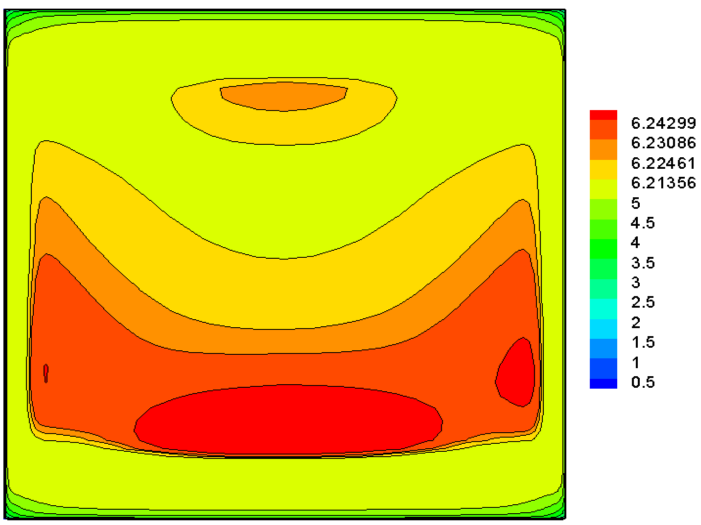
Figure 8



（a）Density of Induced Current

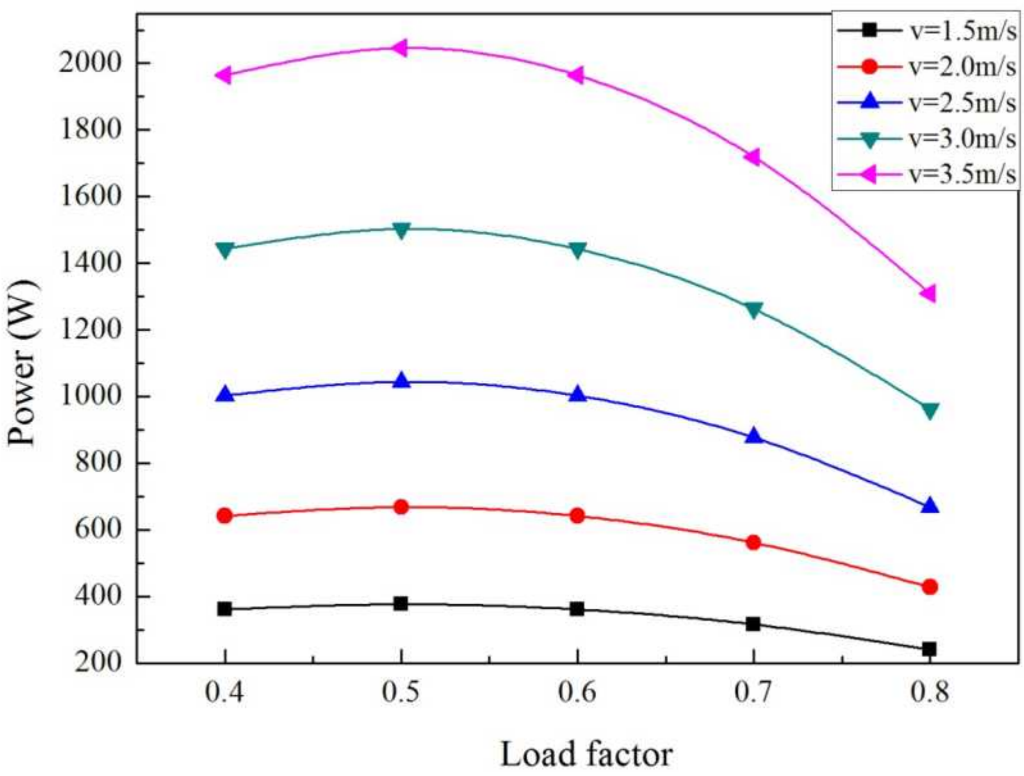


（b）Induced Magnetic Field



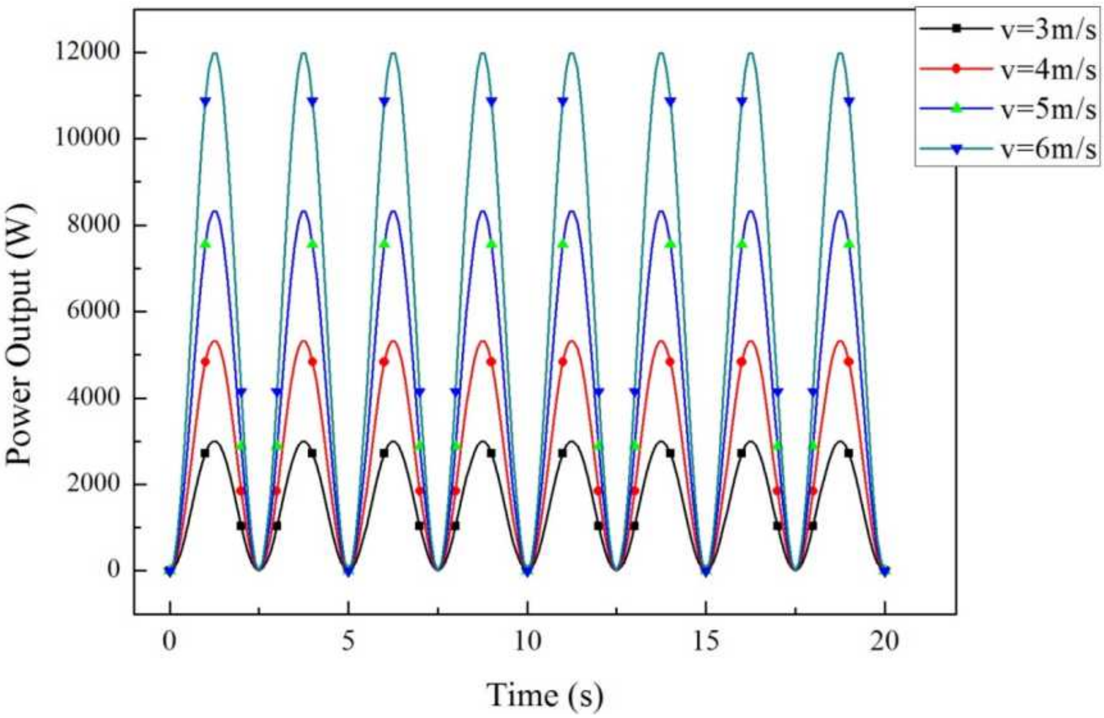
（c）Output Velocity of Channel

Figure 9



v=1.5m/s
v=2.0m/s
v=2.5m/s
v=3.0m/s
v=3.5m/s
2000
1800
1600
1400
1200
1000
800
600
400
200
Power (W)
0.4
0.5
0.6
0.7
0.8
Load factor

Figure 10



v=3m/s
v=4m/s
v=5m/s
v=6m/s
Power Output (W)
12000
10000
8000
6000
4000
2000
0
0
5
10
15
20
Time (s)