Fundamental Study on Alternating Magnetic Field MHD Thruster

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Abstract

This article is focused on AC Magnetohydro-dynamic (MHD) Ship Propulsion. With the electromagnetic field and hydrodynamic theory, a 2-D mathematics model of AC MHD thruster is built. On the basis of the mathematics model, the coupled fields of magnetic field and fluid field in a mimic seawater MHD thruster are analyzed and simulated. The results of the simulation are specified and discussed. The relationship between the velocity of the traveling-wave magnetic field and the maximum velocity of the mimic seawater is given. The results of the simulation confirm that higher seawater velocity can be achieved at high magnetic field and high frequency of the exciting current.

1 Introduction

MHD ship propulsion is one of the promising future propulsion systems. The idea of using MHD for propelling seawater vehicles was firstly brought forward by W.A. Rice forty years ago. As a new type of ship propulsion, MHD propulsion is an appealing scheme with a number of apparent advantages. It eliminates the conventional rotating drive components. The absence of mechanical propeller system will lead to reductions in the vibration level and in the mechanical noise generated in the ship or submarine. MHD propulsion surmounts the physical restriction on the speed of seawater vehicles with conventional propellers, which is limited by cavitations, and make the arrangement of ship more expedient.

Previous research on MHD propulsion mostly concentrated on DC mode, which has both magnetic poles and electrodes. Compared with DC MHD propulsion, AC mode has no electrode and doesn't apply electric field to fluid directly. Thus it avoids the detriment and noise caused by the air bubble generated by electrolysis, and makes the ship more quietly. It is the purpose of this article to give a fundamental discuss on AC MHD propulsion, and to investigate the factors that have influences on the performance of the MHD thruster.

2 Principle and Classification

AC MHD thruster uses multiphase AC exciting coil to generate traveling-wave magnetic field. There are two main configurations of AC MHD thruster: planar channel thruster and cylindrical channel thruster. Both of these configurations can be classified as internal or external thrusters, according to whether the thrust is generated by the MHD forces internal or external to the hull. Figure 1 shows a schematic diagram of a typical configuration of the external planar channel thruster.

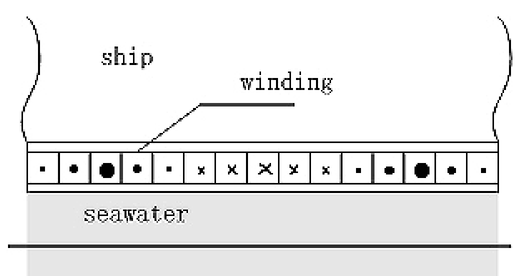


Fig. 1 A typical configuration of the external planar channel thruster

AC MHD thruster uses seawater as conductor. The magnetic field is generated by multiphase AC exciting coil. As sinusoidal voltage is applied to the exciting coil, the magnetic field in the channel will change as time goes on.

Figure 2 shows the magnetic field in the planar channel thruster at $t=0$. As time goes on, the magnetic field seems to move along the X axis, such moving magnetic field is called traveling-wave magnetic field.

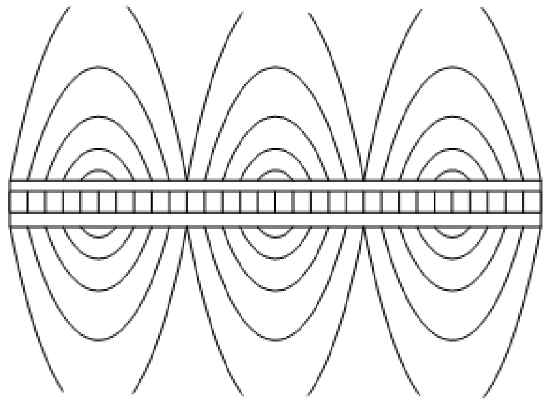


Fig. 2 Magnetic field in the planar channel thruster

The traveling-wave magnetic field induces a potential in the seawater, which also changes as magnetic field moves. The potential will generate eddy current in the seawater, and the current-carrying seawater will be impelled by magnetic force. The counterforce of magnetic force will thrust the ship to move. The magnitude of magnetic force rests with the intensity of the traveling-wave magnetic field and the velocity of its movement. Higher intensity of magnetic field and higher velocity of its movement will lead to bigger magnetic force, and thus higher seawater velocity.

3 Performance of Planar Channel Thruster

AC MHD thruster can be arranged in many different ways. In this study, the analysis is limited to the case where the thruster is an internal planar channel thruster.

In order to simplify the analysis, the fo llowing assumptions should be specified:

1. The exciting current flows along Z axis, while the direction of magnetic induction is perpendicular to Z axis.
2. The magnetic field moves along X axis at a speed of u_r relative to seawater.
3. The width and length of the channel are far greater than the height of it, so the end effect of the channel is ignored.

Thus the magnetic field can be treated as a 2-D field. A 2-D mathematics model of thruster is shown in figure 3.

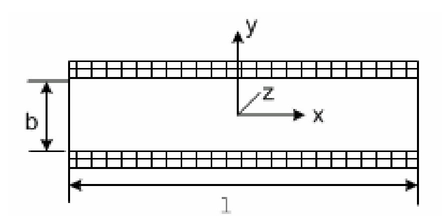


Fig. 3 2-D mathematics model

From the M-field equations we can deduce the following equation in the MHD duct of the planar channel thruster.

$$\nabla \times \nabla \times B = -m_0 s \frac{dB}{dt}$$

where s is the electric conductivity of the seawater. In order to simplify the analysis, $-m_0 s \dfrac{dB}{dt}$ is ignored in this equation, as m_0 and s of seawater are very small. The simplified equation is:

$$\nabla \times \nabla \times B = 0$$

The boundary conditions of the mathematics model are as follows.

$$B_y = B_m \cos b\,(x - u_r t) = \mathrm{Re}\left[B_m e^{jb\,(x-u_r t)}\right]$$

$$y = \pm\frac{b}{2}$$

where B_m is the amplitude of magnetic induction, b is the phase angle of B_y, and b is the height of the channel. Then we can get the solution of this equation.

$$B_x = \mathrm{Re}\left[jB_m \frac{\sinh\, by}{\cosh\frac{1}{2}bb} e^{jb\,(x-u_r t)} \right]$$

$$B_y = \mathrm{Re}\left[B_m \frac{\cosh by}{\cosh\frac{1}{2}bb} e^{jb\,(x-u_r t)} \right]$$

The electric field intensity is:

$$E_z = \mathrm{Re}\left[-B_m u_r \frac{\cosh by}{\cosh\frac{1}{2}bb} e^{jb\,(x-u_r t)} \right]$$

The induced current density is:

$$J_z = sE_z = \mathrm{Re}\left[-sB_m u_r \frac{\cosh by}{\cosh\frac{1}{2}bb} e^{jb\,(x-u_r t)} \right]$$

The magnetic force can be achieved from the following equation.

$$F_e = h\int_{-b/2}^{b/2}\int_{-l/2}^{l/2} -\frac{1}{2}\mathrm{Re}\left[J_z \times B_y\right] dxdy$$

$$= \frac{sB_m^2 bhlu_r}{2}\left[\frac{1+\dfrac{\sinh\, bb}{bb}}{1+\cosh bb}\right]$$

where l is the length of channel and h is the width of the channel.

The ideal electrical efficiency of the thruster can be calculated with the assumption that the thrust F_T and the magnetic force F_e are equal.

The MHD thrust power is:

$$P_s = F_T u_s = \frac{s B_m^2 bhlu_s u_r}{2}\left[\frac{1+\dfrac{\sinh bb}{bb}}{1+\cosh bb}\right]$$

where u_s is the velocity of the ship.

The ohmic loss power is:

$$P_r = F_e u_r = \frac{s B_m^2 bhlu_r^2}{2}\left[\frac{1+\dfrac{\sinh bb}{bb}}{1+\cosh bb}\right]$$

The ideal electrical efficiency is:

$$h = \frac{P_s}{P_s + P_r} = \frac{u_s}{u_s + u_r}$$

4 Simulation and Analysis

On the basis of the mathematics model, simulation is performed for a theoretical AC MHD thruster model. The model is shown in figure 4.

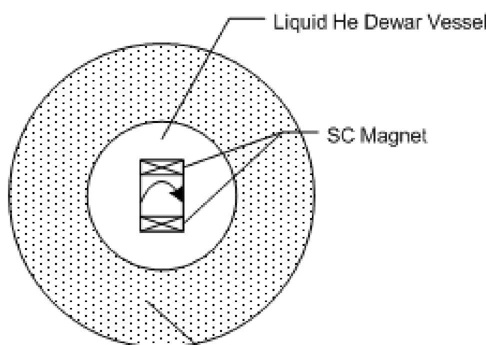


Fig. 4 Theoretical AC MHD thruster model

The model consists of a seawater tank, a superconducting magnet, and a liquid He Dewar vessel. As the superconducting magnet, which is composed of a superconducting solenoid, is rotated up by a motor, the magnetic field in the seawater tank, which is generated by the magnet, will alter periodically. This moving magnetic field acts on the seawater in the tank, and the mimic seawater will begin to flow by undergoing Lorentz force in the same direction as that of the magnet.

The inner diameter of the magnet is 10 cm, the outer diameter is 14cm, and the length is 10mm. The number of turns is assumed to be 2000. The inner diameter of the sea water tank is 32cm, and the outer diameter is 64 cm. On the central axis of the coil at an exciting current of 200A, the magnetic flux density B is shown in figure 5.

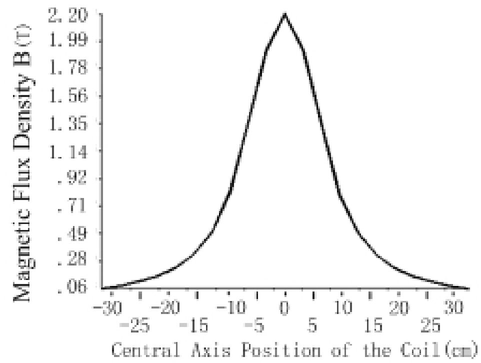
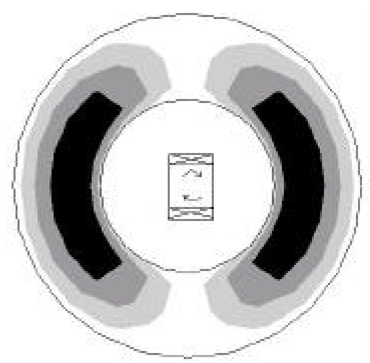


Fig. 5 The magnetic flux density on the central axis of the coil

The magnetic flux density reaches its maximum (2.2T) at the central point of the superconducting magnet. It is 0.3T inside the water tank, and .06T outside.

In the simulation of this model, the conductivity of the mimic seawater is assumed to be 10S/m, the density of the mimic seawater is assumed to be 1100kg/ m^3, and the viscosity of the mimic seawater is assumed to be 0.0017kg/ms. The Reynolds number is nearly 1×10^5, so the flow in the seawater tank is a turbulent flow.

The simulation is performed with Finite-Element Method (FEM) analysis software. Figure 6 shows the magnetic force in the mimic seawater tank. Fig. 6(a) shows the magnetic force in contour, and Fig. 6(b) shows the magnetic force in vector.


(a)

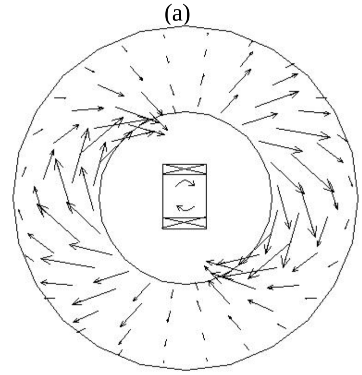

(b)

Fig. 6 Magnetic force in the seawater tank (a) in contour (b) in vector

While the superconducting magnet rotates in the LHe vessel, the distribution of the magnetic force will change as time goes on. The direction of the magnetic force coincides with the direction of the rotation of the magnet.

Figure 7 and Figure 8 show the variation of the mimic seawater velocity for different rotational frequencies of the superconducting magnet and different exciting currents.

The result of the simulation shows that there are two main factors that influence the velocity of the seawater:

1. The magnitude of the magnetic field. Higher exciting current will generate higher magnetic field, and lead to higher velocity of the seawater.
2. The moving speed of the magnetic field. As the rotational frequency of the magnetic field increases, the velocity of seawater will increase p roportionally.

Besides these two factors, the number of phases of the exciting coil and the conductivity of the mimic seawater also influence the velocity of the seawater.

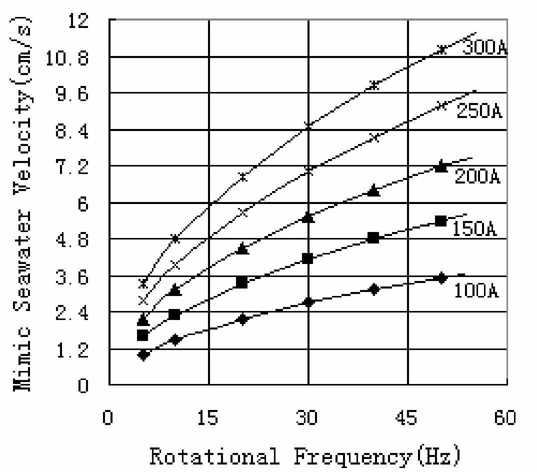


Fig. 7 Seawater velocity versus rotational frequency

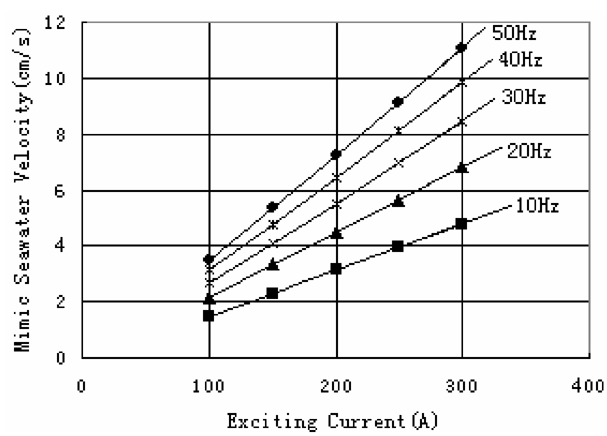


Fig. 8 Seawater velocity versus exciting current

5 References

1. W.A. Rice. *Propulsion System*, U.S. Patent, 2997013. 1961-08-22

2. O.M. Phillips. *The Prospects for Magnetohydrodynamic Ship Propulsion,* Journal of Ship Research, Vol. 43, March 1962, pp. 43-51.

3. R.A. Doragh, *Magnetohydrodynamic Ship Propulsion Using Superconducting Magnets,* Proc. Naval Arch. And Marine Engineers Transaction, Vol. 71, 1963.

4. Y. Saji, M. Kitano, and A. Iwata, *Basic Study of Superconducting Electromagnetic Thrust Device for Propulsion in Seawater,* Advances in Cryogenic Engineering (K.D. Timmerhans, editor), vol. 23, 1978, pp. 159-169.

5. L.G. Yan, C.W. Sha, K,Zhou, Y. Peng, A.H. Yang, and J.Q.Qin, *Progress of the MHD Ship Propulsion Project in China,* IEEE Trans. On Applied Superconductivity, vol. 10, No. 1, March 2000.