STUDY OF SHIP'S MAGNETOHYDRODYNAMIC PROPULSION

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Abstract: *The paper deals with the interaction between electromagnetic and hydrodynamic field of electromagnetic thruster. The mathematical model of the interaction defines the constant ruler of MHD interaction.*

Key words: electromagnetic field, propeller's channel, absorption area, electromagnetic force.

1. INTRODUCTION

The electromagnetic propulsion of the ship is based on the interaction between a magnetic field generated on board and an electric current "injected" (half-induced) in the seawater and as a result of this interaction the ship moves.

The equations of magnetohydrodynamic interaction applied locally for an infinitesimal element of seawater are obtained from a combination of equations in the electromagnetic and hydrodynamic field.

The electromagnetic field is highlighted by Maxwell's equations. Applying these equations to seawater links are established between electromagnetic field vectors and parameters that physically characterize seawater. Since the field equations (induction law) include also speed of movement of sea water, it is evident that the electromagnetic field cannot be determined independently of movement.

Movement of sea water into the channel induced by the electromagnetic field corresponding to Maxwell's equations; field which affects movement by electromagnetic force density leads to an interaction between the electromagnetic and hydrodynamic fields.

2. MATHEMATICAL MODEL OF M.H.D. INTERACTION

The starting point of MHD analysis is the deviation of particle in the electromagnetic field. As it is known, sea water subjected to the action of the electromagnetic field is decomposed into positive and negative ions of n_+ and n_- concentrations.

Mathematical model of MHD interaction includes the following hypotheses:

- seawater is composed of two ionized fluids inside MHD propeller;
- a number of particles contained by each fluid per volume unit meets the relation:

$$\frac{\partial n}{\partial t} + \nabla\left(n \cdot \bar{v}\right) = 0 \tag{1}$$

The equation of motion of the form fluid:

$$\rho\left[\frac{\partial\bar{v}}{\partial t}+(\bar{v}\nabla)\bar{u}\right]=\bar{f}-\nabla p \tag{2}$$

where:

v - speed of unit volume;

ρ - fluid density;

$\bar{f}$ - electromagnetic force;

p - pressure.

By decomposing the speeds of the fluid $\bar{v}_+$ and $\bar{v}_-$ corresponding to two directions where $\bar{v}_0$ is perpendicular to the electric and magnetic field and $\bar{v}_{11}$ is parallel to the electric field, we obtain by multiplying the equation (1) by q_+ and q_- and resulting in the law of conservation of electricity.

$$\frac{\partial\rho^*}{\partial t}+\nabla\left(\bar{I}+\rho^*\bar{v}_D\right)=0 \tag{3}$$

where:

$\bar{J}=n_+q_+\bar{v}_{11_+}+n_-q_-\bar{v}_{11_-}$ - represents current density associated with the movement of energy.

In this case, the electromagnetic force volume is:

$$\bar{f}=\bar{f}_++\bar{f}_-=\rho^*\cdot\bar{E}+\rho^*\bar{v}_D\times\bar{B}+\bar{J}\times\bar{B} \tag{4}$$

where:

$\rho^*\cdot\bar{E}$ - electric force of volume due to applied electric field;

$\rho^*\cdot\bar{v}_D\times\bar{B}$ - force due to reaction field

$\bar{J}\times B$ - Lorentz force.

Decomposing the equation of motion of ideal fluid and assuming that one infinitesimal element of seawater goes through the propeller, it is obtained:

- $\rho\frac{d\bar{v}_{11}}{dt}=\left(\bar{E}+\bar{v}_D\cdot B\right)=0$ - pa axis of $\bar{E}$
- $\rho\frac{d\bar{v}_D}{dt}=\bar{J}\times\bar{B}$ on flow axis.

Integrating the flow equation in which $v_0=v_0+v$.

$$\int_0^v\frac{dv}{u_0=v_0-v}=\int_0^x\frac{\sigma B^2dx}{\rho v_0} \tag{5}$$

the solution is:

$$v=(u_0-v_0)\left(1-e^{-x/\lambda}\right) \tag{6}$$

where:

v_0 – speed at the entrance in the propeller;

v – rate of rise in channel with v_0;

$\lambda = \frac{\rho v_0}{\sigma B^2}$ - length characteristic.

Assuming that an infinitesimal volume of seawater dΩ penetrates the propeller area with v_0 speed, the result of dissociation of the centre of speeds in positive and negative ions at x distance will be:

$\overline{v}_+ = \overline{u}_0 + \overline{u}_+$, respectively $v_- = \overline{u}_0 + \overline{u}_-$

where: $\overline{u}_0 = \frac{\overline{E} \times \overline{B}}{B^2}$ and at the entrance area of the propeller $\overline{v}_+ = \overline{v}_- = \overline{u}_0$.

Covering x distance under the action of the electromagnetic field, the density of the electromagnetic force which acts on ions is angularly pivoted with $\beta = \omega \cdot t$ and this thing also happens with speeds containing -β. Associating electric current density $\overline{J}_n = \sigma \cdot (\overline{u} \times \overline{B})$ to the resulting electrical field direction, covering x distance, it results in less electric current density associated with the movement of the applied electric field:

$$J = \sigma \cdot (E - v_D B) = \sigma \cdot B \cdot (u_0 - v_0) \cdot e^{-x/\lambda}$$

and electromagnetic pressure $p_{em} = \int_0^x J \cdot B dx = \rho v_0 \cdot (u_0 - v_0) \cdot (1 - e^{-x/\lambda})$

The propellant channel is short, and we have:

$$e^{-x/\lambda} \cong 1 - (x/\lambda).$$

and thus the electric current density and electromagnetic pressure become:

$$J = \sigma \cdot \cdot B \cdot (u_0 - v_0)$$

$$p_{em} = J \cdot B \cdot x$$

3. THE EXCHANGE INSIDE THE PROPELLER

The components of an electromagnetic propeller placed under the hull are:

- a horizontal channel of open water at both ends placed on L_c length of the ship;
- a magnet or any other device for producing a strong magnetic field placed along the entire length of the channel;
- electrodes supplied from a power source one on each side of the channel, which are intended to apply power density $\overline{J}$ perpendicular to $\overline{B}$ induction.

The geometry of the channel of the propeller shown in Figure 1 has three areas:

- the absorption area with A_0 opening and v_0 sea water speed
- the propeller surface area A_c and water speed in v_w channel;
- water drain area with A_j opening and v_j flow rate.

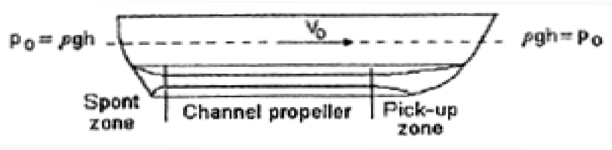

***Fig. 1** Ship with MHD propulsion*

The connection between the three areas emerges from the equation of current continuity while Bernoulli's relationship applied both to the absorption area and water drain area leads to the following relationship of dependency:

$$p_i = p_0 - \frac{1}{2}\rho v_0^2\left(A_{01}^2 - 1\right)$$

$$p_e = p_0 + \frac{1}{2}\rho v_0^2 A_{01}^2\left(\frac{1}{A_{j1}^2} - 1\right) \tag{7}$$

(8)

Since the electromagnetic propulsion is carried out in an electric and magnetic field the pressure difference between the ends of the propeller must be carried out by the electromagnetic pressure as a result of the interaction between the magnetic field and the electric current along the propeller's channel.

Electromagnetic power required to propel a fluid dΩ can be determined by:

$$W_E = \int \overline{E}\,\overline{J}d\Omega = \int\left(\overline{J} \times \overline{B}\right)\overline{u}_0 d\Omega \tag{9}$$

The equation of idealized motion of seawater in the propeller's channel for infinitesimal volume, projected on the axis of the electric field applied also to the axis of flow ($\overline{u}_0$ axis) and multiplied with the speed planned on the respective directions leads to:

$$\rho\frac{d}{dt}\left(\frac{v_{11}^2}{2}\right) = \rho^* \cdot v_u \cdot \overline{E} + \rho^* \cdot v_u \cdot \left(\overline{v}_0 \times \overline{B}\right) = p_j$$

$$\rho\frac{d}{dt}\left(\frac{v_D^2}{2}\right) = \left(\overline{J} \times \overline{B}\right) \cdot \overline{v}_D = p_{mec} \tag{10}$$

Adding together these relationships it results the equation of equilibrium of energy for an ideal fluid.

$$\rho\frac{d}{dt}\left(\frac{v_{11}^2}{2} + \frac{v_D^2}{2}\right) = \overline{E} \cdot \overline{J} = \left(\frac{\overline{E} \times \overline{B}}{B^2}\right) \cdot \left(\overline{J} \times \overline{B}\right) = \overline{f}_m \cdot \overline{u}_0 = p_j + p_{mec}$$

(11

Adding to the differential equations of energy balance specific losses due to dissipative effects caused by apparent viscosity, the following relation results for the established working conditions:

$$\bar{f}_m \cdot \bar{u}_0 - p_j - p_A = p_{mec} \tag{12}$$

Integrating power equations specific to volume of the propeller's channel leads to the following distribution of powers at an average speed of sea water

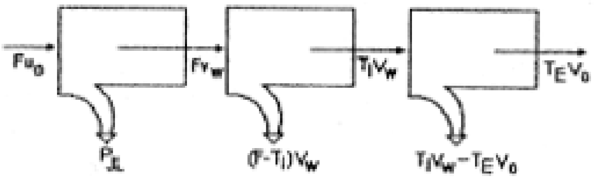

Fig. 2 *Power distribution*

In the diagram of distribution of powers above the slip factor has been used which is defined by the relationship below:

$$s = \frac{\bar{u}_0 - \bar{v}_w}{\bar{u}_0} \tag{13}$$

Under the action of the electromagnetic field sea water leaves the propeller's channel as jet and as experimental research conducted in Japan demonstrated, not all Lorentz force developed in seawater is converted into thrust force.

$$\eta_n = \frac{T_E \cdot v_0}{F \cdot u_0} = \frac{T_E \cdot v_0}{T_i \cdot v_w} \cdot \frac{T_i \cdot v_w}{F \cdot v_w} \cdot \frac{F \cdot v_w}{F \cdot u_0} = \eta_j \cdot \eta_p = \eta_j \cdot \eta_C \cdot \eta_E \tag{14}$$

where η_j - capacity of water jet

$$\eta_j = \frac{2}{\alpha + 1 + f\left(\frac{\alpha^2}{\alpha - 1}\right)} \tag{15}$$

- η_p -.efficiency of electromagnetic propeller

The efficiency of η_p electromagnetic propeller is the ratio between the propeller output and the power introduced (consumed). It may be considered as a double efficient product: one of conversion and the other one electric. Conversion or transformation of Lorentz force within the traction is also found in theoretical and experimental Japanese research.

In electromagnetic conversion, Lorentz force has two components: a useful one produced by electric current density associated with the axes of the electric field applied to electrodes and a Hall component.

Hall component is not engaged for operating the efficiency of conversion considering that the component is:

$$\eta_C = \frac{T_i}{F} \cdot \frac{1}{\sqrt{1+\beta^2}} \tag{16}$$

At the same time from the equation of equilibrium of pressure results:

$$\overline{F} \cdot \overline{v}_w - \frac{1}{2} C_f \cdot \rho \cdot \frac{1}{d} \cdot W_w^2 \cdot Q = T_i v_w \tag{17}$$

and the conversion efficiency

$$\eta_C = 1 - C_f \cdot \frac{\lambda}{d} \cdot \left(\frac{v_w}{u_0 - v_w} \right) \tag{18}$$

Electrical efficiency is the ratio between the power developed by Lorentz force and the electrical power consumed in the power plant of the ship and has the relationship:

$$\eta_F = \frac{v_w}{u_0} \tag{19}$$

Maximum value of such efficiency is achieved for
s = 0 when the speed of seawater is equal to the speed of the electromagnetic field. In this case the force of interaction is null and as a result the conversion efficiency is also null. As in the definition relationships of efficiency we associate power but not the ratio of powers or speeds (as seen in force or electric efficiency) and there is the possibility to minimize them with changing the speed of seawater in the propeller channel (s sliding).

4. NUMERICAL SIMULATION AND EXPERIMENTAL DETERMINATION OF ENERGY TRANSFORMATION

Mathematical model of energy transformation was applied to a propeller channel located under the hull. The channel is characterized by the following geometric dimensions: L_c length; Δr radial opening and π/6 angular opening.

Since the energy transformation also involve the geometric dimensions of the propeller (through the volume of interaction) they were nondimensionalized as follows:

- the length of the propeller through the length of the ship;
- suction and discharge surface through the surface of the propeller channel;
- radial opening through the radius of the ship.

The studied variable was the dependence of the efficiency of magnetic induction applied to values given to other dimensions $(v_0; A_C; L_C; \Delta r)$. High values of magnetic induction lead according to (10) and (11) relations to the increasing of efficiency by reducing λ limit constants and slipping

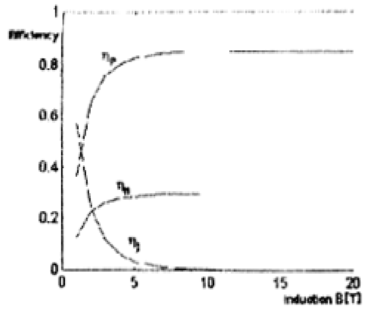

Fig. 3 *Efficiency of magnetic induction*

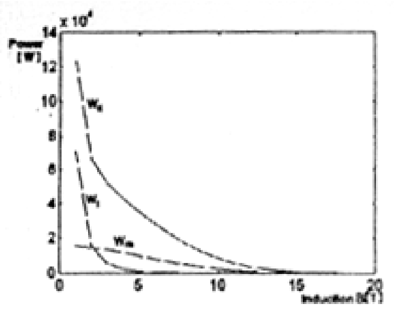

Fig. 4 *Power necessary for propulsion*

As a result, the level of power necessary for propulsion is reduced, while their distribution can be found in Figure 4.

Two models electromagnetically governed to check the principle of electromagnetic propulsion and energy transformation.

Experimental models of ships containing the two types of propulsion have been tested in the test basins (Figure 5 and Figure 6). The transformations of energy were determined from the experimental results.

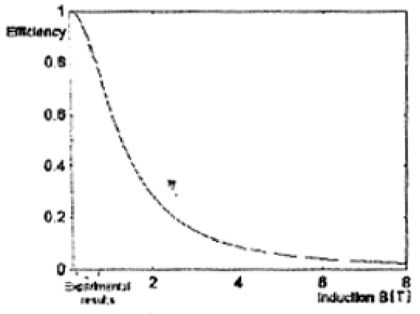

Fig. 5 *Experimental power and efficiency*

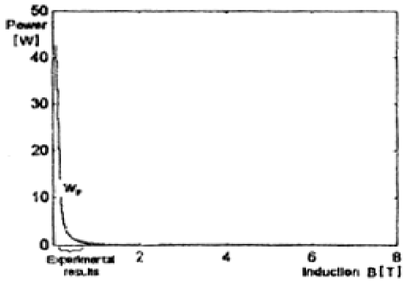

Fig. 6 *Experimental efficiency*

They were subsequently compared with those offered by numerical simulations carried out by the approached mathematical model.

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