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The Performance Analysis of Direct Current Electromagnetic Propulsion in Seawater

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Abstract—Electromagnetic seawater thrusters may be classified into four general categories : internal duct dc, external field dc, internal peristaltic ac, and exrternal peristaltic ac. Internal duct dc thrusters offer the advantages of low magnetic field leakage, simple construction, and potentially high reliability. The most efficient internal duct configuration consists of converging inlet nozzle and a straight discharge duct. Ideal efficiency calculations based on the one-demensional Bernoulli equation show that thrusters should be designed with large cross-sectional areas and operate at low discharge velocities.

In practice, this may be accomplished by using multiple thruster ducts. Conductivity enhancement, high magnetic fields, and long electrodes will also improve efficiency.

1. Introduction

This paper describes the practicality of internal duct, direct current electromagnetic propulsion of submersible ocean vessels, ranging from full size submarines down to small maneuverable underwater platforms. The performance and efficiency calculation were accomplished, and the resulting cuvres will be used for comparisions and trade-off analyses.

These curves are able to determine overall thrust efficiency as a function of duct area, magnetic field strength, electrode length, and multiple ducting. This information is presented in each of three submersible classes : full, one-third, and one-tenth sizes corresponding to hull diameters of about 10, 3, and 1 meters, respectively. The assumed drag characteristics for these three sizes are given in Fig. 1(refer to Eq. (4)).

As will be shown later, overall performance is a strong function of the magnetic flux density. The magnetic flux density used for the performance curves given here ranges from conventional (0.5 T) to superconducting (10 T) excitation sources. Duct dimensions are restricted to reasonable ranges of engineering capability, limited by the volume requirements for the magnetic field. It does not seem reasonable, for instance, to consider a thruster design that requires magnetic flux density of 10 Tesla (superconducting excitation) throughout a duct interior of several hundred cubic meters. Duct dimensions, therefore, range from two to ten meters long and up to one square meter of cross-sectional area.

2. Problem Formulation

2-1. General Description

Electromagnetic propulsion of sea vessels may be divided into four categories : internal duct dc, external field dc, internal peristaltic ac, and external peristaltic ac. All four types of propulsion have been analyzed and discussed in the literature[1-4]. As a study result, Kong *et al* generally announced the papers on the Superconducting Magnetohydro-dynamic Ship Propulsion[5-8]. While three types of electromagnetic propulsion pose significant technical problems, the internal duct design is simpler and probably more reliable than the others, and this work was commissioned specifically for a study of internal duct dc propulsion.

2-2. Parameter Specification

Clearly, we are not able to choose independent values for each of the indendent parameters that could change performance. If, for example, the electrode voltage and current are specified, then for a given duct size, the thrust requirement determines magnetic field intensity as a function of speed : all of these quantities can not be selected independantly. Mathematically, we cannot exceed the degrees of freedom that exist between the performance equations. The approach has

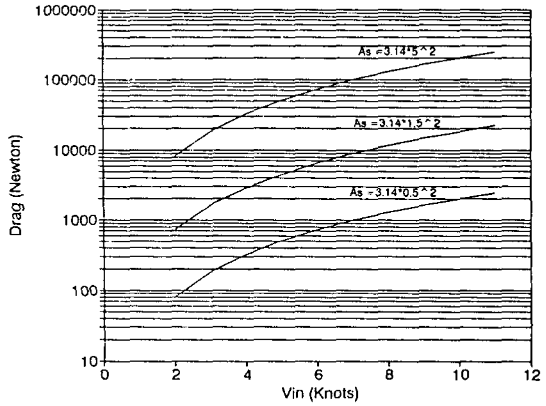

Fig. 1. Drag characteristics used for performance calculations

been to permit electrode voltage and current to remain unspecified they are dependent variables whose values are determined as a consequence of other parameter selections. Since dc electrical power source may be configured to match or nearly match most power requirements (e.g., 10 volts at 200 amps or 200 volts at 10 amps), this is a reasonable engineering approach.

The folllowing parameters are treated as independent variables and must be specified :

- magnetic flux density
- electrode length
- cross-sectional area of duct
- number of ducts
- conductivity

2-3. Range of Parameter Variation

The ranges of variation must be specified, and here again we are guided by practical engineering limitations rather than theoretical speculation. All five of the independent variables listed above are related in the sense that choosing one places practical constraints on the others. An extremely high, uniform magnetic field, for instance, can not be established through a large volume. Duct dimensions must reflect this : we cannot seriously discuss duct lengths of hundreds of meters, nor can be considered cross-sectional areas greater than one or two square meters.

The following ranges, therefore, were defined and specific calculations were made for various combinations of these values :

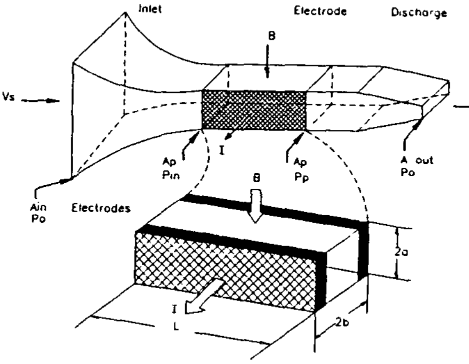

Fig. 2. Thrust model of internal duct thruster with converging inlet and outlet nozzles

Variable	Range
○ Duct Area	0.25, 0.5, 0.75, 1 square meters
○ Electrode Length	2, 10 meters
○ Magnetic Flux Density	2, 5, 10 Tesla
○ Number of Ducts	1, 4, 9
○ Conductivity	4 mhos

3. Thruster Performance Analysis

3-1. Thruster Model

Water-thrusters work on the principle of momentum conservation : an increase in stream momentum from intake to discharge produces a net reaction thrust. As shown in the pictorial sketch of Fig. 2, the electromagnetic thruster is composed of three sections; 1) converging inlet nozzle; 2) electrode-magnetic field region; 3) converging discharge nozzel. Definitions of the electrode (or pumping) region dimensions are also given in Fig. 2.

The converging inlet nozzle provides a smooth transition from the free-stream region immediately ahead of the intake to the internal pumping region, and if we assume that a fixed uniform crusing speed, V_s, the inlet area is just large enough to provide the volumetric flow required, then no power will be expended drawing water into the inlet from ahead of the inlet plane. Matching the converging inlet opening to cruising speed also has the advantage of minimizing the thruster's displacement drag under the condition that incident flow is directed into the duct, rather than around it.

The electrode or active pumping region consists of parallel electrodes mounted along the channel walls with a magnetic field estiablished normal to the current-flow direction. The rectangular cross-sectional area, A_p, is assumed to be constant throughout the electrode region. The third and last section of the thrust is the converging nozzle, which directs flow from the pumping region to a discharge orifice.

3-2. Assumptions

In the calculations that follow, the following assumptions have been invoked unless otherwise noted:

- Thrust = velocity-squared drag

The thrust required to maintain a fixed speed is equal to total drag. Total hull drag, we assume, may be described by one equivalent drag coefficient that includes both frictional and displacement component. Total drag is then proportional to velocity squared times the cross-sectional area.

- Negligible thruster drag

Based upon a thruster design that utilizes a converging inlet nozzle, this is a reasonable assumption.

- Negligible electrode-electrolysis losses (electrolysis voltage ≪pump voltage). The validity of this assumption depends to a large extent upon the aspect ratio.

- Nozzle inlet velocity = relative velocity between submersible and surrounding water.

- Absence of cavitation within the inlet nozzle. A convergent inlet nozzle forces a static pressure drop with respect to the inlet or free stream pressure. Assuming no cavitation is equivalent to assuming that the absolute pressure at the pump inlet (P_{in}) is greater than the vapor pressure of water (several psia).

3-3. Thrust Performance Equations

3-3-1. Thrust and Velocity Relationships

From the conservation of momentum, we have thrust = outlet momentum − inlet momentum or

$$T=\dot{m}(V_{out}-V_{in}) \tag{1}$$

where the mass flow rate, $\dot{m}$ is given by

$$\dot{m}=\rho\ V_pA_p=\rho\ V_sA_{in}=\rho\ V_{out}A_{out} \tag{2}$$

Combining these two equations, we can express thrust as

$$T=\dot{m}\ V_p\left[\frac{A_p}{A_{out}}-\frac{V_s}{V_p}\right]=\rho\ A_pV_p^2\left[\frac{A_p}{A_{out}}-\frac{V_s}{V_p}\right] \tag{3}$$

But thrust developed by the duct is equal to the submersible's drag force

$$D=(C_DA_s\rho/2)\ V_s^2=K_sV_s^2 \tag{4}$$

or

$$T=K_sV_s^2 \tag{5}$$

where $K_s=C_DA_s\ \rho/2$

Combining Eqs. (3) and (5), we get for K_I the ratio of internal duct velocity to inlet velocity

$$K_1=\frac{V_p}{V_s}=\frac{A_{out}}{2A_p}[1+(1+4K_s/\rho A_{out})^{1/2}] \tag{6}$$

Also, note that from Eq. (2), $V_pA_p=V_sA_{in}$, so that $K_1=A_{in}/A_p$ = ratio of inlet area to area of pumping region.

3-3-2. Voltage and Current

ΔP_p get from P_p-P_{in}

$$\Delta P_p=1/2\ \rho Vs^2\left[K_1^2\left(\frac{A_p}{A_{out}}\right)^2-1\right] \tag{7}$$

Neglecting electric and magnetic fringe effects near the electrode edges, we have

$$\Delta P_p=JBL=\sigma BL\left(\frac{V}{2b}-V_pB\right) \tag{8}$$

Substituting for ΔP_p from Eq. (7) and solving for the electrode voltage V in Eq. (8), we get

$$V=\frac{\rho V_s^2bf}{\sigma BL}+2BV_sK_1b \tag{9}$$

where $f=[(K_1\ A_p/A_{out})^2-1]$.

Now we can use Eqs. (7), (8) and (9) to solve for the current density J, and hence the total current I (=2aLJ):

$$\begin{aligned}I&=2aL\sigma\left(\frac{V}{2b}-V_pB\right)\\&=a\rho V_s^2\ f/B\end{aligned} \tag{10}$$

3-3-3. Efficiency

Pumping efficiency η is the ratio of thrust power to electrical input power

$$\eta=TV_s/IV \tag{11}$$

Substituting from Eqs. (5), (8) and (10), we have

$$\eta=2K_s/[A_p\rho fK_1(f/(2K_1^2N))+1]$$

$$=\frac{A_s}{A_{in}}[C_D/(f(1+f/2K_1^2N))] \qquad (12)$$

where we introduce the interaction parameter N, a measure of the interaction between electromagnetic and inertial body forces in the fluid, defined as

$$N=\sigma B^2L//\rho V_p \qquad (13)$$

Efficiency may also be expressed in terms of the propulsive and electrical efficiencies, which are defined, respectively, as

$$\eta_p=\frac{TV_s}{W_f} \qquad (14)$$

$$\eta_e=\frac{W_f}{IV} \qquad (15)$$

where the fluid power, $W_f=V_p\ \Delta P_p\ A_p$.

Substituting from the expressions for these quantities, we have

$$\eta=\eta_p\cdot\eta_e \qquad (16)$$

with

$$\eta_p=\frac{2}{K_1\ A_p/A_{out}+1} \qquad (17)$$

$$\eta_e=\left\{1+\frac{1}{2N}\left(\frac{A_p}{A_{out}}\right)^2-\frac{1}{K_1^{\ 2}}\right\}^{-1} \qquad (18)$$

From Eqs. (17) and (18) we note that efficiency increases as the nozzle discharge area A_{out} approaches the pump area A_p. To maximize overall efficiency, then, we set $A_{out}=A_p$. This corresponds to the maximum cross-sectional discharge area consistent with no nozzle cavitation, and the governing equations become :

ｏ Velocity ratio :

$$K_1=\frac{V_p}{V_s}=\frac{A_{in}}{A_p}=(1/2)[1+(1+4K_s/\rho A_p)^{1/2}] \qquad (19)$$

ｏ Electrode voltage :

$$V=2BV_sK_1b\ [f/(2K_1^2N)+1] \qquad (20)$$

where $f=(K_1^{\ 2}-1)$ and N=interaction parameter defined above.

ｏ Electrode current :

$$I=a\rho V_s^2f/B \qquad (21)$$

ｏ Efficiency :

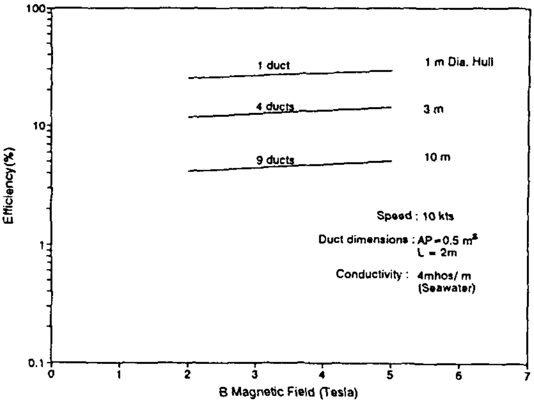

Fig. 3. Ideal efficiency vs. magnetic field intensity for selected ducts & hull sizes

$$\eta_p=2/(K_1+1)$$

$$\eta_e=\left\{1+\frac{1}{2N}(1-K_1^{\ -2})\right\}^{-1} \qquad (22)$$

where overall efficiency $\eta=\eta_p\cdot\eta_e$. Equations (19) through (22) provide a basis for evaluating performance of a single duct propulsion system. The results of the performance analysis of direct current electromagnetic propulsion in seawater are shown in Fig. 3~Fig. 9.

4. Conclusions

Electromagnetic thrusters offer a silent, nearly undetectable means of submarine propulsion. Based upon efficiency calculations included in this study, it seems unlikely that a practical thruster system could be developed for a full size (2000 ton, 10 m hull diameter) submarine. The chief reason for this conclusion lies in the difficulty of establishing high magnetic flux density throughout the active pumping region contained between the elctrodes. A reasonably efficient thruster cannot be designed and built until a superconducting dewar/winding capable of functioning reliably in a submersible environment has been demonstrated. Once this has been achieved, then efficiencies ten percent or more may be possible for reduced hull size of one to three meters diameter, provided that speed is limited to approximately ten knots or less. It may be feasible to use electromagnetic propulsion for maneuvering small submersible platforms requiring either modest continuous thrust or occasional bursts of high thrust levels.

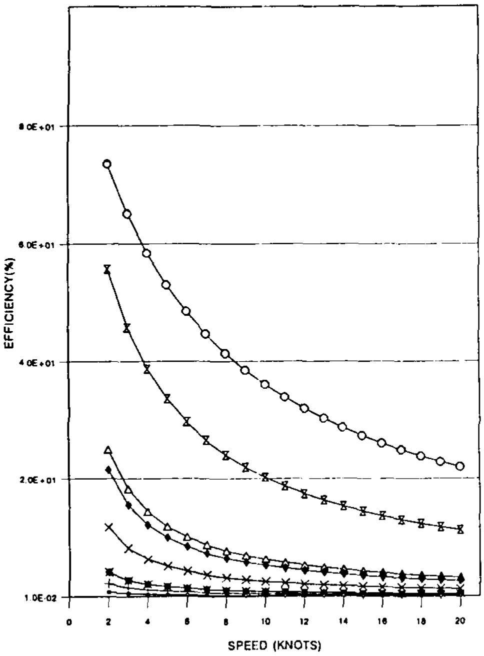

Fig. 4. Ideal efficiency vs. speed with single and multiple ducts
Magnetic Filed = 2.0 T, Each Duct Area = 0.5SQM, Electrode Length = 2.0 M

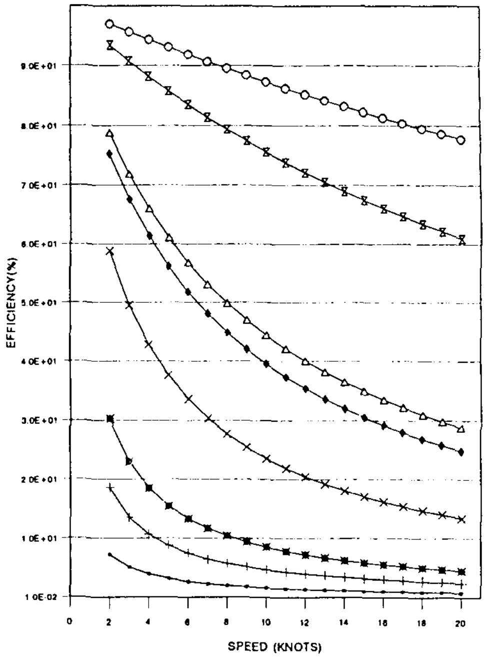

Fig. 6. Ideal efficiency vs. speed with single and multiple ducts
Magnetic Filed = 5.0 T, Each Duct Area = 1.0SQM, Electrode Length = 2 M

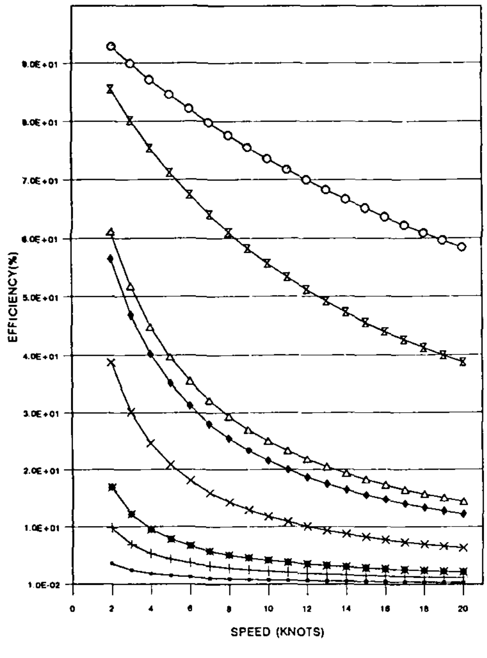

Fig. 5. Ideal efficiency vs. speed with single and multiple ducts
Magnetic Filed = 2.0 T, Each Duct Area = 0.5SQM, Electrode Length = 10 M

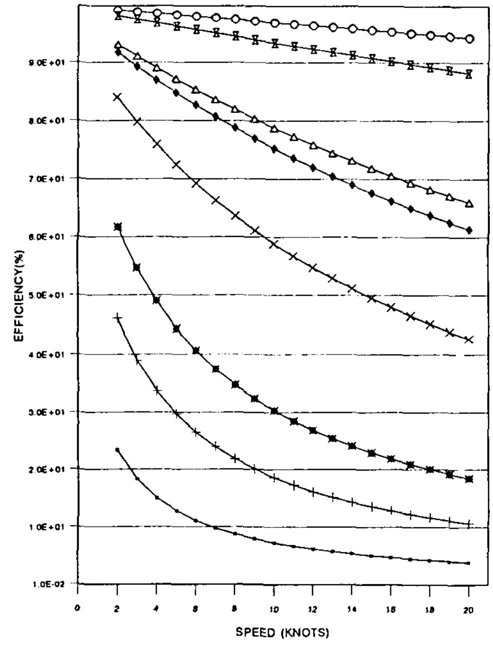

Fig. 7. Ideal efficiency vs. speed with single and multiple ducts
Magnetic Filed = 5.0 T, Each Duct Area = 1.0SQM, Electrode Length = 10 M

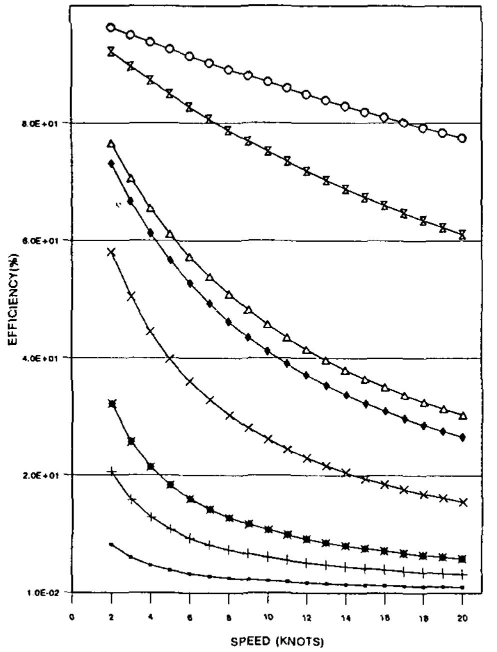

Fig. 8. Ideal efficiency vs. speed with single and multiple ducts
Magnetic Filed = 10 T, Each Duct Area = 0.25SQM, Electrode Length = 2.0 M

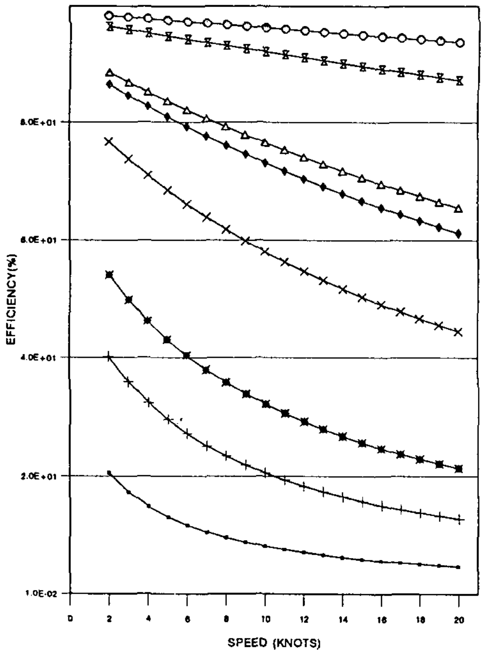

Fig. 9. Ideal efficiency vs. speed with single and multiple ducts
Magnetic Filed = 10 T, Each Duct Area = 0.25SQM, Electrode Length = 10.0 M

In this study, efficiency may be improved by the following components.

a) Minimizing thrust requirements; small hulls operating at low velocities.

b) Using large areas, low velocity thruster; multiple thrust-ducts are the most practical way of achieving this objective without requiring excessive cross-sectional area per duct.

c) Operating at high magnetic fields; preferably at field intensities much greater than that of conventional iron-copper magnetic circuit.

d) Enhancing conductivity; seeding seawater with a strong electrolyte such as hydrochloric acid has a pronounced effect upon overall efficiency.

Nomenclature

T	: thrust (newtons)
$\dot{m}$	: mass flow rate through duct (kg/s)
V_{out}	: outlet velocity (m/s)
V_{in}	: inlet velocity (m/s)
ρ	: density of seawater (kg/m^3)
V_p	: *velocity in pumping region of duct (m/s)*
A_p	: cross sectional area of duct in pumping region (m^2)
V_s	: relative velocity between submerged body and water (m/s)
A_{out}	: cross sectional area of outlet (m^2)
ΔP_p	: pump head ($=P_p-P_{in}$)
P_p	: pressure in pumping region (Nt/m^2)
P_{in}	: pressure in pump inlet (Nt/m^2)
K_1	: derived parameter ($=V_p/V_s$, A_{in}/A_p)
A_{in}	: cross sectional area of inlet (m^2)
b	: one-half electrode spacing (m)
a	: one-half duct with along B-field direction (m)
f	: factor appearing in voltage, current and efficiency expressions
B	: magnetic flux density (Tesla)
J	: electrical current density (A/m^2)
σ	: electrical conductivity of seawater (mho/m)
A_s	: effective drag cross-sectional area (m^2)
L	: electrode length (m)
η	: efficiency ($=TV_s/IV$)
N	: interaction parameter
η_p	: propulsive efficiency
η_e	: electrical efficiency
W_f	: fluid power (watts)

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