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# **Status of MHD Ship Propulsion**

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## **Abstract**

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MHD propulsion is a promising concept to thrust directly a ship in sea water without propeller and mobile mechanical part. The combined action of magnetic field and electric field produces Lorentz forces in a sea water which is an electrolyte. Consequently the MHD community has to face three kind of phenomena which are coupled together: hydrodynamics, electromagnetics and electrochemistry. An important theoretical and experimental work is presently on progress in several countries. It produces promising results. The key point of the industrialisation of MHD thruster is the development of very large on board high induction superconducting magnet.

## Introduction:

During the past 30 years, MHD thruster has been examined as a promising concept of direct ship propulsion in sea-water [1, 2]. The major change in this period concerns the technological development of very large superconducting magnets which enable industrial applications of this concept with acceptable performance. The primary advantage of MHD propulsion is that it is silent because it requires no moving mechanical components to transform into thrust the electric power of any power supply. One of the major difficulties is to produce this thrust with acceptable efficiency.

The idea seems very simple to directly generate a volumique Lorentz force by applying to a sea water flow an electric and a magnetic field, both perpendicular to the mean flow. One of the obstacles of this problem, which presently interest a large part of the MHD team in the world, is that sea water is not a conductor but an electrolyte. This has two main consequences:

- When a conduction process is used to apply the electric field, the interface between the conductor (electrode) and the electrolyte (sea water) is the place for losses (electrolysis overpotentials) and for gas

production (i.e. oxygen, hydrogen).

- The bulk current in the sea water suffers the very poor apparent conductivity of the flow which could produce unacceptable Joule dissipation if the current is not minimum.

The other difficulty is that the MHD thruster has to be integrated in a ship without generating unacceptable added hydrodynamic losses. Finally the problem posed to the international MHD community combine MHD, naval hydrodynamics and electrochemistry.

### Idealised performance analysis:

Basically four families of MHD thruster can be considered. The sea water flow submitted to Lorentz forces can be channelled in a duct (inner case) or external to the ship hull (outer case). The coupling between the electric power supply and the sea water can be conductive (d.c. case) or inductive (a.c. case). Initial MHD thruster studies were considering all these solutions. The following presentation concerns mainly the d.c. inner MHD thruster which is the more probable candidate for industrial application, first of all because of its performances, but also because it permits a persistent mode of operation for the magnet and minimal magnetic leakage.

As in any propulsion process two main performance criteria have to be considered. The first relies on the necessity to produce enough thrust to propel the ship at the nominal velocity (momentum balance) which fixes the magnitude of the total MHD force. The second relies on the ability to produce this thrust with minimal losses (energy balance). In the following we will concentrate on the ideal electric balance of MHD propulsion in order to understand the basic stake of this concept. Let us consider that **E** the external electric field, **V** the mean flow velocity and **B** the magnetic induction are all uniform and orthogonal fields in the useful volume  $v_{MHD}$  where the Lorentz forces apply (see figure 1).

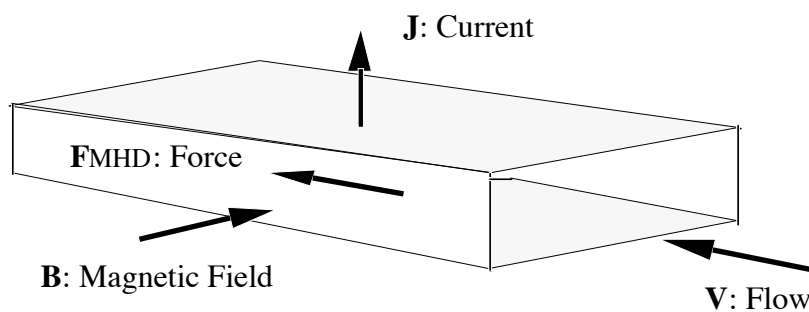


Figure 1: MHD thruster dc inner type

Using the conventional load factor  $f=E/VB$  as a non dimensional parameter it is easy to extract from Ohm's law that the total MHD force is:

$$F_{\text{MHD}} = sVB^2 (f-1) v_{\text{MHD}}$$

The electric ideal efficiency  $h_{el}$  is the ratio of the useful electric power (MHD forces power) to the total electric power (MHD forces power + Joule dissipation power). It is easy to obtain that the ideal electric efficiency is the inverse of the load factor  $h_{el}=1/f$  which means that a good efficiency is obtained for a load factor close to unity. Meanwhile, when the load factor tends to unity, the MHD force tends to zero. Consequently a compromise has to be done between momentum and energy considerations. The total MHD force has to balance the entire ship hydrodynamic drag:  $T$  which is roughly proportional to  $V^2$ .

$$T = k V^2$$

Based on the previous equations one obtain the following expression for the ideal electric efficiency:

$$h_{el} = \frac{1}{1 + \frac{k*V}{s v_{\text{MHD}} B^2}}$$

For a nominal velocity  $V$ , as  $s$  the apparent electrical conductivity is not a free parameter, the larger the product  $v_{\text{MHD}}B^2$  can be, the better it is. The previous expression of the ideal electric efficiency, is probably the best in order to understand why the performances require a product  $v_{\text{MHD}}B^2$  as large as possible. Nevertheless this recommendation is also limited for the two following reasons:

- The useful volume  $v_{\text{MHD}}$  can not be too large otherwise the added drag due to the MHD thruster would be excessive.
- The magnetic induction is bounded by technological feasibility: superconductor wire, mechanical structure and cryostat.

The lesson drawn from performance analysis is the need for very large superconducting magnet with useful volume of several hundreds of cubic meters and an induction as large as possible.

### State of the art in the world:

There are several countries involved in MHD propulsion as for instance: USA, Japan, Russia, France [3, 4, 5, 6]. The papers studies concern performance prediction and optimisation which are usually the first step of the analysis. These models are based on global one dimensional balances. Their objective is to compare the predicted performances of various solutions as for instance inner or outer MHD propulsion, but also for a given type of thruster (i.e. dc inner type) to compare the conceptual arrangement: for instance pod or annular thruster. From the various analysis known in open literature it is presently admitted that the more probable MHD submarine should be a dc inner annular one (see figure 2).

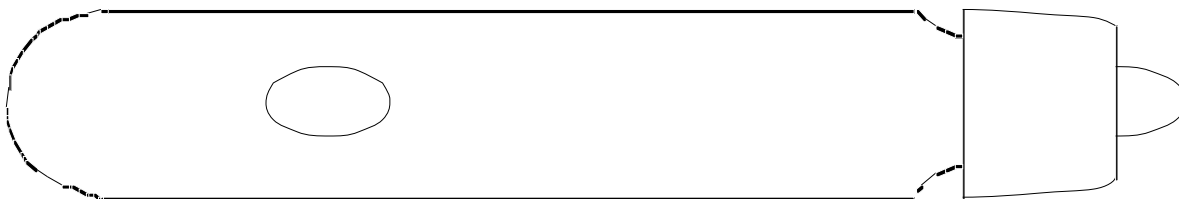


Figure 2: Schematic top view of a dc inner annular submarine

The reason for this is that this geometry is well adapted to large useful volume with satisfying uniformity of the electric and magnetic fields. The concluding results of these comparison studies could be summarised with the following recommendations [3, 6, 7, 8]:

- The axial length (in the velocity direction) has to be moderate because of hydrodynamic losses but not too much because of end effect.
- The magnetic field lines can turn around the hull of the submarine in such a way that each magnetic coil tends in the same time to enhance the magnetic induction created by its neighbour coils and to reduce magnetic leakage.
- The radial length (electric field direction) can be short in order to reduce the Joule dissipation.

These recommendations are fulfilled by annular geometry.

At the second level more refined models (multi-dimension) are also developed to give a precise analysis of the discrepancies and precision of 1D global models. As this accounts for non uniformities these models can be used to quantify more precisely the performance of thrusters dimensioned by the previous models. In some cases, as for instance outer MHD propulsion, a multi-dimensional modelling is imposed. In the case of an outer MHD propulsion it is very tendentious to consider that the fields are uniform: the MHD force harmonically varying around the hull while the velocity field modification nearby the hull is the dominant mechanism for thrust production.

Concerning experimental programmes two strategies are possible:

- The first one (used in USA, Russia, France) consists, in a laboratory, to place an MHD test section in a closed loop using either real sea water or salted water. In these loops the flow can be MHD driven or it can be mechanically pumped. When a pump is used the flow velocity can be adjusted independently from the MHD working conditions (current, magnetic field). That is the reason why it is the more interesting situation to explore an extended domain [3, 9]. There are also several experiments which concern only a part of the phenomena involved in MHD propulsion. For instance they concern the coupling between electrochemistry and fluid mechanics without magnetic fields. These experiments are still very interesting because they permit detailed analysis with moderate cost. In any case it is very difficult to obtain in the same time hydrodynamic, electrochemical and electromagnetic similarities. The very first objective of these experiments is model validation. It is now clearly established that the models predict well the performances including for the low efficiency working conditions which are due to the reduced useful volume of these experiments compared to full scale MHD thruster. In addition the nature of the inlet flow of the MHD test section (quasi 1 D) of a closed loop is not similar to the inlet free flow of an open thruster which is necessarily multi-dimensional because of the suction effect [6]. Another question is the validity to use salted water in place of sea water. It is clear that salted water is only a transitory fluid and that finally

sea water is the only real size fluid even if most of the basic are well modelled with instant ocean.

- The second strategy consist to realise reduce scale MHD ship propelled like in Japan. This method is probably very interesting from the industrial point of view because it necessarily include all the element, except scale, of a real ship. On the other hand this approach is may be less quantitatively informative because on board measurment are not as convenient as laboratory ones. The published results of the sea trails of YAMATO-1 are very interesting because it is the first MHD ship [10]. It seems that the measured performances are in good agreement with the predictions except hydrodynamic performances. This underestimation of the viscous losses is probably due to the fact that the inlet flow (necessarily multidimensional) and the inner flow (non developed) were not enough accurately modelled.

### Conclusion:

At the present level of knowledge it is established that MHD thruster is a promising direct and silent propulsion concept. An important modelling effort has been done in various countries, which for most of them also validate experimentally the predictions of the models. There is not presently a full size industrial product of MHD propulsion. It is clear that the main progress have to be concentrated on in-board large volume (several hundreds of cubic meters) and large induction (larger than 8 T) superconducting magnet.

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