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Electromagnetic properties of a modular MHD thruster

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Abstract. The magnetic field of an annular MHD thruster made of independent superconducting modules has been studied with analytical and numerical methods. This configuration allows to obtain large magnetized volumes and high induction levels with rapidly decreasing stray fields. When some inductors are out of order, the thruster remains still operational, but the stray fields increase in the vicinity of the failure. For given structural materials and superconductors, it is possible to determine the size of the conductor in order to reduce the electromagnetic forces and the peak field supported by the conductors. For an active field of 10 T in a 6 m ray annular active channel of a thruster with 24 modules, the peak field is exactly 15.6 T in the Nb_3Sn conductors and the structure has to sustain 10^8 N/m forces. The necessity to place some magnetic or superconducting shield is discussed, particularly when the thruster is in a degraded regime.

Résumé. Nous présentons une étude analytique et numérique du champ magnétique d'un propulseur MHD naval annulaire, constitué de secteurs inducteurs supraconducteurs. Cette configuration nécessite des champs magnétiques élevés dans des volumes importants, et permet une décroissance rapide des champs de fuite. Lorsque quelques inducteurs sont en panne, le propulseur reste toujours opérationnel, mais les champs de fuite sont importants aux environs des modules hors service. Étant donné un matériau supraconducteur, il est possible de déterminer la forme des inducteurs dans le but de réduire à la fois les forces électromagnétiques et le surchamp supporté par le bobinage. Pour un propulseur annulaire constitué de 24 modules inducteurs, et un champ actif de 10 T au centre de la partie active du canal ($r = 6$ m) on obtient avec du Nb_3Sn un champ maximun sur le conducteur de 15,5 T et la structure supporte une force de 10^8 N/m. De plus, la nécessité de placer des écrans magnétique ou supraconducteur en régime dégradé (mise hors service d'un ou de plusieurs modules inducteurs) est discutée.

PACS. 85.25.Ly Superconducting magnets; magnetic levitation devices – 75.40.Mg Numerical simulation studies

1 Introduction

MHD propulsion needs very high magnetic fields in very large volumes of sea water to obtain a good efficiency. On an other side, in order to reduce the magnetic signature of the vessel, it is necessary to design a thruster with very small leakage fields: a modular cylindrical thruster can provide answer to these requirements and keep its propulsion ability even when one or more modules are out of order. Superconducting conductors are necessary to produce the active magnetic fields and, for given structural materials and superconductors, it is possible to determine the size of the conductors in order to reduce the electromagnetic forces and the peak field supported by the conductors.The magnetic field of the annular MHD thruster has been studied with analytical and numerical methods, using 2D or 3D modelizations. When some modules are out of order, the thruster remains still operational, but the stray fields increase in the vicinity of the failure. In this degraded regime, it may be necessary to place some magnetic or superconducting shield either inside or outside the active channel.

2 MHD propulsion requirements

The power corresponding to the Laplace forces is JBV_{mag} V_{mhd} where J is the electrode current density, B the magnetic induction, V_{mag} the magnetized volume and V_{mhd} the relative speed of the sea water flow in the MHD channel. This propulsive power which compensates the resistive drag power on the vessel varying as $(V_{\mathrm{mhd}})^3$, is associated to Joule effects varying as J^2: for a given speed V_{mhd}, the multiplication of the propulsive power by a factor of 2 increases fourfold the losses; then it appears that, for large speeds, the MHD propulsion is at a disadvantage by comparison with classical propellers whose losses vary as $(V_{\mathrm{mhd}})^3$. Nevertheless, the global efficiency of MHD propulsion can be higher than classical one.

An approximate expression for the MHD propulsion efficiency is given by [1]:

$$\eta = (1 + kV_{\mathrm{mhd}}/\sigma B^2 V_{\mathrm{mag}})^{-1}$$

σ: sea water conductivity; k: magnetic force/V_{mhd}.

This expression shows that the small value of the sea water conductivity ($\sigma = 4$ S/m) imposes large magnetic fields B and active volumes V_{mag}. The product $V_{\mathrm{mag}}B^2$ is a designing parameter (of the order of 10^4 $\mathrm{T}^2\,\mathrm{m}^3$) related to the stored energy E_0 of the magnet which is good criterion to design large superconducting magnets. An empirical relation [2], which can be explained by mechanical and protection considerations, links E_0 to the overall current density $J_{\mathrm{c_{ov}}}$ in the conductors:

$$E_0(J_{\mathrm{c_{ov}}})^2 = 10^{24}\ \mathrm{J\,A^2\,m^{-4}}.$$

For NbTi and Nb_3Sn, the superconducting materials which are used at low temperature to obtain large magnetic fields, stability and mechanical requirements demand a ratio between J_{c} and $J_{\mathrm{c_{ov}}}$ around 10 or 20. Taking these values and the MHD propulsion requirements, we obtain for $V_{\mathrm{mag}} = 100$ m^3, $B = 10$ T *i.e.* $E_0 = 2.5$ GJ, $J_{\mathrm{c}} = 5 \times 10^8$ A m^{-2}. It is also necessary to know the peak fields on the winding to determine the working conditions of the conductors.

Several configurations can be used for a MHD thruster to achieve the largest propulsive force ($F_{\mathrm{mhd}} = \sigma B^2 V_{\mathrm{mhd}}(u-1)V_{\mathrm{mag}}, u = E/BV_{\mathrm{mhd}}, E$: electric field) with the lowest stray fields [3]. Solenoid configuration gives very small peak fields but the stray fields vary as r^{-3} [4] and the flow geometry is complicated [5]. The best stealthiness is given by a toroidal design; this configuration being approached with independent modules which allows damage.

3 MHD thruster ideal model: perfect torus

The toroidal configuration is ideal and the systems which we studied are close to this configuration with an annular MHD channel around the hull delimited by the active parts of the magnet and by the electrode (Fig. 1). In this ideal case, the inhomogeneity of the magnetic field in the propulsion channel (Fig. 2) is sufficient to create instabilities in the hydrodynamic flow leading to inverse thrust forces [6].

It is possible for a given operating point *e.g.* $V_{\mathrm{mhd}} = 10$ m/s, $\eta = 0.6$ to optimize a toroidal MHD thruster, taking into account

- the superconductor characteristics $J_{\mathrm{c}}(B)$;
- the mechanical properties of the materials (maximal stress $\sigma_{\max}$);
- the drag of the thruster.

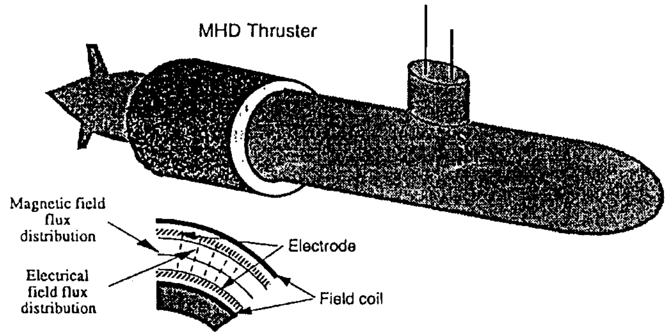

Fig. 1. Annular MHD thruster for the reference vessel: $L = 100$ m, displacement $= 7850t$, $V_{\mathrm{mhd}} = 10$ m/s.

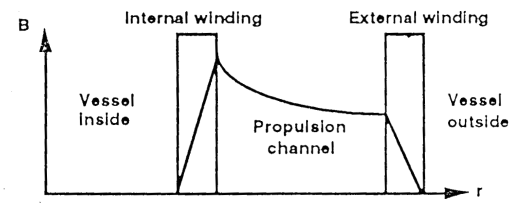

Fig. 2. $B(r)$ for a MHD thruster ideal model.

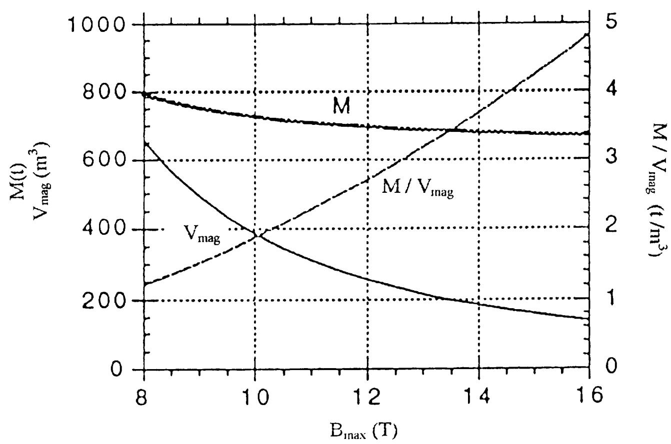

Fig. 3. Ideal torus thruster optimization when the inner radius is fixed ($R_1 = 5$ m, $\alpha = R_2/R_1$); operating point: $V_{\mathrm{mhd}} = 10$ m/s, $\eta = 60\%$.

Usually, the mechanical stress is more severe than the $J_{\mathrm{c}}(B)$ limitation. When the inner radius R_1 is fixed (corresponding for example to the vessel hull), the mass M of the thruster is minimum when the length of the thruster is minimum and when $B_{\max}$ and the outer ray R_2 are maximum. As shown in Figure 3, the thruster optimized for the reference vessel (Fig. 1) will have a mass of about $700t$ and a volume of 200 m^3.

4 Modular MHD thruster

The ideal torus configuration can be approached using n modular inductors regularly spread along the hull of the vessel. Each module is made of flat coils delimiting the

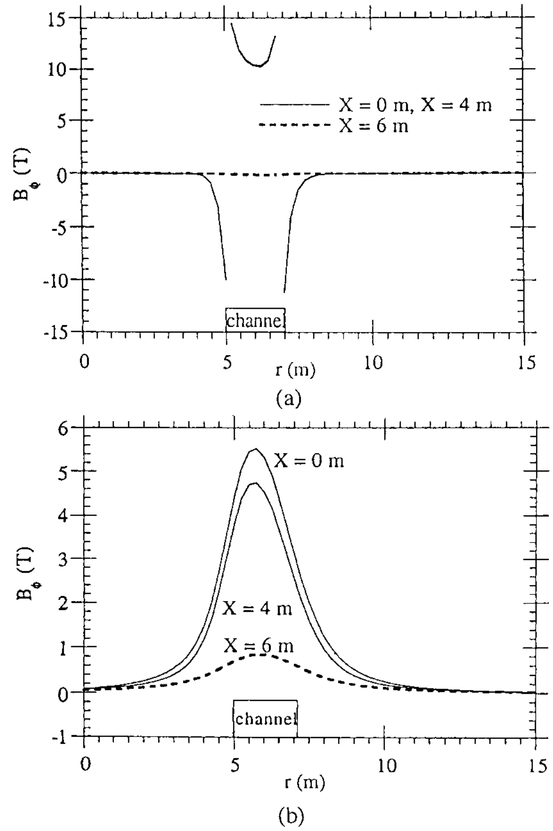

Fig. 4. Effect of module failure in the direction $\phi = 0, n = 24, X$ (axial direction): (a) thruster without failure; (b) the module placed in $\phi = 0$ fails.

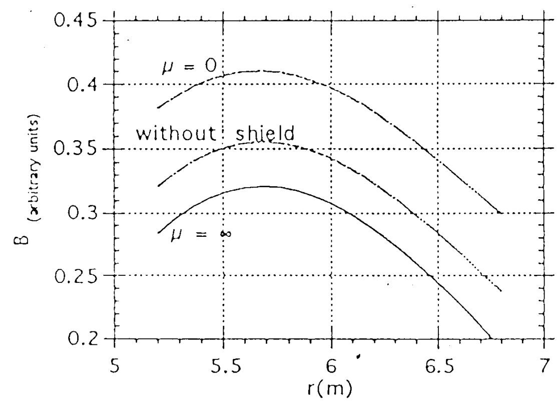

Fig. 5. Action of shields on the magnetic field in the propulsion channel (locate at $r_i = 5$ m and $r_e = 7$ m) at the level of a failed inductor module. Shields are situated at $r = 4$ m and $r = 8$ m.

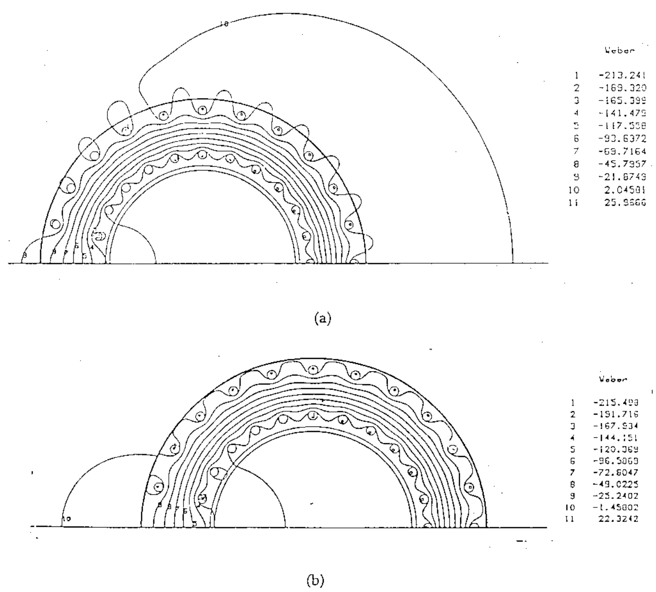

Fig. 6. Magnetic flux distribution (a) without shields, (b) in the presence of shields (ferromagnetic shield is internal and superconducting shield is external).

active channel [7]. The stray fields inside and outside the thruster, depend on the number of modules in operation. When the thruster is completely symmetrical, the outer stray field varies as $r^{-(n+1)}$.

Although the active magnetic field remains quite unaffected in the undamaged modules [8], the effect of a failure of one ore more modules is dramatic on the inner and outer fields variation. As shown in Figure 4 the failure of one module changes deeply the magnetic field produced by the thruster: the active field is lowered by a factor of two in the faulty module and this perturbation extends to the two adjoining modules; the stray fields become prohibitive as they reach 1.8 $\times 10^{-3}$ T at $r = 30$ m.

5 Action of magnetic and/or superconducting shields

As shown in Section 4, when one or more modules of the thruster fail, it can be necessary to use shields to maintain the leakage fields at a sufficiently low level. The presence of magnetic and superconducting shields around the active channel can be effective without great influence on the active field. Without any failure, the multipolarity gives a very small effect in the active field (less than 1%). When one module is out of order, a superconducting shield ($\mu_{sc} = 0$) has a magnetising effect and a ferromagnetic shield ($\mu_{iron} = \infty$) has a demagnetising effect in the vicinity of the failed module (Fig. 5). This is easily explained using the superposition of a regime without failure and a regime where the failed module has an inverse polarity.

Using a 2D finite elements method, the influence of different pairs of shields placed inside and outside the propulsion channel has been studied.

The results obtained from the numerical method (Fig. 6) show the magnetic flux distribution in the presence of shields (ferromagnetic shield is internal and superconducting shield is external) and without shields. The

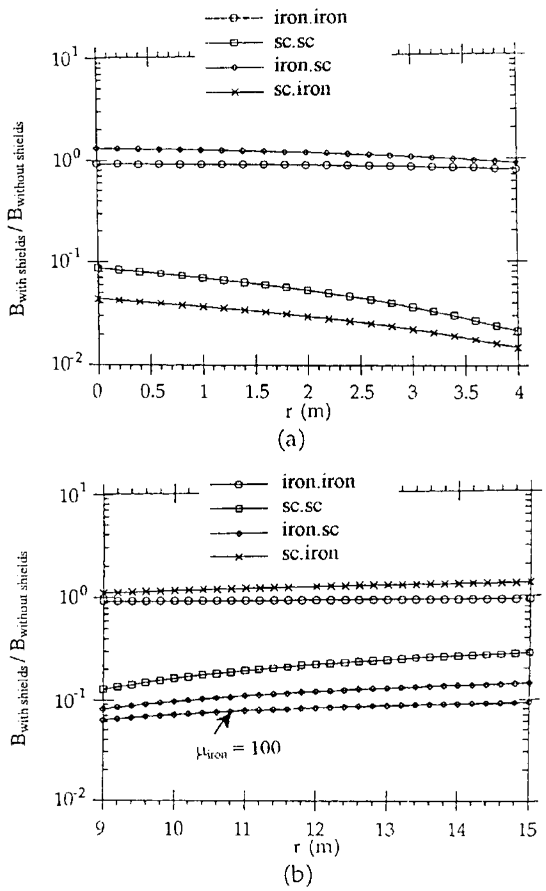

Fig. 7. Action of different pairs of shields near the failed inductor module; relative permeability: $\mu_{\text{acier(iron)}} = 5$ (or 100), $\mu_{\text{supra(sc)}} = 10^{-3}$; $n = 24$, $r_e = 5$ m, $r_i = 7$ m; shields are situated at $r = 4$ m and $r = 8$ m.

magnetic flux crosses the shields in the vicinity of a failed inductor module and his confinement has been reinforced in the propulsion channel.

To decrease the leakage field in the vicinity of a failed inductor module, inside and outside the propulsion channel, it is possible to use the diamagnetic effects of a superconducting shield when it is located next to the side where the magnetic field has to be lowered; in this case, a ferromagnetic shield on the opposite side of the channel will enforce the effect of the superconducting shield as shown using a value of 100 instead of 5 for the permeability (Fig. 7).

A good compromise may consist in using superconducting shields on both sides of the propulsion channel.

6 Conclusion

We focused our attention on the use of analytical and numerical methods to study magnetic field of modular MHD thruster made of independent superconducting inductors. For a given operating point, we optimized a toroidal MHD thruster taking into account mechanical properties of structural materials (maximal stress $\sigma_{\max}$), then we studied the degraded regimes when one or more modules fail. Using a 2D finite elements method, the influence of different pairs of shields placed inside and outside the active channel (to reduce the leakage fields in the vicinity of a failed module) has been treated: it appears that a good compromise may consist in using superconducting shields on both sides of the active channel.

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