Modelling of degaussing coils effects on ships

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***Abstract*- This paper presents our work on magnetic modelling of ships, especially their degaussing coils. We first focus on these coils effects in the FEM computations. The main reason of bad results is a locally inadequate mesh. We propose a method named "reduced potential jump" to avoid the use of a very fine mesh. Then, comparison of results is presented for a simple geometry.**

I. INTRODUCTION

In the earth's magnetic field, a ship creates a local magnetic anomaly. To reduce these perturbation, the most usual method is to install degaussing coils onboard the ship. The computations of equilibrium magnetizations without these coils using a Finite Elements Method gave very good results [1]. On the contrary, the computation of the degaussing coils effects gives bad results.

The purpose of our work is to analyse the reasons of these bad results and to propose solutions bringing the same accuracy than in the case of equilibrium magnetizations.

II. STUDIED CONFIGURATIONS

A. 2D Problem

We study a simple geometry for which a reliable numerical 2D solution is given by the FEM software FLUX2D. It's a ferromagnetic cylindrical ship and a circular coil (Fig. 1).

With the mesh generator of FLUX2D which allows to mesh automatically with triangular elements and manually with rectangular elements, we got a very accurate mesh which gives a reliable solution (Fig. 2).

The mathematical model uses magnetic vector potential $\vec{A}$ in magnetostatic in axisymetric configuration:

$$\nabla^2 \vec{A} = \mu \vec{j} \tag{1}$$

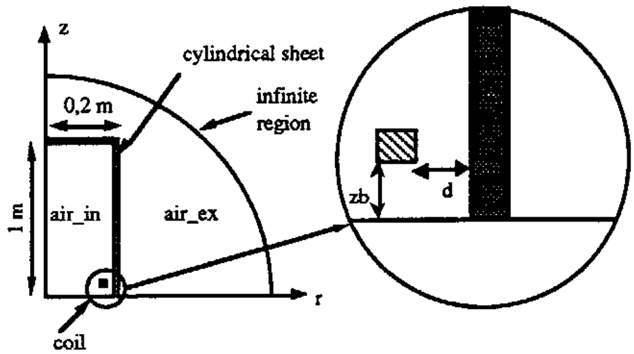

Fig. 1. Two dimensional axisymetric geometry

where $\vec{j}$ is the current density in the coil and μ the magnetic permeability of the sheet.

B. 3D Problem

The same problem (Fig. 3) has been studied by using the FEM 3D software FLUX3D with the numerical tools developped for the computation of the equilibrium magnetizations with a reasonable number of elements, that is:

- the 3D surface elements with potential gap to describe the volumic thin sheet [1]

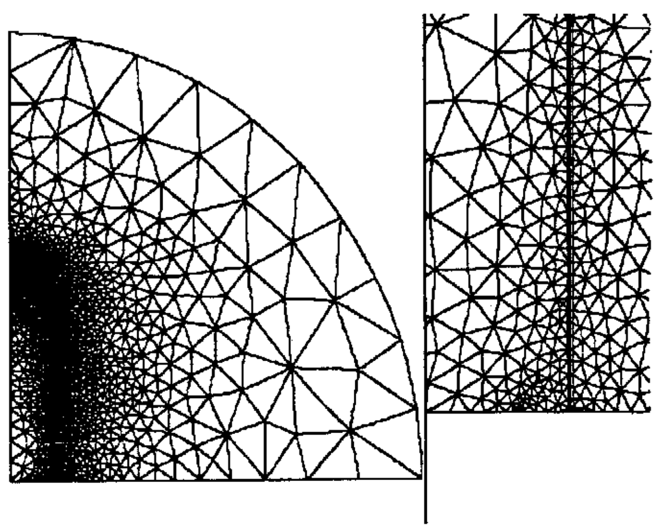

Fig. 2. Two dimensional mesh

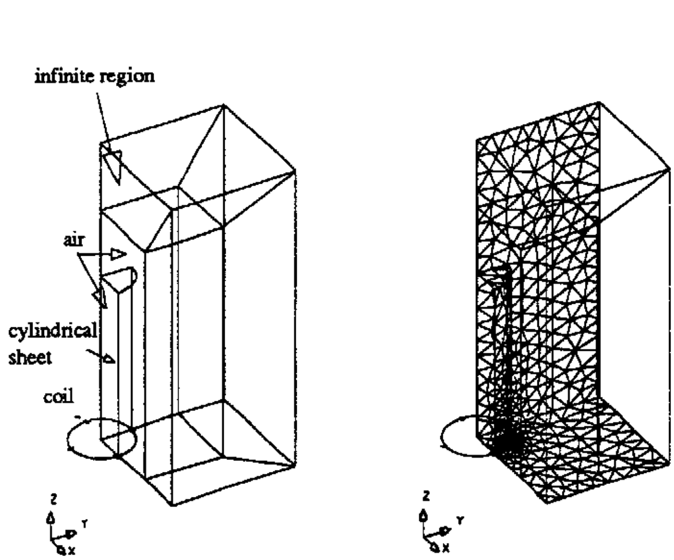

Fig. 3. Three dimensional geometry and mesh

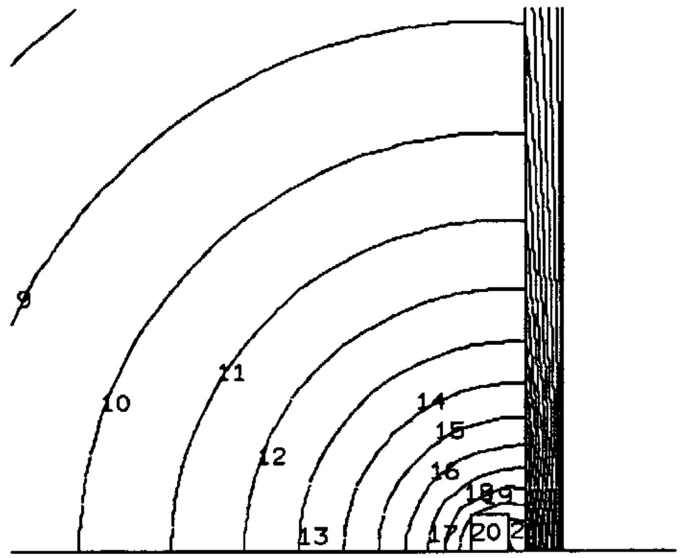
Fig. 4. Equiflux in the sheet

- the reduced scalar potential to reduce the number of unknowns per node,
- the modelling of the infinite domain by a mapping method [2].

The mathematical variable was the reduced scalar potential Ψ in magnetostatic:

$$div \{ \mu [\vec{Hj} - \vec{Grad} \Psi] \} = 0 \qquad (2)$$

where $\vec{Hj}$ is the field created by the coil analytically computed by the Biot and Savart law.

III. COMPARISON OF 2D AND 3D RESULTS

A. Hypothesis of 3D Surface Elements

Figure 4 shows the equiflux in the cylinder of the 2D problem. It reveals that the field in the sheet is nearly tangential to it, thus verifying the validity of the hypothesis of the 3D surface elements without potential gap. It consists in a null normal tangential component of the field in the sheet. So we can integrate analytically through the thickness of the sheet. For exemple, the source term in the finite elements formulation can be written:

$$\int_{\text{volumic sheet}} \mu \vec{Hj} . \vec{Grad} \Psi dV =$$

$$\int_{\text{3D surface elements}} \mu \vec{Hj} . \vec{Grad} \Psi Ep dS \qquad (3)$$

where Ep is the thickness of the sheet.

The integration is done not on the volumic sheet but on the 3D surface elements.

B. Magnetic anomaly at standard depth

We compare the field of the ferromagnetic cylinder at a standard distance (typically one time the radius of the cylinder) from its axis in 2D and 3D (Fig. 5) for different distance d between the sheet and the coil.

We notice a good agreement of the 2D and the 3D results when d is large enough ($d \geq 5$ times the thickness of the sheet Ep). But when d decreases ($\approx Ep$ or $0.5*Ep$), the 3D results become incorrect. The 3D mesh is so large near the coil compared to the distance coil that the local variations of field are not correctly taken in account- sheet

$$\left(\frac{\text{elements dimension}}{\text{distance sheet - coil}} = 100 \right).$$

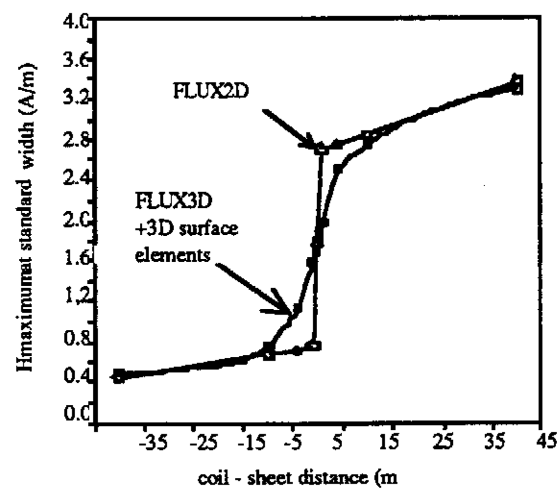

Fig. 5. Maximum field at the standard depth in 2D and 3D as a function of the distance sheet - coil

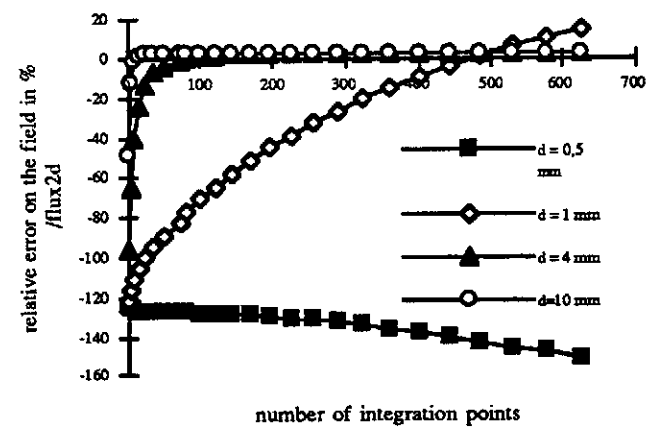

Fig. 6. Error on the field as a function of integration points number

C. Increasing the Number of Integration Points

We can improve the accuracy of numerical integration by increasing the number of integration points. In fact, in the Finite Elements Method appear integrals which are numerically calculated with a certain number of points in the elements [3]. Increasing the number of integration points decreases the error of the 3D field compared to the 2D field for $d \geq 4 * Ep$ but gives unsatisfying results for a coil very close to the sheet ($d \approx Ep$), which is the most common case in real ships.

D. Improvement of The Local Mesh

Another test was to describe manually a high density mesh around the coil. It leads to a 4% error in field, compared to 2D results. The error was 120 % when using the standard mesh. Thus, we took this 3D results as reference for the following analysis.

IV. Proposed Solutions

The disadvantages of the preceeding improvement of the local mesh are:

- the need for a manual description of a particular aera for each coils with a local high density mesh.
- the significant increase of the number of elements and the computation time.

We lose partially the advantages of the special numerical tools developed for the ship magnetizations computation. Such a solution is not realistic for the whole complex structure of a real ship.

We see two possibilities to solve the coils effects problem:

- the adaptative meshing realised by a mesh generator able to determine automatically where an improved mesh is required.
- the modification of the mathematical model.

We will explore this solution here. The purpose is to take into account the reaction of the material with a coarse FE mesh on the iron sheets near the coils. The idea is to add the local reaction of the ferromagnetic material that the FEM could not calculate. This local reaction can be described as:

- the effect of a density of magnetic poles or dipoles equivalent to the magnetized sheet,
- the effect of a magnetic potential jump along the sheet.

A. Magnetic Dipoles

In the reduced scalar potential model, the field created by the coil is described analytically by the Biot and Savard law. The idea is to add a correction field $\vec{H_d}$ taking the reaction of the ferromagnetic material into account.

Locally, the coil and the cylindrical sheet can be considered as an infinite wire close to an infinite sheet. The magnetized portion of this sheet is assimilated to a linear distribution of dipoles which create the field $\vec{H_d}$ [4] whose polar components are :

$$\begin{cases} H_\rho = \dfrac{\lambda}{2\pi\rho^2}\cos\theta \\ H_\theta = \dfrac{\lambda}{2\pi\rho^2}\sin\theta \end{cases} \qquad (4)$$

where λ is the magnetic moment density per length unit.

Adding that correction field to the source field $\vec{H_j}$ improves the total field but not the reduced scalar potential. There is no reaction of the FEM model to that correction and we are totally dependant on the quality of the analytical correction, which is unrealistic for real ships.

B. Reduced Scalar Potential Jump

1) *Application of the jump*: The reference 3D results (that is with a locally densified mesh) reveals a reduced scalar potential jump in the sheet near the coil (Fig. 7)

If we impose this jump as a Dirichlet constraint in the 3D problem with a coarse mesh, the field at the standard distance become very close to the one given by the 3D reference (Fig.8).

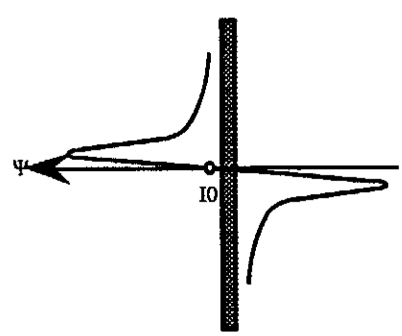

Fig. 7: Reduced scalar potential jump along the sheet

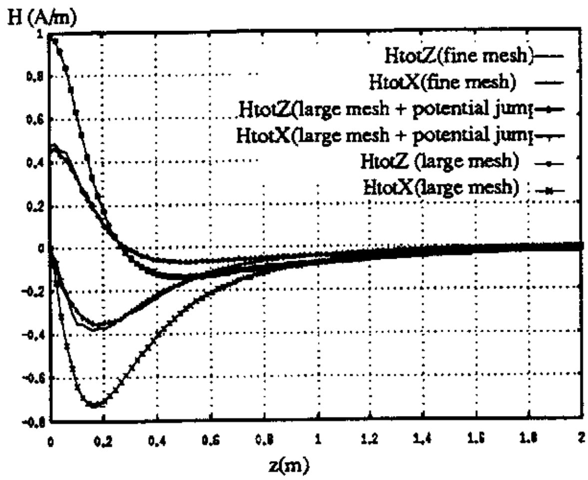

Fig. 8 . Magnetic field at standard width

This method seems to be efficient to solve the problem with a coarse mesh. The jump compensates correctly the incapacity of the FEM model to compute the local effect of the coil on the sheet.

2) *Computation of the potential jump*: To apply this method, we must predetermine the local reduced scalar potential. The distance between the coil and the sheet is so small compared to the dimensions of the cylinder that we can consider locally this 3D axisymetric configuration as an infinite wire close to an infinite sheet. This 2D problem can be solved by the magnetic images method.

The influence of an infinite wire in the air can be described by a complex scalar potential [5], complex combination of the scalar potential Ψ_0 and the flux function F_0

$$W_0 = \Psi_0 + i \cdot F_0 \qquad (5)$$

where

$$\left.\begin{aligned} \Psi_0 &= \frac{I_0}{2\pi} \cdot Arctg(\frac{y+d}{x}) \\ F_0 &= \frac{I_0}{2\pi} \cdot Log\sqrt{x^2 + (y+d)^2} \end{aligned}\right\} \qquad (6)$$

where I_0 is the intensity in the infinite wire.
With $Z = x + i \cdot y$, we have

$$W_0 = \frac{I_0}{2\pi} \cdot Log\,(z + i.d) \qquad (7)$$

With a sheet of relative permeability μ_r, of thickness Ep, at a distance d from the wire, the complex scalar potential inside the sheet is the sum of the potentials created by an infinite series of magnetic images [6] at the points (Fig. 9)

$$\left\{\begin{array}{l} B_{2p} \\ B_{2p+1} \end{array}\right.$$

which affixes are

$$\left\{\begin{array}{l} Z_{2p} = -\,id - 2ip.Ep \\ Z_{2p+1} = id + 2i(p+1).Ep \end{array}\right. \qquad (8)$$

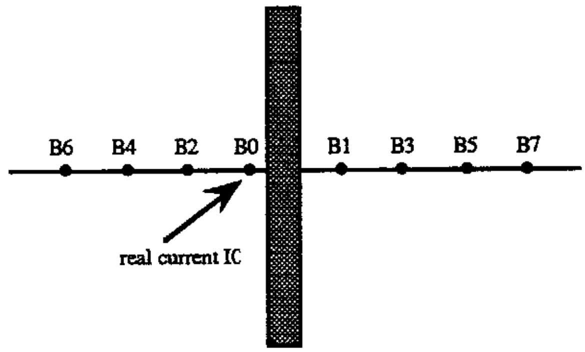

Fig. 9: The magnetic images for the infinite wire- infinite sheet problem

p varies from 0 to infinite.
These images carry the currents

$$\left\{\begin{array}{l} I_{2p} = (1+a) \, . \, A^{2p} \, . \, I_0 \\ I_{2p+1} = (1+a) \, . \, A^{2p+1} . \, I_0 \end{array}\right. \qquad (9)$$

where

$$A = \frac{1 - \mu_r}{1 + \mu_r} \qquad (10)$$

This result is obtained like in optics by expressing the transmission through the interfaces with a factor $(1 + A)$ and the reflection with a factor A

The complex potential inside the sheet is then

$$W = -\frac{1+A}{2\pi} I_0 \left\{ \sum_{p=0}^{+\infty} A^{2p}.\, Log(\, Z - Z_{2p}) + \sum_{p=0}^{+\infty} A^{2p+1}.\, Log(\, Z - Z_{2p+1}) \right\} \qquad (11)$$

Using back the real notation and substracting the source potential, we get the reduced scalar potential inside the sheet

$$\Psi = -\,\Psi_0 - \frac{1+A}{2\pi} I_0 \left\{ \sum_{p=0}^{+\infty} A^{2p}.\, Arctg\frac{y + d + 2p.Ep}{x} + \sum_{p=0}^{+\infty} A^{2p+1}.\, Arctg\frac{y - d - 2(p+1).Ep}{x} \right\} \qquad (12)$$

The figure 10 shows the reduced scalar potential inside the the sheet for $\mu_r = 200$ calculated both with the formula (12) and by FLUX3D using a locally densified mesh.

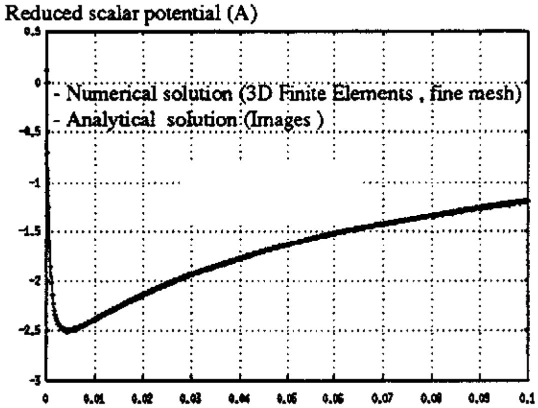

Fig. 10. reduced scalar potential in the sheet

We notice an excellent correlation between the two curves. The analytical series converges less quickly when the permeability of the sheet is higher.

V. CONCLUSION

Thanks to the comparisons between 2D and 3D results on a simple geometry, we have shown that the significant errors in computation of degaussing coils effects on ships occur when the local mesh density is largely unsufficient and can not take the local reaction of the material into account.

To avoid the refinement of the mesh, we propose to introduce a reduced scalar potential jump in the sheet plane which simulate the local reaction of the material. This jump can be calculated a priori by the magnetic images method for the simple 2D case infinite wire - infinite sheet. To generalize the method to more complex geometries, we have to calculate the potential jump for other 2D cases like an infinite wire in an edge sheet or a T - shaped sheet, for which analytical or simple numerical solutions can be found.

So this method seems to be a good alternative for the computation of degaussing coils effects in ships with reasonable number of elements and computation time.

REFERENCES

[1] X. Brunotte, G. Meunier, "Line Element for efficient computation of the magnetic field created by thin iron plates", *IEEE Trans. Magn.*,Vol. 26, September 1990, pp 613-616

[2] J. F. Imhoff, G. Meunier, X. Brunotte, J. C. Sabonnadière, "An original solution for unbounded electromagnetic 2D and 3D problems throughout the finite element method", *IEEE Trans. Magn.*,Vol. 26, September 1990, pp 2196-2199

[3] G. Dhatt and G. Touzot, *Une présentation de la méthode des éléments finis*, second edition, Collection Université de Compiègne, 1984

[4] J. P. Yonnet, *Rare Earth Permanent Magnets*,Oxford University Press,1996,chapter 9

[5] E. Durand, *Magnétostatique*, Masson et Cie, Paris, 1968

[6] K. J. Binns and P. J. Lawrenson, "Electric and Magnetic Fields Problems", Mdc Millan, New York, 1963