Efficient Methodology for Optimizing Degaussing Coil Currents in Ships Utilizing Magnetomotive Force Sensitivity Information

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Abstract — This paper presents an efficient methodology for optimizing degaussing coil currents in ships to minimize magnetic field anomaly underwater. For fast search for an optimum, a magnetomotive force sensitivity formula is adopted. Especially the method does not require any numerical field analyses to assess an objective function during optimization process providing experimental field data on each coil effect are given. The validity of the proposed method is tested with a model ship.

I. Introduction

In the earth's magnetic field, the ferromagnetic ship hull is magnetized and it creates a local magnetic perturbation underwater. To minimize such the magnetic signal from the ship, degaussing coils consisting of longitudinal (L), athwartship (A) and vertical (V) coils have been usually used in the ship. In degaussing technique, most important thing is to decide optimal currents individually allotted to degaussing coils for reducing the magnetic anomaly as least as possible. To achieve this, a few attempts based on the stochastic approach have been made to date. However, they require huge computation time to find out an optimum for three-dimensional (3D) inverse problems including the local magnetization of the ferromagnetic hull [1].

To tackle the aforementioned problem, this paper presents an efficient methodology for optimizing degaussing currents in ships as taking the hull magnetization into account. Instead of executing 3D finite element analysis (FEA) at each iterative design, the method utilizes experimental field date on each coil effect including the hull magnetization to assess an objective function. This is valid because the material linearity is guaranteed below the maximum degaussing current permitted. Thus the technique results in saving computation time dramatically. Moreover, in order to fast search for an optimal solution, the magnetomotive force (mmf) sensitivity formula containing the first-order gradient information of an objective function with respect to the coil mmf is adopted. Finally, the proposed method is tested with a model ship and its results are verified by means of 3D FEA.

II. Modeling of Degaussing Problems

A. Forward Problem Modeling

To deal with an inverse problem regarding degaussing coils, it is necessary to solve the forward problem first, where underwater magnetic fields called the coil effect are predicted. The coil effect should include the fields created by the coil mmf itself and additional fields due to the hull magnetization locally induced around the coil. The 3D FEA can be applied to the field calculation but it takes more than one hour at least for obtaining only one coil effect. As known, a ship is usually equipped with several tens of degaussing coils. Therefore FEA is not adequate for the practical degaussing technique.

To overcome this difficulty, this paper exploits experimental field data instead of the numerical field solutions for estimating the coil effects. Fig. 1 shows the measurement system of the coil effects where *np* triaxial magnetic sensors are placed on the measuring line under the keel. When all the degaussing coils do not work, each coil effect should be measured as feeding a reference mmf value $\Im_R$ to the individual coil one by one. The whole measurement process for obtaining all the coil effects can be completed within a few hours.

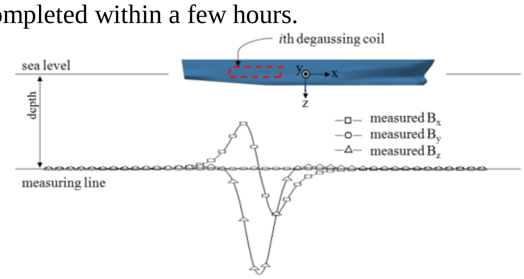


Fig. 1. Measurement of each coil effect

The three components of the measured magnetic field shown in Fig.1 are corresponding to the *i*th degaussing coil effect. After all, the field created by the *i*th coil at a certain mmf value $\Im$ can be given by (1) due to the material linearity.

$$\mathbf{B} = \mathbf{B}_j \frac{\Im}{\Im_R} \quad j = 1, \cdots np \tag{1}$$

where the subscript *j* is the measuring point.

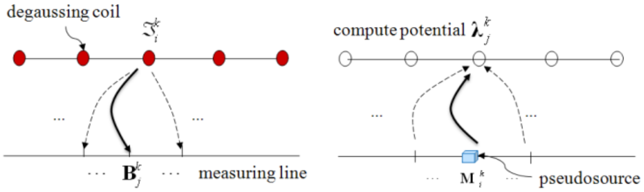
B. Magnetomotive Force Sensitivity Formula

A mmf sensitivity formula of (2), which gives the first-order gradient information of an objective function, is analytically derived by exploiting the governing integral system equation, augmented objective function, and adjoint variable method (AVM) [2].

$$\frac{dF}{d\mathbf{p}} = \int_{\Omega} (\frac{\partial \Im}{\partial \mathbf{p}}) \cdot \boldsymbol{\lambda} \, d\Omega \tag{2}$$

where F is the objective function, $\mathbf{p}$ is the system parameter, Ω is the coil cross-section, and $\boldsymbol{\lambda}$ denotes the Lagrange multiplier interpreted as the adjoint vector potential.

Using the analytical formula (2), the first order gradient information of the objective function F can be easily calculated from the analysis results on the dual solution system consisting of the primary and adjoint systems shown in Fig. 2. While the field distribution along the measuring line in the primary system is estimated from (1), the adjoint potential is calculated by means of a numerical integration of the pseudosources (i.e. virtual magnetizations).

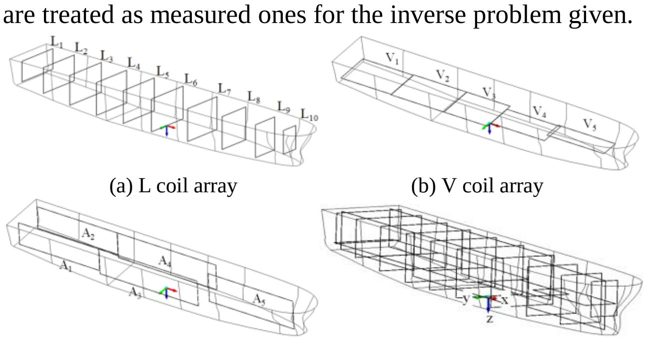


(a) Primary system (b) Adjoint system

Fig. 2. Dual system for current sensitivity analysis at the *k*th design iteration

III. RESULTS

In order to validate the proposed method, a ship with a length of 200 m, width of 30 m and height of 20 m is considered. The ship is equipped with the three kinds of degaussing coils, called L coil, V coil and A coil, as shown in Fig. 3. To unify the coordinate system used, the x axis in Fig. 3(d) heads for the North Magnetic Pole. For easy verification, the coil effects are calculated by using a commercial software packages, MagNet VII, and the results are treated as measured ones for the inverse problem given.



(a) L coil array (b) V coil array

(c) A coil array (b) Degaussing coils

Fig. 3. Schematic of degaussing coils installed inside the hull

The aim of the inverse problem is to optimize degaussing currents for reducing the underwater magnetic perturbation of the ship within an acceptable level. The objective function defined on the measuring line in a depth of 20 m under the keel depicted in Fig. 1 is written as:

$$\begin{aligned} &\text{minimize} \quad F = \sum_{i=1}^{3}\sum_{j=1}^{np} | B_{ij}^{mea} - B_{ij}^{\deg} |^2 \\ &\text{subject to} \quad \text{mmf of each coil} \le 1{,}500 \text{ A} \cdot \text{turn} \end{aligned} \tag{3}$$

where the superscripts, *mea* and *deg*, mean the measured and degaussing fields and the subscripts, *i* and *j*, denote the directional component and magnetic sensor position, respectively. Before optimizing the degaussing currents, the experimental field data of all the coil effects are given. For instance, Fig. 4 shows the coil effects of five V coils when a reference mmf value of 10 A·turn is imposed on each coil.

To simplify numerical implementation of the proposed method, mmf is forced to be a linear function of the system parameter **p** [2]. A general optimizer, DOT, based on the Broydon–Fletcher–Goldfarb–Shanno (BFGS) algorithm in [3] is adopted to accelerate the convergence of the objective function. The optimization procedure for degaussing consists of two stages: V and A coil currents are first optimized when heading the bow west and then L coil currents are adjusted to minimize longitudinal and vertical perturbation fields when heading the bow north. Starting with the coil effect data, the degaussing fields produced by optimal degaussing currents after around 40 iterations are compared to the initial perturbation fields before degaussing in Fig. 5 and Fig. 6 where the opposite degaussing fields are depicted for easy comparison. From the results, it is observed that the perturbation fields after degaussing is smaller by 85 % than the initial field before degaussing.

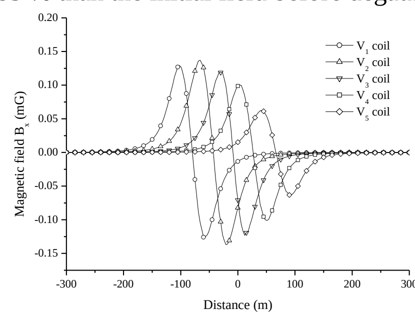


Fig. 4. Comparison of magnet dimensions after optimization

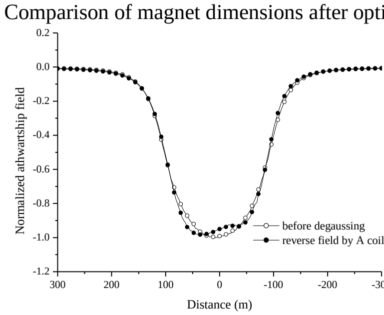


Fig. 5. Comparison of magnet dimensions after optimization

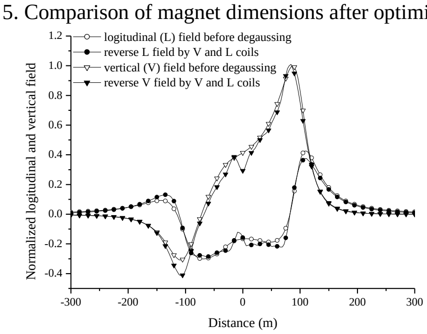


Fig. 6. Comparison of magnet dimensions after optimization

IV. CONCLUSION

The magnetomotive force sensitivity formula in conjunction with the experimental field data has been successfully applied to the degaussing problem of a ship. The results show that the proposed method is very efficient and accurate degaussing technique.

V. REFERENCES

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