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Indirect Fault Detection Method for an Onboard Degaussing Coil System Exploiting Underwater Magnetic Signals

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This paper proposes an indirect fault detection method for an onboard degaussing coil system, installed to reduce the underwater magnetic field from the ferromagnetic hull. The method utilizes underwater field signals measured at specific magnetic treatment facilities instead of using time-consuming numerical field solutions in a three-dimensional space. An equivalent magnetic charge model combined with a material sensitivity formula is adopted to predict fault coil locations. The purpose of the proposed method is to yield reliable data on the location and type of a coil breakdown even without information on individual degaussing coils, such as dimension, location and number of turns. Under several fault conditions, the method is tested with a model ship equipped with 20 degaussing coils.

Keywords : diagnosis, electromagnetics, inverse problem, design sensitivity, magnetic charge

1. Introduction

The earth's magnetic field induces magnetization of the ferromagnetic hull of a ship. The hull itself also possesses permanent magnetization due to mechanical/thermal stress during manufacture and operation. Consequently, the hull generates an underwater magnetic field around the ship even though the magnitude is much smaller than that of the earth's magnetic field. However, the magnetic field anomaly may expose a ship to serious hazards, such as mines or torpedoes equipped with highly sensitive magnetic sensors [1-8]. To ensure the security of modern naval vessels, magnetic treatment consisting of deperming and degaussing techniques have been highlighted in defense-related industries. Generally, the deperming process is first conducted to eliminate permanent magnetization on the hull, then the degaussing process is performed to reduce the underwater field anomaly due to induced magnetization as well as residual permanent magnetization after the deperming process [4]. Finally, the degaussing technique includes a treatment to achieve magnetic silencing of a ship. To date, a number of related studies have been reported and their main focus has been to highly tune individual current values flowing through onboard degaussing coils [7, 8]. Several optimization methods such as evolution strategy, particle swarm and design sensitivity have been successfully applied to degaussing coil systems in order to optimize individual coil currents [2, 3, 5-8].

Meanwhile, from a maintenance point of view, the diagnosis of degaussing coil systems is another important issue in the magnetic treatment of a ship. This is because a breakdown of either one or more degaussing coils causes a large perturbation in underwater magnetic field signals, and could subsequently expose a ship to fatal hazards. However, research on this topic is rare within the electromagnetics community. The authors recently proposed a fault detection method for a degaussing coil system in [7] and [8]. On the assumption that all the information for individual degaussing coils, such as dimension, location and number of turns, were given, underwater field data and a sensitivity formula with respect to the magnetic-motive force can be exploited. The method was verified with various fault conditions of a model ship equipped with 20 degaussing coils. However, the method cannot be applied to special situations where the specifications of the degaussing coil system are unknown.

To tackle the aforementioned problem, this paper proposes an indirect fault detection method for an onboard degaussing coil system with unknown specifications. This

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is achieved by replacing the hull of the ship with an equivalent magnetic charge model in combination with a material sensitivity formula. Utilizing a field difference between normal and abnormal/fault conditions of a degaussing coil system, the method extends a magnetic charge distribution on the hull, and the pattern strongly depends on the location and type of a coil breakdown. As a result, coil breakdowns can be inferred from unique magnetic charge distributions on the hull. The main advantage of the proposed method is the identification of the location and type of a coil breakdown without detailed coil specifications. Under several fault conditions, the method was tested with a model ship equipped with 20 degaussing coils. The results show that the method is very useful for predicting coil breakdowns without prior information on the degaussing coil system.

2. Basic Principle of the Degaussing Technique

In this section, the basic principle of the degaussing technique is briefly explained for a better understanding of the goal of this paper. An illustration is presented in Fig. 1, where the underwater magnetic field is measured at a certain depth under the keel line. Only four of the onboard degaussing coils are depicted with rectangular boxes. As described earlier, induced magnetization on the ferromagnetic hull by the earth's magnetic field causes a perturbation in the underwater magnetic field, which has three magnetic field components in a rectangular coordinate system. To mitigate such perturbation, degaussing coils have to produce a compensation field (called a degaussing field), which correspond to a vector sum of individual coil fields. If the waveforms of degaussing field components are exactly the same as those of the perturbation field components with opposite directions, the perturbation field is perfectly eliminated. This example is an ideal case, where the resultant field (called the degaussed field) is zero as seen in Fig. 1.

In practice, a ship is usually equipped with several tens of degaussing coils to reduce the perturbation field from the hull as much as possible. The coils are classified into three types with a reference direction heading from the stern to the bow: longitudinal coil (L coil), athwartship coil (A coil) and vertical coil (V coil) [7, 8]. As an example, Fig. 2 shows 20 degaussing coils installed in a ship, where the arrows denote positive current directions flowing through the three-type degaussing coils, respectively. Fig. 3 presents z components of individual coil fields at a certain depth under the keel line when a reference current of 1 A is sequentially imposed on V coils. As seen in the figure, the z components of V coils have different maximum values and different spatial field distributions with each other.

The coil currents must therefore be optimized to minimize degaussed field values, which correspond to the sum of degaussing and perturbation fields. The degaussing performance is evaluated by the ratio of a maximum value of the degaussed field components to that of the perturbation field components. In essence, the smaller the magnitude of the degaussed field, the better the degaussing performance. Since a breakdown of even one coil rapidly deteriorates the degaussing performance, an efficient fault detection system is inevitably required to maintain a good degaussing performance.

3. Indirect Fault Detection Method

To predict fault coil locations without information on the degaussing coil system, the proposed method exploits

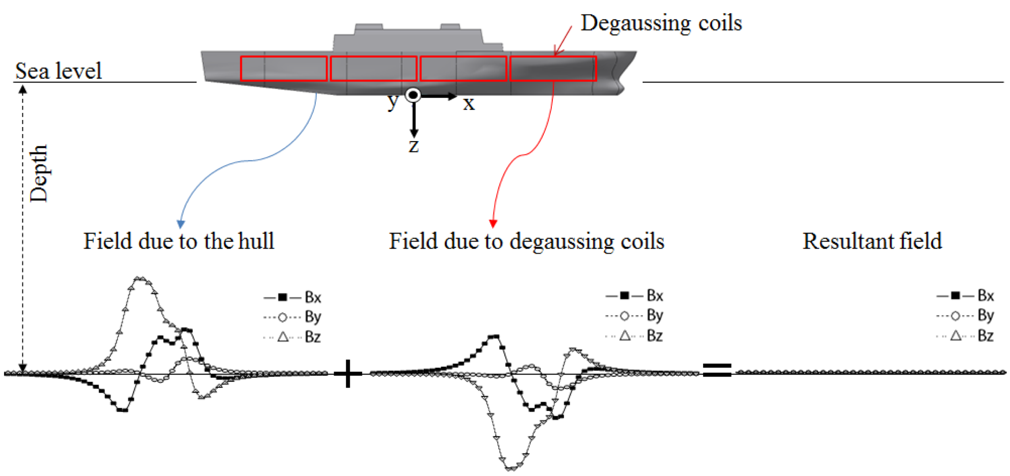

Fig. 1. (Color online) Basic principle of degaussing technique.

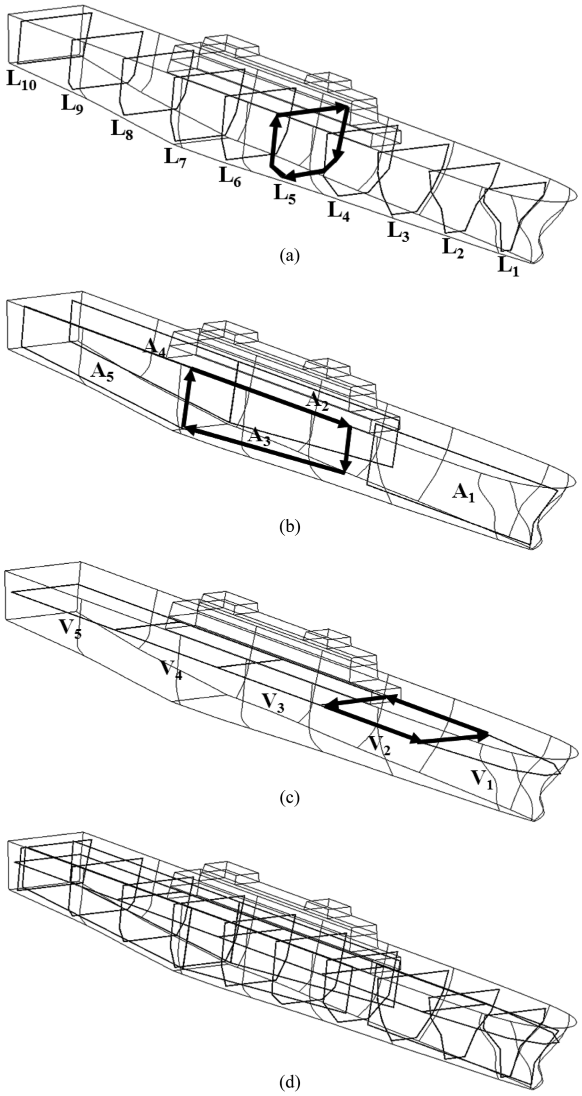

Fig. 2. Schematic of onboard degaussing coils: (a) L coil array, (b) A coil array, (c) V coil array, (d) Assembly coils.

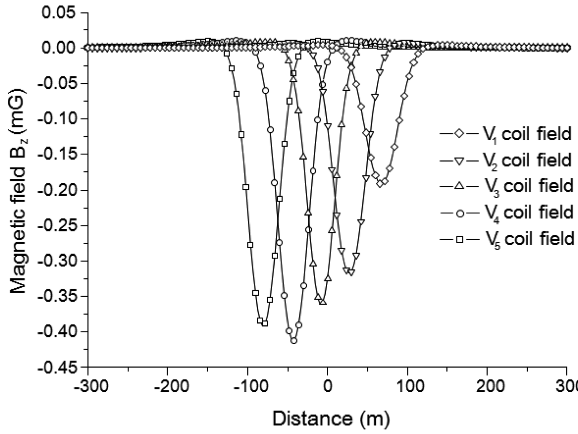

Fig. 3. Z-components of V coil fields at a certain depth from the keel line.

magnetic charge distributions on the hull, which is obtained from the underwater field difference between normal and abnormal degaussing conditions of a ship. For accurate prediction, a three-dimensional (3D) magnetostatic inverse problem consisting of the forward and backward problems has to be solved. To handle the inverse problem effectively, a magnetic charge model is combined with an analytical material sensitivity formula. At the last part of this section, numerical implementation is described in detail.

3.1. Forward Problem Modeling

In order to minimize system unknowns of the forward problem, the equivalent magnetic charge method is adopted to determine the underwater field difference before and after a breakdown of degaussing coils. The hull surface is divided into a number of sheet elements, and the magnetization is assumed to be constant and parallel to the hull because of the relatively high permeability and thinness of the hull. In this case, the magnetic line charge σ_m is determined by (1) at edge lines consisting of a sheet element as seen in Fig. 4.

$$\sigma_m = \mathbf{M}\cdot\mathbf{n} \tag{1}$$

where **M** is the magnetization occurring on the element, and **n** is a unit vector outward normal to each edge line.

The underwater magnetic field caused by the equivalent magnetic charge distribution is then expressed in an integral form as follows:

$$\mathbf{B} = \frac{\mu_0 t}{4\pi} \int_s \sigma_m \frac{\mathrm{r}}{r^3} dl \tag{2}$$

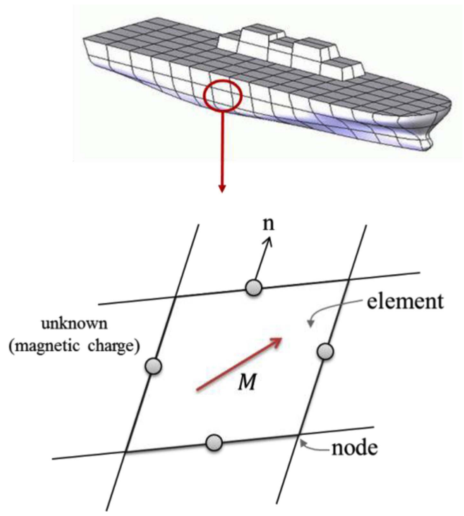

Fig. 4. (Color online) A magnetic charge model equivalent to the hull's magnetization.

where μ_o is the permeability of free space, t is the thickness of the hull, l is the length of the element line edges, S is the hull surface, and $\mathbf{r}$ represents the displacement vector from the magnetic charge to a measurement point [3, 5, 6].

3.2. Backward Problem Modeling

Exploiting the adjoint variable method and the augmented objective function, a material sensitivity formula with respect to the magnetic charge can be analytically derived [5-10]. Let's consider an objective function F, which occurs when dealing with magnetostatic inverse systems,

$$F = \int_{\Omega} g(\mathrm{B}(\sigma_m(p)))d\Omega \tag{3}$$

where g is a scalar function differentiable with respect to the magnetic field **B**, which is itself an implicit function of the magnetic charge σ_m and its parameter p. Ω is the analysis domain of interest. To obtain an analytical sensitivity formula of (3), relatively complicated mathematical expansions are needed. However, they comply with a fairly routine procedure as presented in [5-8], where analytical material sensitivity formulas for magnetostatic inverse problems have been developed. Such analytical sensitivity formulas facilitate computing the first-order gradient information of an objective function.

In this study, a final mathematical expression of the material sensitivity formula of (4) is briefly explained.

$$\frac{dF}{dp} = \int_S \left(-\frac{\partial \sigma_m(p)}{\partial p}\right)\lambda\, dS \tag{4}$$

where λ is the adjoint variable interpreted as a solution of the adjoint system, which is the counterpart of a primary system [6]. The magnetic charge is usually defined as either a low-order polynomial or an exponential function of p [11, 12]. For simplification of its numerical implementation, the magnetic charge function $\sigma_m(p)$ is forced to be a linear function of p. After all, the material sensitivity is easily calculated from (4) after a dual system consisting of the primary and its adjoint systems is solved.

3.3. Numerical Implementation

To identify the location of a breakdown in a degaussing coil system, an objective function is defined on the measurement line depicted in Fig. 5 as follows:

$$\text{minimize F} = \sum_{i=1}^{3}\sum_{j=1}^{np}\left((B_{ij}^{nor} - B_{ij}^{abnor}) - \sum_{k=1}^{nl} B_{ij}^{k}\right)^2 \tag{5}$$

where B_{ij}^{nor} is the degaussed field under a normal degaussing condition, B_{ij}^{abnor} is the anomaly in the underwater field due to a breakdown of either one or more degaussing coils, B_{ij}^{k} is the underwater field generated by a magnetic charge distribution on the hull, and the symbols, i, np and nl, denote the directional component, total measurement points, and total edge lines of sheet elements forming a hull surface, respectively. As seen in Fig. 5, a coil breakdown causes a sudden change in the normal degaussed field. The field difference between B_{ij}^{nor} and B_{ij}^{abnor} directly corresponds to the compensation field, which should be produced by the lth fault coil before its breakdown. A solution of (5) results in finding a magnetic charge distribution, which realizes the compensation field components of fault coils before their breakdown.

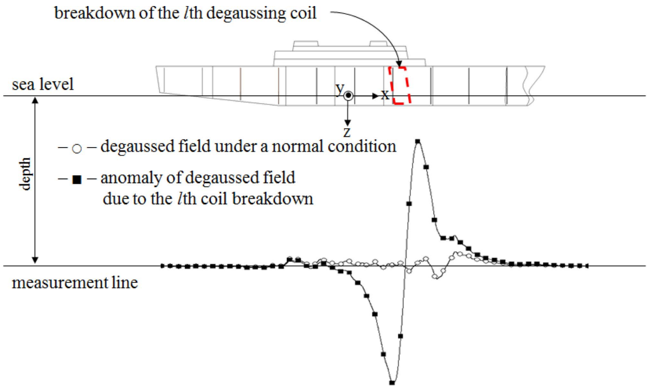

Fig. 5. (Color online) Comparison of underwater fields between normal and abnormal degaussing conditions when a breakdown of the lth degaussing coil occurs.

A general-purpose optimizer, called DOT based on the Broydon–Fletcher–Goldfarb–Shanno (BFGS) algorithm in [13], is adopted to accelerate the convergence of the objective function. The optimum magnetic charge values are sought at the middle points of edge lines consisting of sheet elements (refer to Fig. 4) and their initial values are set to zero. The iterative process of Fig. 6 to solve the inverse problem of (5) involves the following steps:

1) Divide the hull into a number of sheet elements and define unknowns as magnetic line charges,

2) Compute field components due to magnetic charges with (2) at measurement points,

3) Assess the objective function and then solve the adjoint system.

4) Compute sensitivity values at the edge lines of sheet elements with (4),

5) If the convergence of (5) is satisfied, stop. Otherwise, go to step 6,

6) Update a magnetic charge, σ_m ($\sigma_{mj}^{k+1} = \sigma_{mj}^{k} + \alpha\Delta p$), at the kth iteration with DOT, where j is the edge number and α is a relaxation factor. Go to step 2.

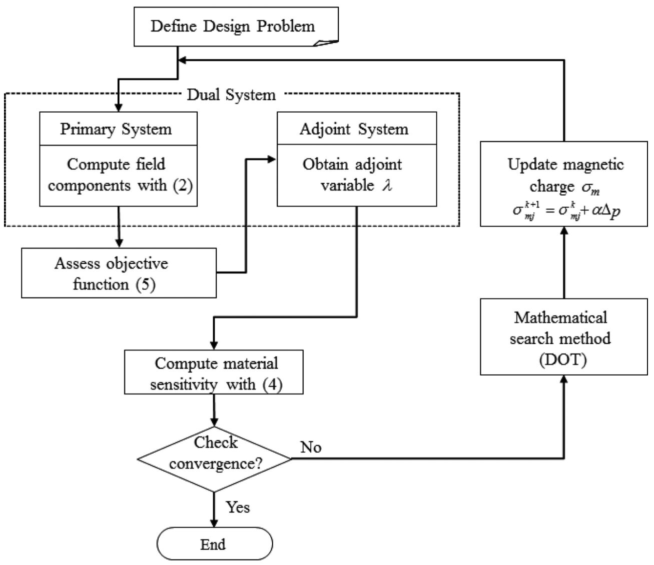

Fig. 6. Program architecture for solving a 3D magnetostatic inverse problem.

4. Case Studies

The model ship used for this exercise has a length of 200 m, width of 30 m and height of 20 m, and is equipped with 20 degaussing coils shown in Fig. 2. To unify the coordinate system, the x axis in Fig. 1 is set to the North Magnetic Pole. For an easy way to validate the propose method, the finite element analysis (FEA) solutions at a depth of 30 m are treated as measured field data. FEA was performed with a commercialized electromagnetic analysis code, MagNet VII [14], where the ship was divided into more than 5 million tetrahedral elements. The relative permeability of the hull was 320. Three fault scenarios for individual degaussing coil types are assumed as shown in Table 1. These scenarios are tested with the model ship.

The field differences obtained before and after a breakdown of degaussing coils in the specified fault cases are shown in Fig. 7. It is observed that the fault cases have different field waveforms with each other. As explained previously, such field differences are the compensation fields produced by fault coils before their breakdown. In other words, they correspond to the remaining perturbation fields from the ferromagnetic hull, which are not compensated because of a coil breakdown.

In Fig. 8, the hull was divided into 994 sheet elements consisting of 2,047 edge lines, where optimized magnetic

Table 1. Three fault scenarios for a three-type degaussing coil system.

Failure case	Fault coil number (Fig. 2)
Case I	L_6
Case II	A_3
Case III	V_2 and V_3

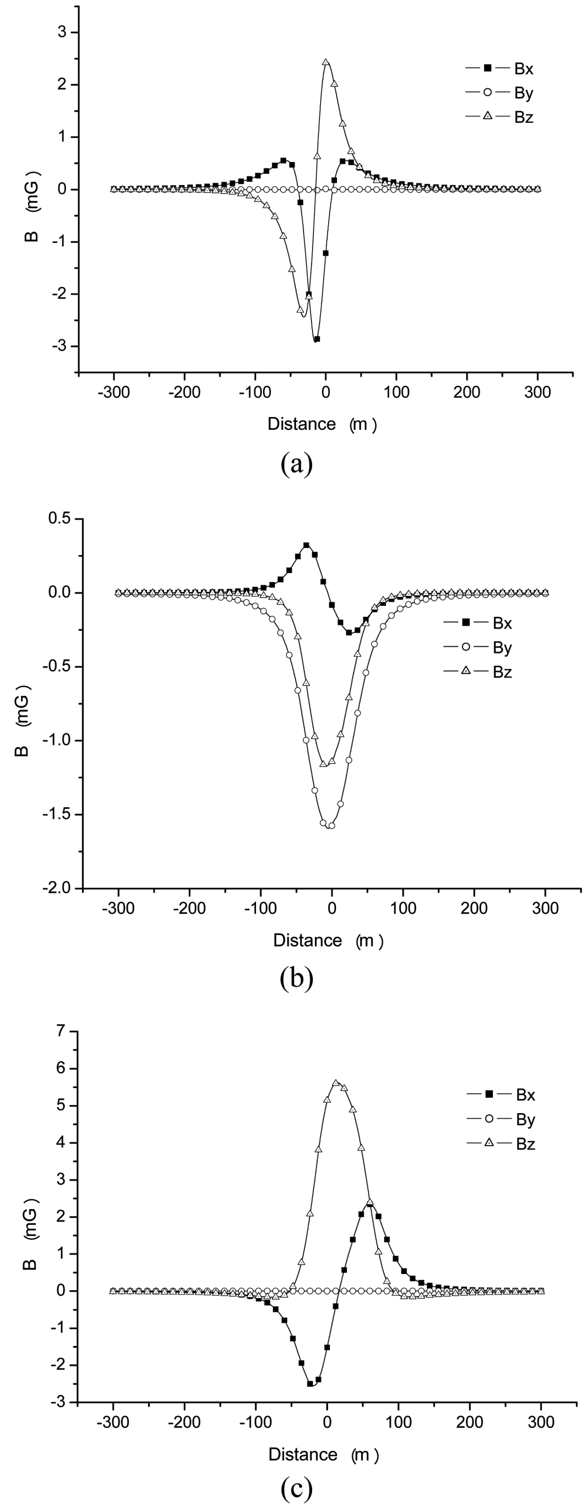

Fig. 7. The field differences for three fault scenarios: (a) Case I, (b) Case II, (c) Case III.

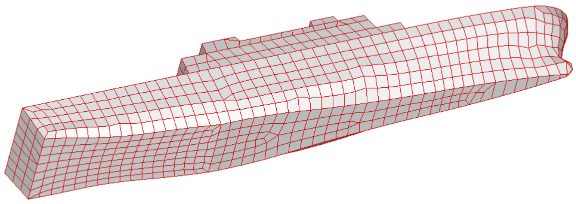

Fig. 8. (Color online) Sheet elements forming the hull surface.

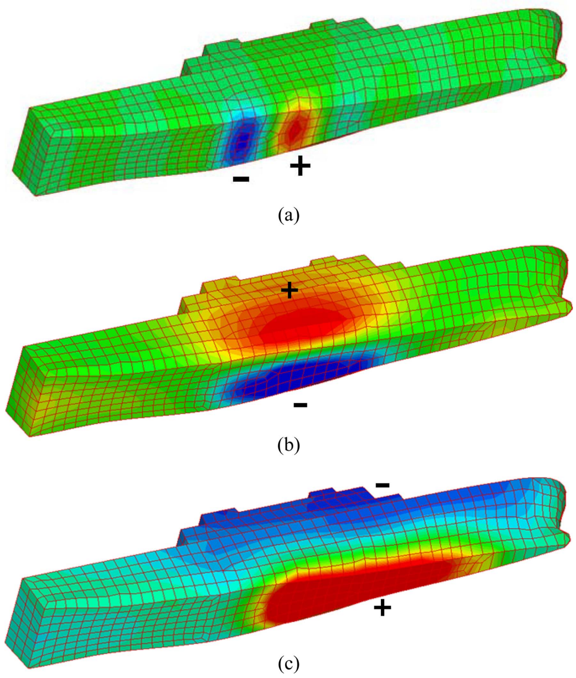

Fig. 9. (Color online) Magnetic charge distributions for three fault scenarios: (a) Case I, (b) Case II, (c) Case III.

charge values were sought to satisfy the objective function of (5). On the assumption that the specifications of the degaussing coil system were unknown, magnetic charge distributions on the hull surface were computed from only the field difference data presented in Fig. 7. The contours of magnetic charges at the three fault cases are compared in Fig. 9, where plus and minus signs denote positive and negative charge values, respectively. As seen in the figure, it is obvious that the magnetic charge has a unique distribution strongly depending on the fault coil types. That is, each breakdown of L, A and V coils results in magnetic charges distributed along a specific portion of the hull surface (i.e. the bottom, side and top-bottom of the ship). The locations of coil breakdowns can easily be predicted from such charge distributions. For instance, Fig. 9(a) implies that a L_6 breakdown of ten L coils in Fig. 2(a) exists between the positive and negative magnetic charges on the bottom of the ship, and Fig. 9(c) shows that the relatively wide charge distributions on both the top and bottom of the ship correspond to two broken V_2 and V_3 coil areas in Fig. 2(c).

5. Conclusion

In this paper, an indirect fault detection method for onboard degaussing coils in a ship is proposed and tested with a model ship equipped with 20 degaussing coils. The method exploits only the difference field measured at magnetic treatment facilities before and after a breakdown of the coils. The results of three fault scenarios show that the proposed method can predicts a fault coil location as well as a fault coil type from unique magnetic charge distributions without information on the degaussing coil system.

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