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Efficiency of Exponential Deperm Protocol

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Magnetic treatment of surface vessels and submarines (Deperm) is required to camouflage them against magnetic detection from enemy marine force. So far, deperm has been accomplished by applying an alternating magnetic field of which amplitude decreases linearly. However, the reduction of the residual flux density in the direction of magnetic field is not linear in the case of the linear protocol, since the ferromagnetic material used to construct a surface vessel, mainly Fe-C, shows a nonlinear behavior in an alternating magnetic field. This is one of main reasons to make an ordinary deperm protocol inefficient. In this paper, we propose the exponential deperming protocol and compare the exponential protocol to conventional linear protocol within the framework of deperm performance. We found out that step number could be reduced in the exponential protocol compare with in the linear protocol, because the larger numbers of deperm steps are dedicated in the irreversible domain process region on the magnetic hysteresis.

Keywords : deperm, submarine, exponential protocol, efficiency

1. Introduction

Magnetic treatment of surface vessels and submarines is required to camouflage them against magnetic detection from enemy marine force. If it is not sufficient to be demagnetized, a surface vessel or a submarine become defenseless state against a magnetic mines which works by measuring small deviations in the Earth's magnetic field caused by large ferromagnetic bodies [1]. There are two ways to magnetically camouflage surface vessel and submarine, deperming and degaussing [2]. Among them, So far, deperming has been accomplished by applying an alternating magnetic field of which amplitude decreases linearly in ordinary case [3]. However, it should be considered that reduction of the residual magnetization vector in the direction of applied magnetic field is not linear even if the applied alternating magnetic field is linear, since the ferromagnetic material used to construct a surface vessel, mainly Fe-C, shows a nonlinear behavior including hysteresis in nature. This is one of main reasons to make an ordinary deperm protocol inefficient (time-consuming and energy consuming). This aspect can become severe when the process object has large size. For example, ordinary aircraft carriers are a few hundred meters in the length, and one needs to spend more than a few days and a few MW for deperming them. There were a few challenges to implement deperming efficiency. Baynes *et al.* investigated to ascertain whether the anhysteretic deperming is practical and whether there is any advantage in using it. They compared the outcomes of a number and variety of anhysteretic deperms with results from the standard deperm method on the same ferromagnetic specimen (steel tube with 300 mm long, 29.6 mm in the inside diameter and 32 mm in the outside diameter) [4]. However, there is some doubt about the anhysteretic deperming, proposed by Dr. Baynes, when the object has a large complicated structure and large demagnetization factor in part, like a practical surface vessel and submarine. Realistically, it is hard to apply a sufficiently large magnetic field as the bias field in the anhysteretic deperming, because practical surface vessel and submarine are so complicated and large.

In this paper, we propose an energy base deperm protocol which was calculated by an hysteresis model, and present how to optimize the deperm protocol with the minor loops of magnetic hysteresis. We found out through

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finite element method (FEM) simulation that step number could be reduced in the energy base deperm protocol compare with in the linear protocol, because the larger numbers of deperm steps are dedicated in the irreversible domain process region on the magnetic hysteresis.

2. Proposal of Exponential Protocol

Fig. 1(a) shows the schematic views of side plain and ground plain of the submarine model which was simulated in this study. Thickness and relative permeability of the model were set to 5 cm and 150 respectively, over all. Fig. 1(b) represents coil-configuration which is used in this simulation. There are two kinds of coil; first one is depermaing-coil on which alternating current is passing though during deperming process, and second is a set of 12 coils (magnetizing-coils) for magnetizing the submarine partly before deperming process.

The submarine was magnetized complexly at the 1st step of FEM analysis and demagnetized gradually during deperming. Series of deperming simulations were achieved

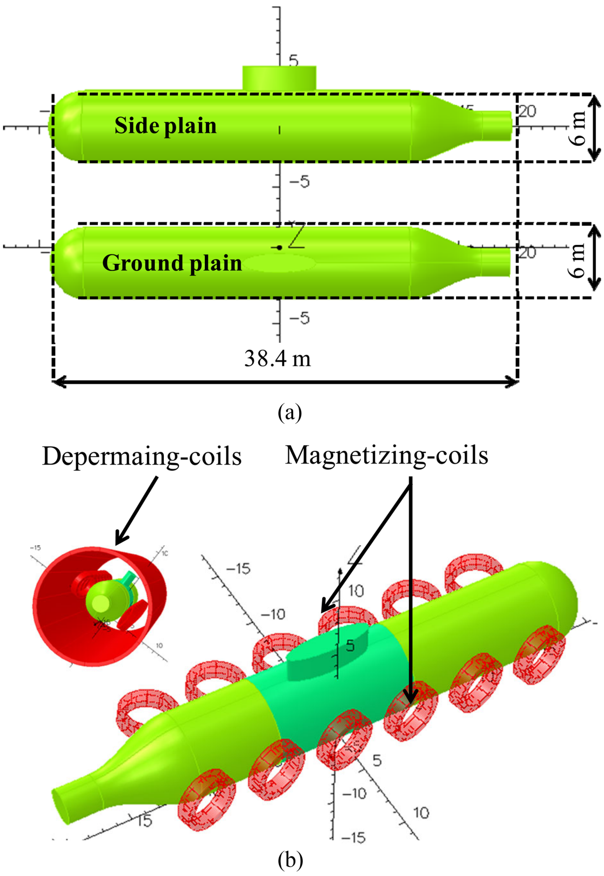

Fig. 1. (Color online) Schematic view of submarine model analyzed in this study (a), and arrangement deperming-coil and magnetizing-coils (b).

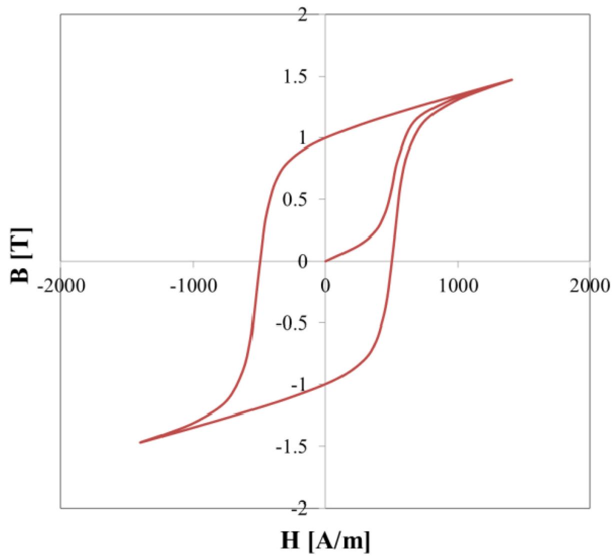

Fig. 2. (Color online) Hysteresis model used for FEM simulation. Coercive force H_c is 500 A/m.

by using commercial FEM tool, OPERA 3D with Demag solver [5]. To express the nonlinear property of the structure material of the surface vessel, we used the hysteresis loop shown in Fig. 1 in FEM simulation. Once we input a major hysteresis loop like Fig. 2 in the preprocessing step of OPERA, the Demag solver calculates automatically the minor loops which are needed to simulate the magnetization state of the object. The coercive force was regarded as 500 A/m in the hysteresis model.

Fig. 3 represents a comparison of linear (a) and exponential (b) protocol. In the linear protocol, there is no change in the step-decline which is defined as ΔH per half period of applied magnetic field over the whole range. In this case, ΔH is varied from 2 to 12%. Meanwhile, the applied magnetic field is changed exponentially according to the function shown in Eq. (1) in the exponential protocol.

$$H_n = H_0 e^{-\frac{n}{\alpha}}, \quad n = 0, 1, 2, 3... \tag{1}$$

$$\Delta H = H_n - H_{n-1} \tag{2}$$

Where, H_0, n, and α are magnetic field intensity of 1st shot, step number (0~n) and adjustment factor, respectively. α was adjusted to make the step number the same between the linear protocol and the exponential protocol. Refer, for example, the step number of 2%-pattern in the exponential protocol is the same with that of the linear protocol. Table 1 shows α values correspondent to step numbers and/or step decline.

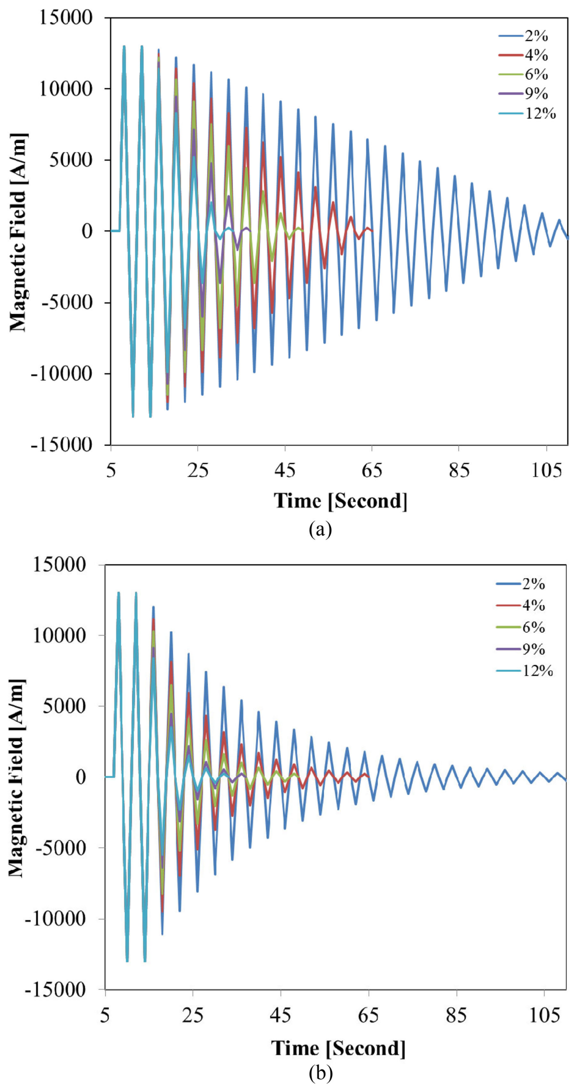

Fig. 3. (Color online) Comparison of protocols for deporming process. Alternating magnetic field damped linearly (a) or exponentially (b) was applied in FEM simulation. Step-decline ΔH per half period of applied magnetic field was 2, 4, 6, 9 and 12%.

Table 1. Summary of step declines, step numbers and α value.

Step decline	2%	4%	6%	9%	12%
Step numbers	24	12	9	6	5
α value	7.2	3.5	2.5	1.6	1.3

3. Results and Discussions

Fig. 4 shows simulated magnetic field distributions generated from the submarine, which were measured at 10 m under the center of the submarine, as one of simulation results, after deperming process with 6% step-decline. In this figure, magnetic field strength represents the deperming efficiency, so, the lower of magnetic field the more efficiency; so long as it's process condition is the same with each other. The maximum magnetic fields in the longitudinal direction were 6.93 A/m for linear protocol and 0.88 A/m for exponential protocol in the case of 6% protocol. The maximum magnetic fields in the perpendicular direction were 16.8 A/m for linear protocol and 2.14 A/m for exponential protocol. In this case, the exponential protocol is about 8 times effective then the linear protocol, even if the process time is the same with each other. If the process time is the same, it is easy to understand the electrical power spent on the exponential protocol is much less than that on the linear protocol; see Fig. 3 and electrical power supplied to electrical cable is proportional to magnetic field in deperming process.

Fig. 5 is for summarizing the results obtained with the linear protocol. Fig. 5(a) shows the magnetic field generated by in the longitudinal derection, while Fig. 5(b) represents the magnetic field generated in the perpendicular direction. The magnetic fields were measured on 10 m below the center of the submarine. There are 5 lines in Fig. 5(a) and (b), for 2%, 4%, 6%, 9% and 12% decline-step. These two figures represents clearly the smaller decline-step is more efficient. However, it should be mentioned that the smaller step requires more time and energy consuming in real deperming process. The maximum magnetic fields in the perpendicular direction are about 3 times larger than that in the longitudinal direction. The reason why the residual magnetization in the perpendicular direction is larger is probably that alternating magnetic field for deperming is only in the longitudinal direction.

Fig. 6 shows the results obtained with the exponential protocol. Fig. 6(a) is for the magnetic field generated by in the longitudinal derection, while Fig. 6(b) represents the magnetic field generated in the perpendicular direction. There are 5 lines in the figures, for 2%, 4%, 6%, 9% and 12% decline-step like Fig. 5.

There are big differences in magnetic field strength after deperming between the linear and the exponential protocols. For examples, the maximum magnetic fields of 12% decline-step after deperming by the linear protocol were 22 A/m in the longitudinal direction and 58 A/m in the perpendicular direction, while 3 A/m in the longitudinal direction and 7.2 A/m in the perpendicular direction after deperming by the exponential protocol. It means the exponential protocol was over 3 times more effective than the linear protocol, although processing time was the same to each other. It should be also emphasized that the exponential protocol is more advantageous than the linear protocol in the viewpoint of electrical power consump-

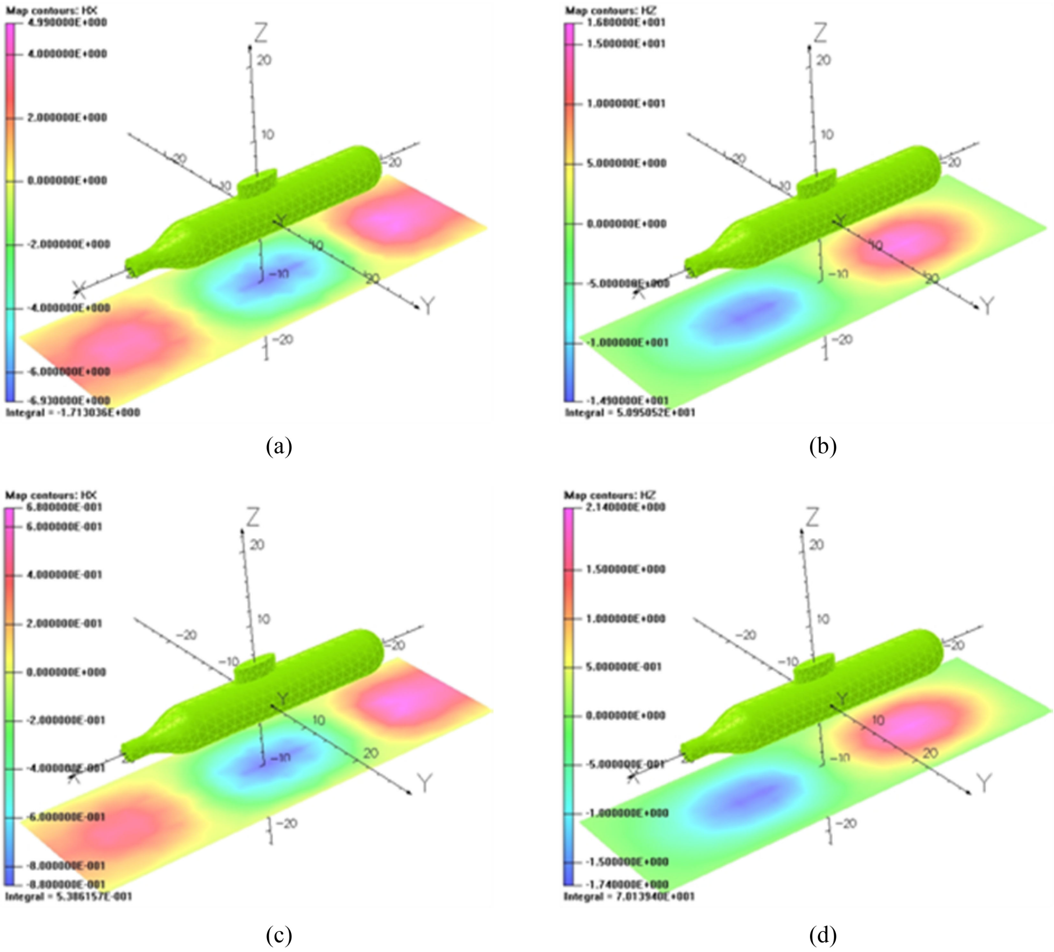

Fig. 4. (Color online) Simulated magnetic field from the submarine. (a) 6% linear protocol, longitudinal magnetic field, (b) 6% linear protocol, perpendicular magnetic field, (c) 6% exponential protocol, longitudinal magnetic field and (d) 6% exponential protocol, perpendicular magnetic field.

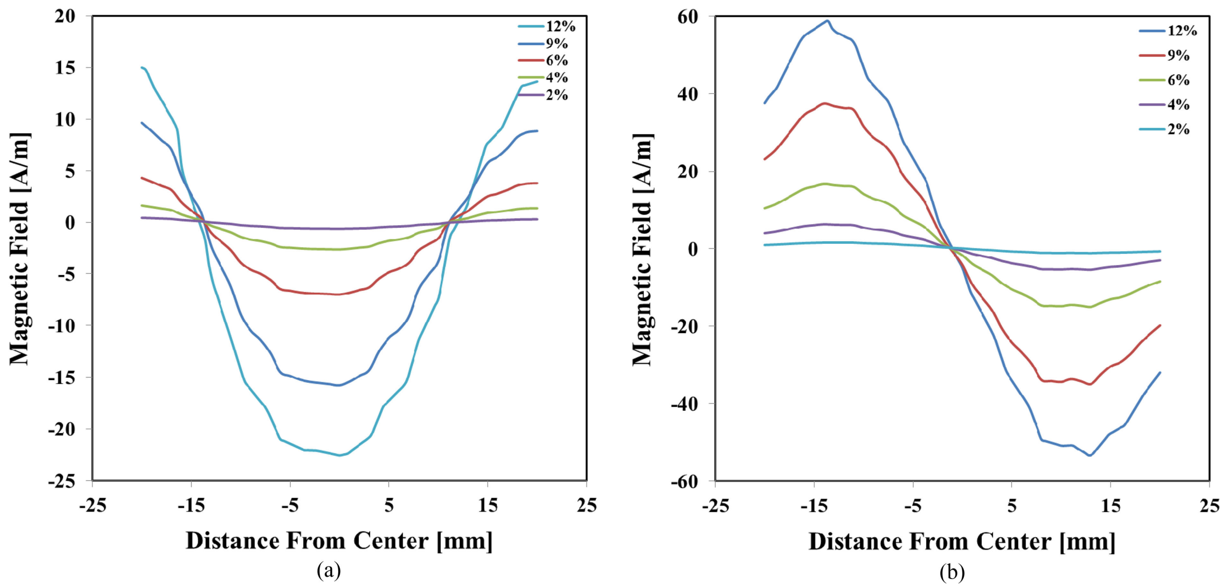

Fig. 5. (Color online) Magnetic field dependent on distance from the center in the longitudinal direction (a) and in the perpendicular direction (b), when the submarine was treated by linear protocol (see Fig. 3(a)).

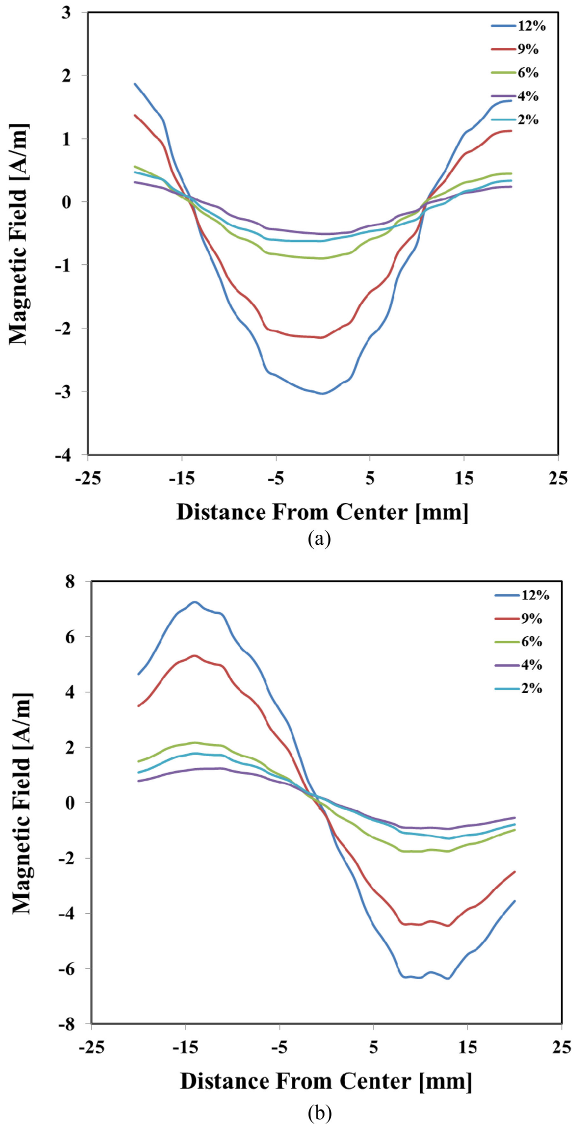

Fig. 6. (Color online) Magnetic field dependent on distance from the center in the longitudinal direction (a) and in the perpendicular direction (b), when the submarine was treated by exponential protocol (see Fig. 3(b)).

tion, because the integration of magnetic field, which is proportional to current, of the exponential protocol is smaller than that of the linear protocol.

Why the exponential protocol is the better could be explained with the hysteresis loop shown in Fig. 2. Basic magnetics says that magnetization is caused by both magnetic domain wall movement and rotation of magnetic moment. And, magnetic domain wall movement is irreversible, while rotation of magnetic moment is reversible. It has to be remembered that deperming is the result of magnetic domain wall movement to form random domain structure. Therefore, more time, more steps and more energy should be spent on irreversible region rather than in reversible region. In the exponential procotocol, more steps are spent in irreversible region (~500 A/m).

3. Conclusion

We compared efficiencies of the conventional linear protocol and the exponential protocol proposed in this study on the supposing that all other parameters, such as coils configuration, maximum current, magnetic property of the submarine, are fixed. A deperming procedure has to deliver an adequately low residual magnetic field under the submarine. From the simulation results, we can say the smaller decline-step is more efficient in deperming performance, but in disadvantageous in time and energy consuming. If the processing time is the same to each other, the exponential protocol is more efficient than the linear protocol, because more steps are spent in irreversible region of magnetization.

Acknowledgement

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