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Simulating the ship's deperming process using the Jiles-Atherton model

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Abstract

Demagnetization of ferromagnetic vessels, or deperming, is a common practice used to reduce the magnetic signature and improve the degaussing operation. To deperm a ship in the longitudinal direction, the Royal Canadian Navy uses the magnetic treatment facility in Norfolk, VA. The procedure consists of passing large electric currents through a set of longitudinal coils temporarily rigged over the exterior of the hull. Signature measurements are taken at each point during the treatment and are used to determine the required current setting and to confirm the success of the procedure.

The general approach for ship deperming presented in the literature is the anhysteretic protocol where the applied field is reduced at equidistant intervals. In reality the method involves the complications of having a bias (Earth's magnetic) field present, and of the practical impossibility of magnetizing the ship to saturation.

At present, past experience is used to empirically estimate the necessary treatment schedule for each vessel. Despite the success of this procedure, a program of work was set up to examine this process on a fundamental basis and hopefully gain some insight into its physics with the aim of developing a predictable deperming procedure. This report outlines the steps undertaken in this direction: (1) the signature of the ship was modelled so that the principal magnetic moments at each point of the demagnetization could be calculated, (2) with these values, the ship magnetization parameters were estimated by inverting the Jiles-Atherton model, (3) using the Jiles-Atherton analysis of hysteresis, a mathematical description of bulk magnetic changes that occur within the ship during deperming has been developed, and (4) based on this analysis, we propose to predict the results of the demagnetization *a priori*. The model simulation study of the demagnetization process is demonstrated with the measurements from HMCS Toronto.

Significance to defence and security

This work analyzes ship deperming from the physical point of view with the aim of developing a predictable deperming procedure. The importance of the work is twofold: (1) to reduce the time required for ship deperming with a guaranteed success of the operation, and (2) to develop a deperming procedure adapted for a future Canadian magnetic treatment facility.

Résumé

La démagnétisation permanente de vaisseaux ferromagnétiques est une pratique courante utilisée pour réduire la signature magnétique et améliorer toute l'opération de démagnétisation. Pour procéder à la démagnétisation permanente d'un navire dans le sens longitudinal, la Marine royale canadienne utilise l'installation de traitement magnétique de Norfolk, VA. La procédure consiste à faire passer des courants électriques importants au travers d'un ensemble de bobines longitudinales fixées temporairement à l'extérieur de la coque. Des mesures de signature sont faites à chaque point pendant le traitement et sont utilisées pour déterminer le réglage de courant requis et confirmer le succès de la procédure.

L'approche générale pour la démagnétisation permanente d'un navire présentée dans les publications sur le sujet est le protocole anhystéritique, dans le cadre duquel le champ appliqué est réduit à intervalles équidistants. En réalité, cette méthode entraîne les complications d'avoir la présence d'un champ biaisé (le champ magnétique de la Terre) et l'impossibilité pratique de magnétiser le navire jusqu'à saturation.

À l'heure actuelle, l'expérience antérieure est utilisée pour estimer empiriquement le calendrier de traitement nécessaire pour chaque navire. Même si cette procédure fonctionne bien, un programme de travaux a été mis sur pied pour permettre l'examen de ce procédé sur une base fondamentale, dans l'espoir d'obtenir certains renseignements sur sa physique afin de développer une procédure de démagnétisation permanente prévisible. Dans le présent rapport, nous soulignons les étapes entreprises à cette fin: (1) la signature du navire a été modélisée de manière à ce que les moments magnétiques principaux en chaque point de la démagnétisation puissent être calculés; (2) avec ces valeurs, les paramètres de démagnétisation du navire ont été estimés grâce à l'inversion du modèle Jiles-Atherton; (3) au moyen de l'analyse Jiles-Atherton de l'hystérésis, nous avons développé une description mathématique des modifications magnétiques générales qui ont lieu dans le navire pendant la démagnétisation permanente; (4) à partir de cette analyse, nous proposons de prédire les résultats de la démagnétisation a priori. L'étude de simulation du modèle de démagnétisation a été corroborée au moyen de mesures faites sur le NCSM Toronto.

Importance pour la défense et la sécurité

Les travaux couverts par le présent rapport ont consisté à analyser la démagnétisation permanente d'un navire d'un point de vue physique, dans le but de développer une procédure de démagnétisation permanente prévisible. Ces travaux sont importants à deux points de vue : (1) réduire le temps requis pour la démagnétisation permanente d'un navire avec une garantie du succès de l'opération; (2) développer une procédure de démagnétisation permanente adaptée à une future installation canadienne de traitement magnétique.

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Acknowledgements

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1 Introduction

Ships, being constructed largely of ferromagnetic materials, develop permanent magnetic fields due to long term exposure to the Earth's magnetic field, and mechanical stress. Permanent magnetism is caused by the structure of the ship, the fabrication method used and the equipment installed. We note that the word "permanent" is actually somewhat misleading since the amount of this magnetization does tend to change over a period of several years due to the effects of mechanical stress and thermal cycling in conjunction with the applied field.

The ship's magnetization has to be reduced to a certain level to protect the vessels against the multi-influence sea-mines. Techniques exist to reduce the permanent magnetism of ships through a demagnetization procedure, also called magnetic treatment. After being successfully demagnetized, the ship-induced magnetization can be better compensated by the ship's degaussing (DG) coils with less power required.

The ship also develops an induced magnetic field due to the magnetization of the ship's steel parts under the influence of the ambient geomagnetic field. Usually, the ship magnetization is decomposed into components defined in a Cartesian coordinate system related to the ship: X-axis corresponding to the longitudinal (L) direction with positive axis toward the bow, Y-axis is the athwartship (A) direction toward starboard, and Z-axis is perpendicular to both X and Y (V). The abbreviations used are PLM, PAM, PVM, ILM, IAM, IVM, where, for example, IAM stands for the induced athwartship magnetization, PAM stands for the permanent athwartship magnetization, and so on.

"Magnetic treatment" is the general terminology, while "deperming" refers to the minimization of the permanent magnetisation in two directions: longitudinal and/or athwartship. Since the vessels are not subjected to the athwartship magnetic treatment, the term "longitudinal deperming" is frequently shortened to "deperming." From the practical point of view, a deperming operation is required when the PLM reaches a value close to the ILM of the ship.

The magnetic treatment that neutralizes the PVM is called vertical wiping or flashing, depending on the arrangement of coils around the ship. The vertical magnetic treatment has been developed mainly for the purpose of providing compensation for the vertical magnetism of those ships which have insufficient power to energize the M-coils. Contrary to deperming, the vertical magnetic treatment induces a permanent magnetism in the ship in a direction opposing the vertical Earth's magnetic field for a specific operation zone. A variety of vertical flushing, called "run-over", has the demagnetizing coils permanently installed on the seabed. The vessel is magnetically treated during its transit over the coils. The system is costly and susceptible to damage from dredging or anchorage. This type of magnetic treatment is not included in this report.

The deperming process requires the presence of a demagnetizing field. Depending on how this field is created, there are two main deperming methods:

1. One method of deperming is passing large currents through a set of longitudinal coils temporarily rigged over the exterior of the hull when the ship is docked. Usually, a fixed or floating Z-coil is also provided. This method is called "close-wrap" and it is, due to the preparation, time consuming, labour intensive and expensive.

2. A similar method, called “drive-in”, has the longitudinal (and vertical) coils permanently installed with the vessel entering and exiting the facility. The construction resembles an Earth’s Field Simulator but the created magnetic field is much bigger than the Earth’s field. Building such system is expensive, so the geometrical dimensions and the power supply capability are limited to small submarines and mine hunting vessels.

In addition to the demagnetizing coils described above, a deperming facility has an array of 3-axis magnetometers installed on the seabed that measure and monitor the signature of the vessel being treated. Signature measurements are taken at various points in the treatment process and are used to determine the required treatment setting and to confirm the success of the procedure. Also the vessel is tracked by a high accuracy GPS system to enable the modelling and the analysis of the signature. The positioning system consists of two differential GPS’s mounted at the bow and the stern of the vessel, and a base station.

For deperming their vessels, the Royal Canadian Navy (RCN) uses the magnetic treatment facility (MTF) in Norfolk, VA, and this report concerns only the deperming process supervised by the Canadian officers at this facility. Despite the proven capability of this MTF, the Canadian approach to the deperming procedure had been empirically formulated over the years with little knowledge of the underlying physics behind the procedure. In practice, the deperming process is monitored visually using a limited number of sensors placed approximately under the keel line. As the result, there is little confidence at the start of each process that the final permanent magnetic signature of the vessel would match the desired values to any degree of accuracy. Past experience was used to estimate the necessary treatment schedule for each vessel especially after it was discovered that the ships of the same class have a different magnetic behavior. Despite the obvious success of the empirical deperming procedure, a program of work was set up to look at this process on a fundamental basis and hopefully gain some insight into its physics with the ultimate aim of developing a more reliable, predictable deperming procedure. Given that deperming ships is costly and time consuming, any improvement in the speed and, perhaps, quality of the procedure would be welcome.

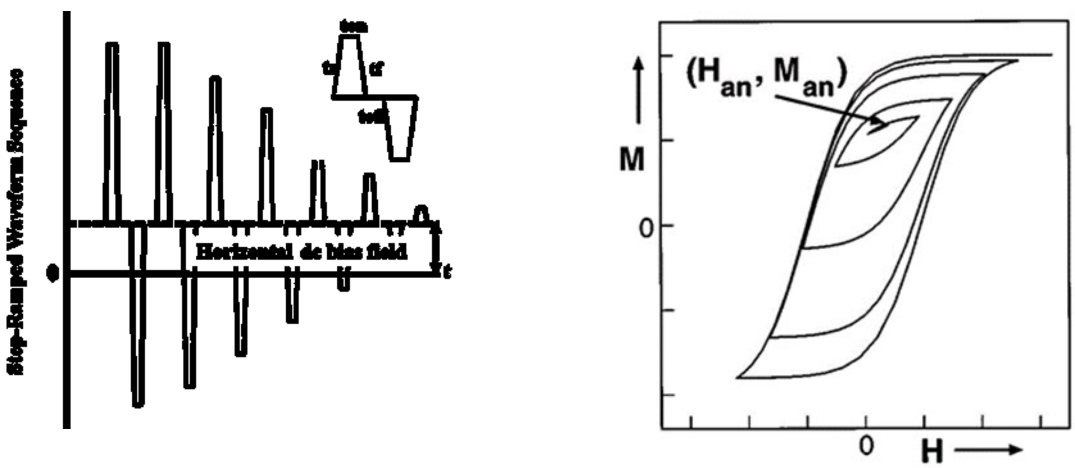
Efficient deperming procedure design requires the use of computer simulation and this in turn depends on a better understanding of the underlying physics and material properties. This report describes the ship deperming process using the well-known Jiles-Atherton hysteresis model that eventually could predict the final magnetization of the ship. This represents a novel approach to the ship deperming operation allowing the process to be automated. The Jiles-Atherton model is chosen because of its flexibility in incorporating the effects of operating conditions on the deperming process. The computed results are compared with measurements.

The steps undertaken in this direction, and detailed in this report, were: (1) the signature of the ship was modelled on a large surface so that the principal magnetic moments of the ship at each point of the demagnetization could be calculated, (2) with these values, the ship magnetization parameters were estimated by inverting the Jiles-Atherton model, (3) using the Jiles-Atherton analysis of hysteresis, a mathematical description of bulk magnetic changes that occur within a ship during deperming has been developed, and (4) based on this analysis we propose to predict the results of an anhysteretic demagnetization *a priori*. The analysis of the demagnetization process is demonstrated with the measurements obtained from the RCN’s Her Majesty’s Canadian Ship (HMCS) Toronto.

2 Theory of ship deperming

Technically, the ship deperming process has been treated in the literature as a stepwise anhysteretic magnetisation [1, 2]. Anhysteretic magnetisation is that which results when a constant static (H_{DC}) field and an alternating field (H_{AF}) of gradually decreasing amplitude with a constant decrement (ΔH_{AF}/cycle) are applied simultaneously to a ferromagnetic sample (Figure 1.a). After the alternating field strength is slowly reduced to zero, the resultant magnetisation is a single valued function of the static field. If the static field is zero then the result is a demagnetized sample.

The anhysteretic magnetisation process is shown in the plot of the magnetization M as a function of the applied field H (Figure 1.b). If the extremes of the field in the first period are large enough to bring the system to saturation, the magnetization switches between the saturation values, M_{sat} and $-M_{sat}$, moving on the major hysteresis loop. The result is that the magnetic history of the sample is wiped out. As the AF amplitude decreases, the field extremes will at a certain time be insufficient for saturation. In the case of a positive H_{DC} field, saturation will happen for the field maximum but not for the field minimum. At this stage, the system follows the major loop at decreasing field and a minor loop at increasing field. When saturation is not reached anymore at the field maxima, the system will “spiral” through ever smaller loops to the point (H_{an}, M_{an}).



(a) (b)

***Figure 1:** The anhysteretic magnetization:*
(a) applied field protocol, and (b) the M-H curves.

In principle, the anhysteretic magnetization value does not depend on the initial amplitude of the AF signal, the AF signal period, the decay per period, and the time evolution of the field between local extremes [3], provided that the initial amplitude is large enough to saturate the material in the first deperming period, the period is large enough to allow a magnetostatic approach, and the decay per period is small enough that the anhysteretic magnetization is independent of the phase of the AF signal.

In practice, it will be shown that these conditions do not apply, so that the deperming process cannot be treated as an anhysteretic magnetisation. The first complication arises from the fact that the field in the first deperming period is not large enough to saturate the magnetization in either direction. In this way, some of the magnetization history is still preserved and, when the field is gradually decreased, the magnetization will “spiral” in an unknown direction.

The second complication is due to the presence of a bias field. The ship deperming process takes place in the Earth’s magnetic field with both the horizontal and vertical components present, so that, at the end of the cycles, it will force the permanent magnetization into a particular point [4]. The anhysteretic magnetization procedure is affected by the ship demagnetizing factor which decreases the applied magnetic field inside the ship.

The demagnetizing magnetic field is the magnetic field H_d generated by the magnetization M within the ferromagnetic body. In practice, H_d is linearly related to M by a geometry-dependent constant called the demagnetizing factor, n. This factor is defined by $n = (H_e - H)/M$, where H is the applied field and H_e is the effective field strength inside the body. The demagnetizing field can be very difficult to calculate for arbitrarily shaped objects, even in the case of a uniform magnetizing field.

Other factor to consider is the ship variable magnetic cargo that may affect all aspects of the magnetization process. The effect of this factor on the final magnetization cannot be anticipated.

For these reasons, instead of using a succession of alternating fields with a constant decrement which would considerably simplify the process, the ship deperming needs to be controlled in the sense that the field amplitude at every step has to be carefully determined, empirically or analytically, to steer the magnetization toward the desired value. At present, the deperming process takes a long time because the calculation of the next value of the field is based on the graphical interpretation of the magnetic signature measured by a line of sensors placed under the keel.

3 Ship deperming at Norfolk, VA

The magnetic treatment facility in Norfolk is a fixed range where the ship is moored over an array of sensors placed on the ocean floor (Figure 2). Before being rigged with the deperming solenoid, the ship signature is measured for the North and South orientations. The purpose of these measurements is to obtain the signature produced by the ILM. Because the goal is to reduce the PLM to zero and the ship is subject to the horizontal Earth's magnetic field, the ILM signature is used as an indication that the deperming process finished successfully.

Figure 2: *Magnetic treatment facility at Norfolk.*

For the undegaussed North and South signatures, the components of the magnetic field measured at the sensors will be respectively:

$$\begin{aligned} B_K^N &= ILM_K + IVM_K + PLM_K + PAM_K + PVM_K \\ B_K^S &= -ILM_K + IVM_K + PLM_K + PAM_K + PVM_K \end{aligned} \tag{1}$$

where K = (X, Y, Z), ILM_K and PLM_K are the field components produced by the induced and permanent longitudinal magnetisations in K direction, and so on. For a perfect North or South run, IAM_K is zero because the Earth's magnetic field in the athwartship direction (H_Y) is zero. From Equation (1), the signature produced by ILM can be evaluated as half of the difference between the North and South signatures:

$$\mathbf{ILM} = (\mathbf{B}^N - \mathbf{B}^S)/2 \tag{2}$$

Next step is the installation of the deperming coils (Figure 3) around the hull with the ship oriented toward South. The deperming solenoid consists of a number of turns of heavy cable passed around the ship and connected in series. Each turn lies in a vertical plane. Thus the resultant field is that due solely to the vertical turns and is reasonably uniform over most of the volume of the ship, provided the turns are not spaced too far apart. After the solenoid has been rigged, a series of longitudinal magnetic field pulses are given, starting with as high a value of the current as possible. The pulses are arranged so that each is of opposite sign to the preceding one and the current is diminished by a fixed (pre-determined) amount.

Figure 3: *HMCS Toronto at Norfolk.*

3.1 Magnetic measurements during deperming

To be able to model the deperming process, the ship magnetization has to be expressed as function of the applied field. From the measured magnetic signature obtained at each stage of (de)magnetization, it is possible to estimate the unique parameters of the magnetic source. The method used in this report for estimating the magnetization does not require any assumptions regarding the shape for the causative body.

The anomaly created by the ship is given by the total magnetization, which is the vector sum of the permanent (residual) and the induced magnetization. Estimating the total magnetization of the ship at each step during the deperming process allows the operator to steer the system in the right direction. One way to estimate the ship magnetization is by visualizing its magnetic signature from a set of sensors placed under the keel. This empirical procedure is used at present for controlling the ship deperming process.

The control method proposed in this report is analytical, and is based on the relation between the integral moments of the magnetic field and the source magnetization. According to Helbig [5], the vector components of the average magnetic moments (m_X, m_Y, m_Z) can be estimated from the first moments of the vector components (B_X, B_Y, B_Z) of the magnetic field created by the source:

$$
\begin{aligned}
m_X &= -\frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} x\, B_Z(x,y)\, dx\, dy \\
m_Y &= -\frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} y\, B_Z(x,y)\, dx\, dy \\
m_Z &= -\frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} x\, B_X(x,y)\, dx\, dy = -\frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} y\, B_Y(x,y)\, dx\, dy
\end{aligned}
\tag{3}
$$

In practice, the infinite integral over the horizontal plane is limited to a finite area which requires that the mean values of the field components be removed [6].

The sensor array at Norfolk is shown in Figure 4. The sensors were placed at different depths but in this report only the sensors at 20 m depth were used. The measurements obtained from the sensors in combination with a ship magnetic model allow the calculation of the signature at each cycle on a finite horizontal plane large enough so that Equations (3) apply (Figure 5).

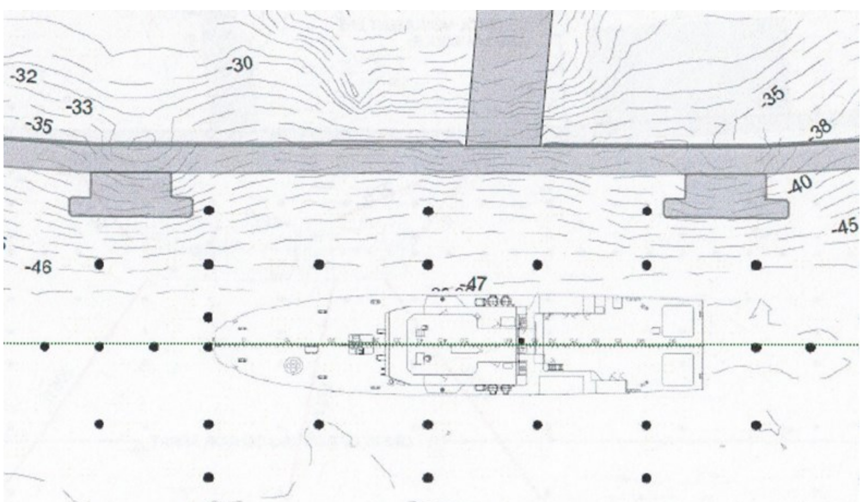
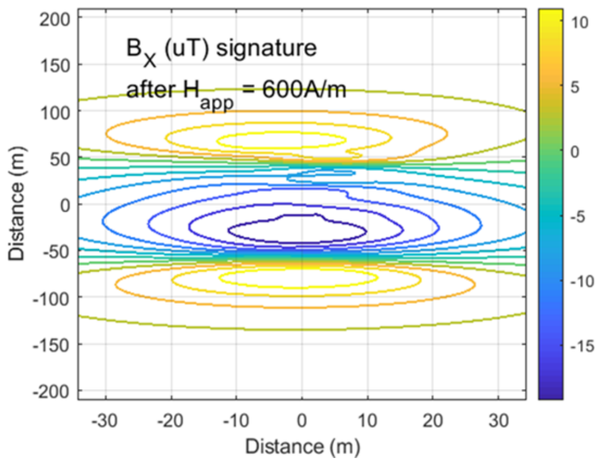
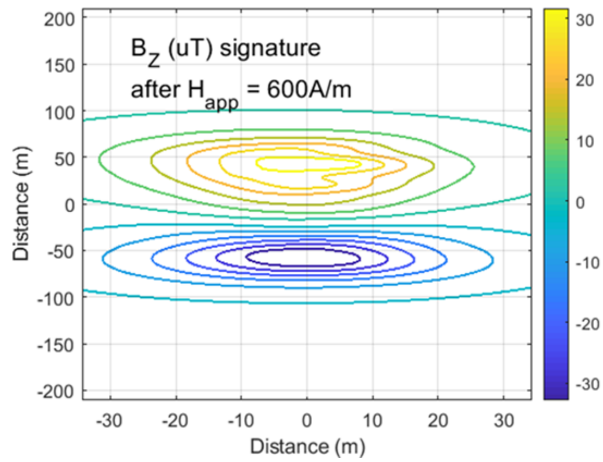


Figure 4: *Distribution of magnetic sensors at Norfolk.*



(a)



(b)

Figure 5: *Calculated signature at 20 m depth after the 600 A/m applied field.*

For the modelling purposes, it is convenient to replace the ship average magnetic moments with the magnetization components (M_X, M_Y, M_Z) = (m_X, m_Y, m_Z)/VOL, where VOL is the volume of the ferromagnetic material the ship contains. This volume was estimated from the ship tonnage (4700 tons) and the density of iron (7.9 tons/m^3) to be 595 m^3. Because not all the ship is ferromagnetic, the volume value was taken as VOL = 500 m^3. The material volume is just a proportionality constant which does not affect the general results. In the following calculation, the ship magnetic moment represents the absolute value, whereas the magnetization is a relative one.

Contrary to Equation (1) where the magnetic signature is obtained as the effect of all three vector components of the permanent magnetization, Equations (3) provide the average value of each component. For example, applying the Helbig Equations (3) on the first of Equation (1), the longitudinal component of magnetization, M_X, represents the summation of ILM and PLM.

At the beginning of the deperming process, the ship average magnetization was obtained with Equation (3) for the ship oriented North and South, respectively, as presented above. After subtracting, respectively summing up these values and dividing by two, we obtained for: ILM = 980 A/m, and PLM = 800 A/m. The deperming process starts with the ship oriented South, so that the longitudinal initial magnetization is PLM-ILM = -180 A/m. At the end of the process, the ship desired final magnetization would be -ILM = -980 A/m because the goal is to have PLM = 0.

During deperming, the measurements are taken at the specific moments: 1, 2, 3, 4, 5, 6, etc., as shown in Figure 6. At each point, the ILM, representing the effect of the horizontal bias field, was included in the measurements.

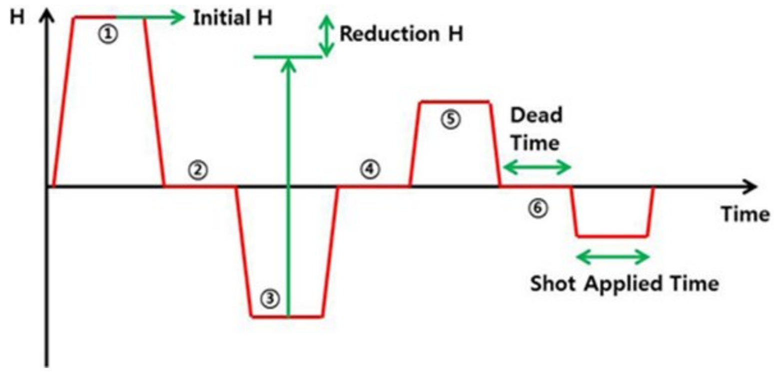


Figure 6: *The measurement points during the deperming process.*

Measurements taken at moments 2, 4, 6, etc., when the applied field is zero, will give the average residual magnetization of the ship (minus ILM). Measurements taken at moments 1, 3, 5, etc., contains, in addition to the new generated induced longitudinal magnetization, the applied field, H. For this reason, the measurements will be expressed as magnetic flux density, $B = \mu_0$ (PLM-ILM + H), where H = 0 or $H = H_{applyed}$. Here μ_0 is the permeability of the empty space.

4 The Jiles-Atherton magnetic model

A new approach to the deperming process is proposed in this report where the variations of the longitudinal magnetization are analyzed using the Jiles-Atherton (JA) model [7]. The goal is to characterize the ship by the macroscopic material properties such as saturation magnetization, coercivity, remanent magnetization, as well as to predict the evolution of the magnetization under different experimental conditions.

The classical JA model is based on physical assumptions. It describes well the isotropic steel under the circumstances that the value of the maximum applied magnetic field is close to the value of the saturation field. The main equation of the JA model is:

$$\frac{dM}{dH} = \frac{(1-c)\frac{dM_{irr}}{dH_e} + c\frac{dM_{ah}}{dH_e}}{1-\alpha(1-c)\frac{dM_{irr}}{dH_e} - \alpha c\frac{dM_{ah}}{dH_e}} \tag{4}$$

with the following complementary equations:

$$M_{irr} = \frac{M - cM_{ah}}{1-c}$$

$$\frac{dM_{irr}}{dH_e} = \frac{\delta_M (M_{an} - M_{irr})}{k\delta}$$

$$M_{ah} = M_s\left[\coth\left(\frac{H_e}{a}\right) - \frac{a}{H_e}\right]$$

$$\frac{dM_{ah}}{dH_e} = \frac{M_s}{a}\left[1 - \coth^2\left(\frac{H_e}{a}\right) + \left(\frac{a}{H_e}\right)^2\right] \tag{5}$$

$$\delta_M = 0.5\left[1 + \mathrm{sign}\left[(M_{ah} - M_{irr})\cdot dH/dt\right]\right]$$

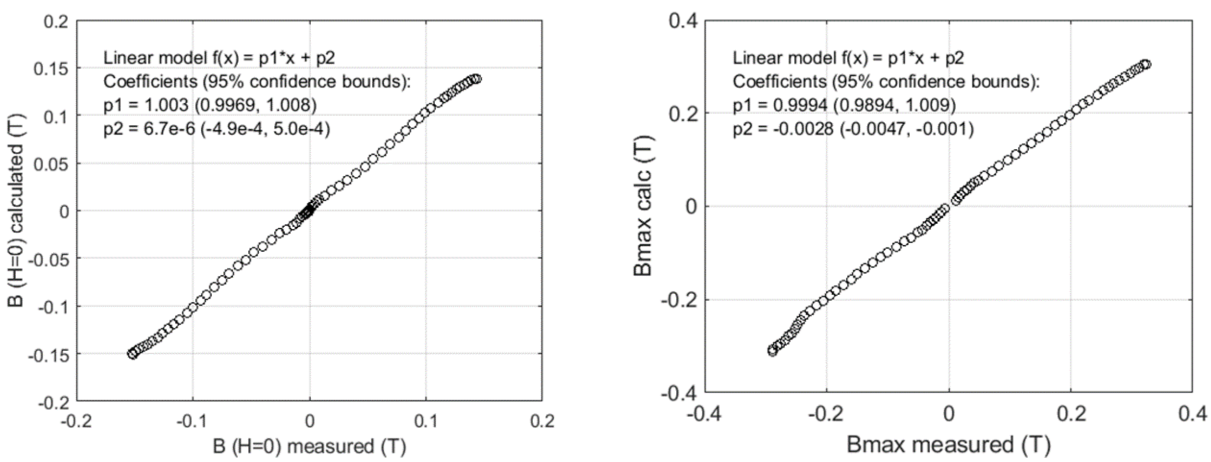
In the above equations, M_{irr} denotes irreversible magnetization, M_{ah} is anhysteretic magnetization, M_s is the magnetization at saturation when all magnetic domains have one orientation, $H_e = H + \alpha M$ is the so-called effective field, α is the inter-domain coupling parameter, k is related to pinning site density and its value is roughly equal to coercivity, *a* quantifies the domain wall density, c describes the reversibility of the magnetization process, and δ is introduced to distinguish the ascending and descending parts of the loop. The additional parameter, δ_M, guarantees that the differential susceptibility is positive, a condition that is physically justified.

Note that, by the introduction of the effective field, H_e, the JA model takes into consideration the demagnetization effect inside the body. The parameter α, called in the JA model the inter-domain coupling parameter, has the same formula as the demagnetizing factor, $\alpha = n = (H_e\text{-}H)/M$.

The values of the model parameters α, *a*, c, k, and M_s are estimated from measured hysteresis loops. As shown in Figure 6, there are three measurement points on each minor loop, i.e., that which does not reach saturation: (1) initial residual magnetization of the cycle, (2) peak magnetization reached during each cycle, and (3) the final residual magnetization of the cycle. Calculating the JA model parameters from the minor loops assures that they are accurately represented. This is not the case if the same parameter set obtained from the major loop were used [8].

A drawback of the JA model is the difficulty of determining its parameters on the basis of the measured hysteresis loop. In the literature, several methods of solving this inverse problem were presented such as simulating annealing [8], differential evolution algorithm [9], artificial intelligence methods [10], or "branch and bound" global optimization methods [11], all preferably applied for the set of magnetic hysteresis loops measured for the different values of the amplitude of the applied field, H. The cost function to be minimized is the squared difference between the measured and calculated values of the magnetic flux density, $B = \mu_0$ (PLM-ILM + H).

After testing a few algorithms, including the above ones, the parameters of the model were determined by the bound-constrained Nelder-Mead simplex method. This method, even if does not guarantee the global convergence, was found to be less dependent on the initial parameter values and converged to the same minimum. The values of the parameters need to be constrained from physical considerations (*a*, α, k, $M_S > 0$, $1 > c > 0$). It should be noted that accurate solving of differential Equation (4) requires the use of the 4th order Runge-Kutta method. The model parameters obtained from optimization are: *a* = 355 A/m, α = 1.01e-3, c = 0.59, k = 334 A/m, M_S = 367,000 A/m. These values are compared with the JA parameters of an ordinary steel in Table 1.

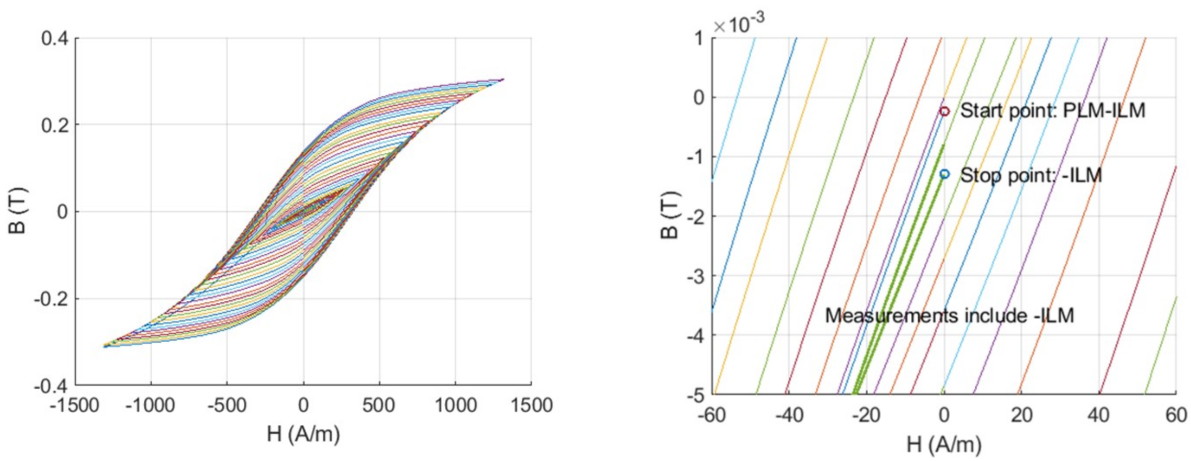


(a) (b)

***Figure 7:** Comparison between measured and calculated data:*
(a) residual, and (b) peak magnetizations.

As explained before, these model parameters correspond to a ferromagnetic volume of the ship of 500 m^3. When calculated for different volumes, it was noticed that the only parameter which depends on volume is M_S. For example, M_S = 407 kA/m for VOL = 450 m^3, and M_S = 458 kA/m for VOL = 400 m^3.

Next, the model with the optimal parameters was validated using measured data. With these parameters, the JA model predicts the measured data. Figures 7 (a) and (b) show the measured and calculated values for the residual and maximum magnetic flux density, B = μ_0 (PLM-ILM+H) together with the parameters obtained from linear fitting. Another indication that the model reproduces well the deperming process of HMCS Toronto is that it correctly predicts the final magnetization of the ship (-ILM) when using all 68 applied field cycles, as shown in Figure 8.



(a) (b)

Figure 8: *Deperming simulation with JA model:*
(a) all 68 cycles of the process, and (b) the central part enlarged.

Table 1: *The values of JA parameters of steel and ship.*

	Steel values	Ship
α [A/m]	6.2 E-5	1.01 E-3
a [A/m]	127.3	355
c	0.7	0.59
k [A/m]	51.7	334
M_s [A/m]	15.2 E5	3.67E5 (500 m^3)

The JA model of the deperming process indicates that the magnetic memory in the ship was not completely erased during the first cycle as intended and a residual magnetic domain structure remains. This fact becomes evident when the measured maximum magnetization attained in the ship during the first cycle (M_{max} = 119,000 A/m) is compared with the saturation magnetization (M_S = 367,000 A/m) from the JA model. Both these quantities are relative to the material volume, VOL = 500 m^3 in this case. Moreover, the comparison between the maximum applied field (about 1200 A/m) and the material coercivity (k = 334 A/m, independ on volume) does not ensure that all the domain walls are swept out during the field cycling. Thus, the system moves only on minor hysteresis loops and the anhysteretic approach for deperming is not justified.

4.1 Simulating the deperming procedure

The main advantage of having a model for ship deperming is that it allows the verification of different protocols, which is not possible in real life because the process is expensive and time consuming.

For example, the number of cycles (69 in the real case) is empirically set up based on two contradictory considerations: (1) the overall duration of the process should not exceed two days, and (2) the decrease of the applied field at each step is small enough to ensure a smooth control. In principle, it would be possible to shorten the allocated time by decreasing the number of cycles as demonstrated in [12] on a small cylindrical sample. The JA model of ship deperming predicts the same value of the final magnetization value when all 68 cycles were used or the number was reduced to every the 3rd or the 5th cycle of the original protocol (Figure 9).

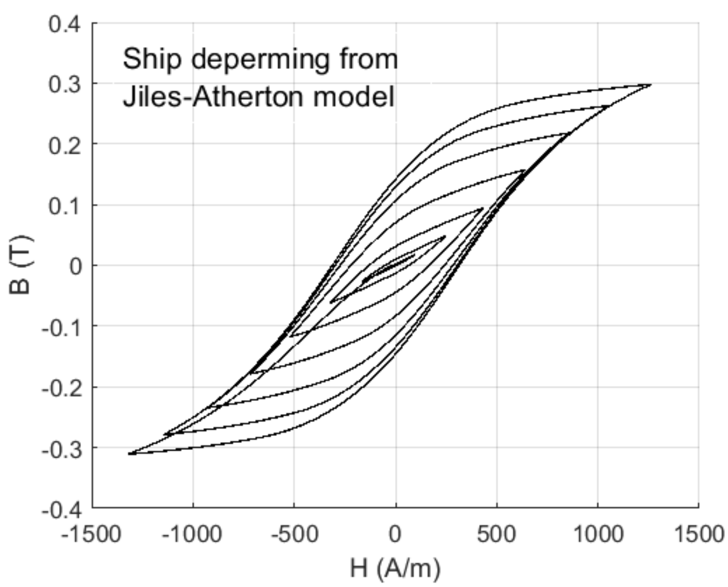
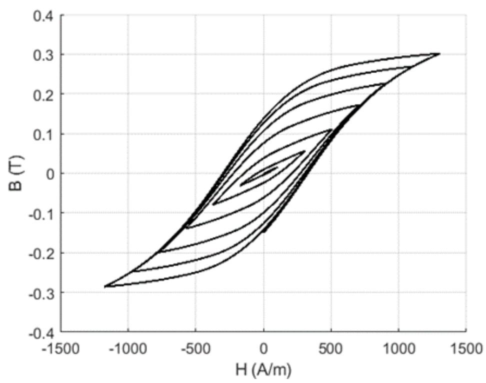


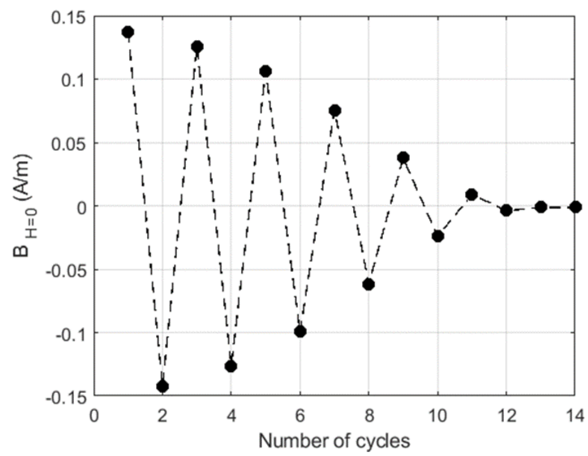
Figure 9: *The JA model for deperming using every the 5th cycle of the original protocol.*

The goal of this work is to automate the deperming procedure: the model should be able to predict analytically the value of the field necessary for the next cycle so that, at the end, the desired magnetization is attained. Because the ship deperming cannot be accomplished by anhysteretic magnetization, the process is not unique. Different scenarios and formulas for field calculation can be imagined and tested on the model, but at the moment the implementation is uncertain because the model is built on a single set of data. It is suggested as future work that a formula developed on this model to be tested in parallel with the visually controlled deperming process and compared with the final results.

The advantage of deperming through anhysteretic magnetization is that it uses a constant field decrement, and thus the procedure is greatly simplified. The disadvantage is that the final result after such process is not the desirable one (-ILM). For example, testing the anhysteretic magnetization protocol on the JA model, the final result is about 7 times larger than -ILM, irrespective the number of cycles. On the other hand, it is possible to devise a protocol similar to an anhysteretic magnetization, i.e. with a constant field decrement, and obtain the desired final magnetization, if an offset of 17 A/m is introduced at every cycle. This protocol, which has only 14 cycles, is shown in Figure 10.



(a)



(b)

Figure 10: *Simulated anhysteretic protocol with 14 cycles: (a) B-H curves, and (b) residual magnetization.*

5 Conclusion

This report presents a novel approach to the ship deperming protocol. Instead of estimating the applied field at each cycle, the measurements obtained from deperming a real ship were used to build a model which accurately reproduces the whole process.

From the mathematical description of bulk magnetic changes that occur within the ship during deperming, it has been concluded that a procedure based on anhysteretic magnetization cannot be applied. This conclusion explains the tedious protocol currently in use which is based on the visual inspection of the ship signature at each step followed by an empirical estimation of the next one.

It is also important to note that, because anhysteretic magnetization is not applicable, the deperming protocol is not unique. This means that the same result can be obtain with a different number of cycles which has influence on the duration of the process.

The main benefit of having a model is that that different protocols can be tested, a possibility which is impossible in practice. This paves the way toward the goal of this work which is to automate the deperming procedure. The task is attainable once it will be certain that the model applies to other ships.

References

[1] T. M. Baynes, G. J. Russell, and A. Bailey (2002). Comparison of Stepwise Demagnetization Techniques, *IEEE Trans. on Magnetics*, Volume 38, No. 4, pp. 1753–1758.

[2] F. Thiel, A. Schnabel, S. Knappe-Gruneberg, D. Stollfus, and M. Burghoff (2007). Proposal of a Demagnetization Function, *IEEE Trans. On Magnetics*, Volume 43, No. 6, pp. 2959–2961.

[3] R. M. Bozorth (1961). *Ferromagnetism*. New York: Van Nostrand.

[4] K.-C. Kim, K.-S. Yoon, C.-S. Yang, K.-H. Shin, H.-Y. Jeong, and Y.-H. Kim (2011). Remnant Magnetization Prediction in the Demagnetization Process by Orthogonal Magnetic Field, *IEEE Trans. on Magnetics*, Volume 47, No. 10, pp. 4360–4363.

[5] K. Helbig (1963). Some integrals of magnetic anomalies and their relation to the parameters of the disturbing body, *Zeitschrift fur Geophysik*, Volume 29, pp. 83–96.

[6] J. D. Phillips (2005). Can we estimate total magnetization directions from aeromagnetic data using Helbig's integrals? *Earth, Planets and Space*, Volume 57, pp. 681–689.

[7] D. Jiles, J. B. Thoelke, and M. K. Devine (1992). Numerical determination of hysteresis parameters for the modelling of magnetic properties using the theory of ferromagnetic hysteresis, *IEEE Trans. on Magnetics*, Volume 28 (1), pp. 27–35.

[8] D. Lederer, H. Igarashi, A. Kost, and T. Honma (1999). On the parameter identification and application of the Jiles-Atherton hysteresis model for numerical modelling of measured characteristics, *IEEE Trans on Magnetics*, Volume 35(3), pp. 1211–1214.

[9] H. M. J. Boots, L. Sander, and K. M. Schep (2000). Dependence of the anhysteretic magnetization on the demagnetization factor, *Physica B*, Volume 275, pp. 168–172.

[10] K. Chwastek, and J. Szczygłowski (2006). Identification of a hysteresis model parameters with genetic algorithms, *Math. Comput. Simulat.*, Volume 71, pp. 206–11.

[11] K. Chwastek, and J. Szczygłowski (2007). An alternative method to estimate the parameters of Jiles-Atherton model, *J. Magn. Magn. Mater.*, Volume 314, pp. 47–51.

[12] J.-W. Kim, S.-H. Kim, J.-h. Kim, H.-B. Lee, and H.-J. Chung (2017). Efficient Search Method of Deperming Protocol for Magnetic Silence of Vessel, *Journal of Magnetics*, Volume 22 (1), pp. 85–92.

List of symbols/abbreviations/acronyms/initialisms

AF	alternating field
DG	degaussing
DND	Department of National Defence
DRDC	Defence Research and Development Canada
FMF	Fleet Maintenance Facility
GPS	global positioning system
HMCS	Her Majesty’s Canadian Ship
IAM	induced athwarship magnetization
ILM	induced longitudinal magnetization
IVM	induced vertical magnetization
MTF	magnetic treatment facility
PAM	permanent athwartship magnetization
PLM	permanent longitudinal magnetization
PVM	permanent vertical magnetization
RCN	Royal Canadian Navy

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Demagnetization of ferromagnetic vessels, or deperming, is a common practice used to reduce the magnetic signature and improve the degaussing operation. To deperm a ship in the longitudinal direction, the Royal Canadian Navy uses the magnetic treatment facility in Norfolk, VA. The procedure consists of passing large electric currents through a set of longitudinal coils temporarily rigged over the exterior of the hull. Signature measurements are taken at each point during the treatment and are used to determine the required current setting and to confirm the success of the procedure.

The general approach for ship deperming presented in the literature is the anhysteretic protocol where the applied field is reduced at equidistant intervals. In reality the method involves the complications of having a bias (Earth's magnetic) field present, and of the practical impossibility of magnetizing the ship to saturation.

At present, past experience is used to empirically estimate the necessary treatment schedule for each vessel. Despite the success of this procedure, a program of work was set up to examine this process on a fundamental basis and hopefully gain some insight into its physics with the aim of developing a predictable deperming procedure. This report outlines the steps undertaken in this direction: (1) the signature of the ship was modelled so that the principal magnetic moments at each point of the demagnetization could be calculated, (2) with these values, the ship magnetization parameters were estimated by inverting the Jiles-Atherton model, (3) using the Jiles-Atherton analysis of hysteresis, a mathematical description of bulk magnetic changes that occur within the ship during deperming has been developed, and (4) based on this analysis, we propose to predict the results of the demagnetization *a priori*. The model simulation study of the demagnetization process is demonstrated with the measurements from HMCS Toronto.

La démagnétisation permanente de vaisseaux ferromagnétiques est une pratique courante utilisée pour réduire la signature magnétique et améliorer toute l'opération de démagnétisation. Pour procéder à la démagnétisation permanente d'un navire dans le sens longitudinal, la Marine royale canadienne utilise l'installation de traitement magnétique de Norfolk, VA. La procédure consiste à faire passer des courants électriques importants au travers d'un ensemble de bobines longitudinales fixées temporairement à l'extérieur de la coque. Des mesures de signature sont faites à chaque point pendant le traitement et sont utilisées pour déterminer le réglage de courant requis et confirmer le succès de la procédure.

L'approche générale pour la démagnétisation permanente d'un navire présentée dans les publications sur le sujet est le protocole anhystéritique, dans le cadre duquel le champ appliqué est réduit à intervalles équidistants. En réalité, cette méthode entraîne les complications d'avoir la présence d'un champ biaisé (le champ magnétique de la Terre) et l'impossibilité pratique de magnétiser le navire jusqu'à saturation.

À l'heure actuelle, l'expérience antérieure est utilisée pour estimer empiriquement le calendrier de traitement nécessaire pour chaque navire. Même si cette procédure fonctionne bien, un programme de travaux a été mis sur pied pour permettre l'examen de ce procédé sur une base fondamentale, dans l'espoir d'obtenir certains renseignements sur sa physique afin de développer une procédure de démagnétisation permanente prévisible. Dans le présent rapport, nous soulignons les étapes entreprises à cette fin: (1) la signature du navire a été modélisée de manière à ce que les moments magnétiques principaux en chaque point de la démagnétisation puissent être calculés; (2) avec ces valeurs, les paramètres de démagnétisation du navire ont été estimés grâce à l'inversion du modèle Jiles-Atherton; (3) au moyen de l'analyse Jiles-Atherton de l'hystérésis, nous avons développé une description mathématique des modifications magnétiques générales qui ont lieu dans le navire pendant la démagnétisation permanente; (4) à partir de cette analyse, nous proposons de prédire les résultats de la démagnétisation a priori. L'étude de simulation du modèle de démagnétisation a été corroborée au moyen de mesures faites sur le NCSM Toronto.