Comparison of Stepwise Demagnetization Techniques

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Abstract—To demagnetize small-scale objects (dimensions less than 1 m) fabricated from ferromagnetic materials, it is standard practice to expose the object to a continuous ac applied magnetic field with a steadily decaying amplitude. For objects of dimensions greater than 10 m, there are problems of scale, and a stepwise procedure is preferred. We have simulated two different stepwise demagnetization techniques with a scaled model of a magnetic treatment facility regularly used in the deperming of military vessels. We used a steel tube as the model of a ship that was to be demagnetized. For each demagnetization method, we calculated the standard deviation in the final magnetization of the tube. This standard deviation provides a measure of how reproducible the results of the respective techniques are. We find that the standard deviation in final magnetization is improved by a stepwise anhysteretic demagnetization method over the conventional Flash D deperm procedure.

Index Terms—Anhysteretic, demagnetize, deperm, steel.

I. INTRODUCTION

THE process of demagnetizing ferromagnetic objects is important for a range of applications involving widely different scales [1]–[3]. With small-scale (<1 m) objects, demagnetization may be achieved using an alternating applied magnetic field whose amplitude is slowly reduced to zero. This may be practically attained, for example, by placing the object inside a long solenoid driven by an ac current source. As the current amplitude is reduced to zero over time, the magnetization of an object inside the solenoid is described by a path along ever-decreasing hysteresis loops (see Fig. 1).

For larger scale objects ($\gg 1$ m), there are the logistical problems of constructing a solenoid or any device large enough to contain the object and to supply enough ac current to generate the necessary field strengths (in practice, currents of up to 6000 A may be required). There is the additional effect of eddy currents that could produce unacceptably high voltages across a large ferromagnetic object. Consequently, a dc technique is favored. This often uses a ramped step function with successive steps having opposite polarity (See Fig. 2).

Of particular interest to the authors are the methods used to demagnetize or “deperm” naval vessels. These methods frequently involve the additional complication of having a bias field present during the deperm process so that a particular permanent magnetization remains. The intention is to obtain a permanent vertical magnetization (VM) that counteracts the induced VM in the vessel due to the earth’s background field

Fig. 1. Hysteresis trajectory for a ferromagnetic material in the (M, H) plane during demagnetization. The circular insets describe the distribution of domain orientations within the material. From Chikazumi [4].

Fig. 2. Ramped dc step function used for demagnetization on the large scale ($\gg 1$ m). Note the steps are evenly spaced because the field strength in successive steps decreases linearly with time. The ramp gradient is constant for maximum control over eddy current generation.

(EBF) for a specific magnetic zone of operation. We define a “bias field” as any persisting magnetic field that causes the net field, in the region of the depermed object, to deviate from zero during the deperm. This does not include alternating dc fields.

The conventional procedure [5] used by the Royal Australian Navy to deperm ships and submarines in the Southern Hemisphere is called “Flash D.” The Flash D deperm involves three stages.

Manuscript received April 17, 2001; revised December 7, 2001.

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Publisher Item Identifier S 0018-9464(02)06382-3.

Fig. 3. (a) Experimental apparatus showing the X and Z Coils and the definition of the longitudinal, transverse and vertical axes with respect to magnetic north. (b) Schematic diagram of electronic control and data collection system.

Stage 1 consists of a ramped step function of applied longitudinal fields (similar to those shown in Fig. 2) with a coarse step decrement, typically about 100 A/m (127 μ T). During Stage 1, there is also a constant vertical down bias field applied opposite to the ambient vertical EBF [see Fig. 3(a) for orientation of axes]. It is important that this establishes an excessive VM in that direction. In later stages, the vertical EBF is used as a fine control bias field to slowly delete the superfluous VM. The purpose of Stage 1 is to erase any magnetic history whilst imparting a surplus VM proportional to a large (500 A/m) vertical bias field.

Stage 2 uses increasing longitudinal applied fields in concert with the vertical component of the EBF to fine-tune the VM to a point just above the final desired level. In doing so, an extraneous longitudinal magnetization (LM) is necessarily acquired.

Stage 3 is similar to Stage 1 only with smaller decrements between applied field steps (typically 25 A/m) and the vertical EBF is again used as a bias field. Stage 3 deletes the unwanted LM whilst the VM decays to the final value.

The Flash D simulations we performed had this basic three-stage structure and all details adhered to the same protocol as for a real vessel. For more information, refer to [5] and Section II-B.

We propose a simpler stepwise deperm method based on a single anhysteretic magnetization stage. We will refer to this as an “anhysteretic deperm.” Anhysteretic magnetization is that which results if an alternating field with decreasing amplitude and a constant dc bias field are applied simultaneously to a ferromagnetic sample [6]. The resultant magnetization (after the alternating field strength has been slowly reduced to zero) is a function of the dc bias field value (H_b). For a range of H_b the anhysteretic magnetization is described by a sigmoid curve (see Fig. 4). This curve has been described theoretically by others [6], [7] using a variety of mathematical models.

Fig. 4. Typical anhysteretic curve. Points on this curve correspond to the induced magnetization in the object at H_b plus the remnant magnetization for a given H_b after the hysteresis cycling shown in Fig. 1. Included for comparison are the initial magnetization curve and the branches of the major hysteresis loop.

The anhysteretic deperm we propose is intended for large ferromagnetic bodies and therefore the alternating field employs the same dc ramped step function as in the Flash D deperm.

Although Stage 1 and Stage 3 of the Flash D deperm involve exactly the same principles as the anhysteretic deperm, the variable duration and outcome of Stage 2 means there is no simple theoretical treatment for the Flash D method.

In the anhysteretic deperm, the alternating field is in the longitudinal direction and the bias field in the vertical direction. Thus longitudinal magnetization is reduced, and a specific vertical magnetization is gained. This is exactly the same result sought by the Flash D deperm. By refining the dc step function and the choice of vertical bias field, we can use just one stepwise anhysteretic magnetization stage and remove the need for any of the “fine-tuning” of Stage 2 in the Flash D deperm.

Given that deperming ships and submarines is often costly and time consuming, any improvement in the speed and, perhaps, quality of the procedure would be welcome. Additionally, it may be possible to apply the theory of anhysteretic magnetization to reliably predict the results of an anhysteretic deperm *a priori*. Strictly speaking, the anhysteretic deperm is anhysteretic magnetization in two orthogonal dimensions (longitudinal and vertical). The bias field in the longitudinal direction is always equal to zero, but it is important to note that the anhysteretic magnetization in the vertical direction may not necessarily be of the form in Fig. 4. A theoretical analysis of orthogonal anhysteretic magnetization and its application to anhysteretic deperming is deferred to a future study.

It is the purpose of the present investigation to ascertain whether the anhysteretic deperm is practical and whether there is any advantage in using it. We measured the latter by comparing the outcomes of a number and variety of anhysteretic deperms with results from the standard Flash D method on the same ferromagnetic specimen.

The object used in all demagnetizations was a CU200T-G steel tube, 300 mm long, with inside diameter 29.6 mm, outside diameter 32 mm. CU200T-G is soft steel, rolled, and electro-

welded to form a tube. For further material specifications, refer to [8] or the Appendix. A steel tube was chosen as the model for a ship or submarine because it provided the simplest geometrical approximation to a hollow vessel on the small scale.

The experiments used a scaled model of a possible naval deperm facility so the two processes could be compared using a similar field geometry to that employed in actual deperms of ships and submarines.

Preceding any deperm the steel tube was demagnetized in a large solenoid with 700 turns/meter driven by a 120-V ac transformer and variac. The current in this large solenoid could guarantee an ac demagnetization with field strengths in excess of the saturation value. This ensured a consistent demagnetized initial state for the steel tube.

It might seem a little circular to then deperm a tube already in a demagnetized state, but it must be noted that we are not comparing the outcome of individual deperms but the variation within the multiple results from different deperm methods. The predeperm, demagnetized state of the tube meant that no magnetic history would influence the results. This particular situation is normally impractical on the large scale, hence the use of small scale models.

II. EXPERIMENTAL SETUP

The tube was placed at the geometric center of two sets of coils [shown in Fig. 3(a)]. The tube was positioned coaxially inside a 200 turns/meter solenoid (X Coil) which supplied the longitudinal (North–South) field. The power supply output to the X Coil was digitally controlled through a parallel connection with a PC and all deperm procedures were directed from software. The vertical applied field was supplied by a rectangular Helmholtz pair (Z Coil) driven by a power supply controlled manually.

Measurement of tube magnetization was made using a linear magnetometer array, aligned parallel to the axis of the tube and 10 cm vertically underneath it [see Fig. 3(b)]. In practice, this array consisted of a single MAG-03 MC three axis magnetic field sensor (range $\pm 250 \mu\text{T}$, sensitivity $\pm 7.5 \text{ nT}$) which was optically switched to record the magnetic field at 2-cm intervals along a 1.4-m track. The data from this array were delivered via serial connection to a PC where the magnetic signature of the tube was modeled as a continuous line source of magnetic moments. Details of the numerical modeling used may be found in [9]. Briefly, this line source was chosen to be the same length as the tube and from this a measure of the magnetic moment along the three axes could be calculated; dividing by the volume of the tube gave magnetization values for a given direction.

A. Stepped Anhysteretic Deperm

Current was supplied to Coils X and Z to produce fields within the coil arrangement that counteracted the EBF [based on measured EBF in the lab of 36 A/m (45 μT) vertical up and 22 A/m (28 μT) longitudinal]. With these offset fields opposing the EBF, the total bias field in all directions was zero ($H_b = 0 \text{ A/m}$). This configuration was used during the measurement of the tube's initial and final magnetization to exclude any induction due to the EBF.

It is important to note one important aspect of the measurement apparatus: If $H_b = 0 \text{ A/m}$ within the coils, this did not translate into zero field as measured at the magnetometer array displaced 10 cm vertically below the tube. The same applied fields that maintained H_b produce nonzero fields at the array. Consequently when the EBF offset fields were applied, a background measurement was made and subtracted from any subsequent data of the tube's magnetization.

After the predeperm demagnetization in the large solenoid, the tube was positioned inside the X and Z Coils and its initial magnetic state was measured using the magnetometer array. Even with careful ac field demagnetization, it was difficult to obtain absolutely zero magnetization in the tube, but acceptable initial magnetic moment values in the three directions measured were $<0.05 \text{ A} \cdot \text{m}^2$ longitudinal (North–South), $<0.001 \text{ A} \cdot \text{m}^2$ horizontally transverse (East–West), $<0.005 \text{ A} \cdot \text{m}^2$ vertical.

As mentioned previously, a real ship deperm usually seeks to have a specific value for the final VM. In a conventional deperm, this is brought about by the combination of different vertical bias fields applied during the three stages (longitudinal and transverse bias fields are always set to be zero). For our purposes, we could arbitrarily select the final desired VM because we were more interested in the variation in the results than setting a particular final VM. For simplicity, we chose the final VM = 0 A/m. Thus, throughout all anhysteretic deperms $H_b = 0 \text{ A/m}$.

We performed stepwise anhysteretic deperms on the tube using the X Coil to supply dc field pulses or “shots” of alternating polarity. In an actual deperm on a large vessel, the first five shots have the same field magnitude to ensure that the magnetic history is wiped and to establish the extrema of the hysteresis cycle. To make the simulation of a potential ship deperm more authentic, the first five shots we performed had the same field strength = 2000 A/m (2510 μT). After these initial shots, the field amplitude was reduced to 0 A/m in decrements of 200, 100, 40, and 25 A/m (100 A/m = 125.7 μT), respectively, as different anhysteretic deperms. The direction of the first shot (North or South) was always selected to oppose the direction of the small initial longitudinal magnetization of the tube. Each shot had a duration of 3 s and the field strength in successive shots was decreased, in decrements of a specific value.

At the end of each deperm, the final vertical and longitudinal magnetizations were measured. Each deperm corresponding to a specific decrement value was repeated 30 times in order to gain a significant number of results for statistical analysis.

B. Flash D Deperm

The following method is adapted from the British standard for Flash D deperms, BR 825 [5], which is also the standard used by The Royal Australian Navy.

1) *Stage 1:* As with the anhysteretic deperms, all initial and final magnetization measurements were made with the X and Z Coils compensating for the EBF and there were the same requirements for the initial magnetic state of the tube. Unlike the anhysteretic method, a vertical bias field, $H_b = 500 \text{ A/m}$ (628 μT) was maintained in the Z Coil throughout Stage 1. This was applied opposite to the direction of the vertical component

Fig. 5. The continuous curve represents the vertical component of the tube's magnetization after the first shot in a pair. The dashed line corresponds to that after the second shot. From the point of intersection, we determine the value for VM_n used in (1).

of the EBF. In our Southern Hemisphere laboratory, H_b was therefore directed vertical down. The final desired VM for these deperms was still 0 A/m. This Stage 1 vertical bias field is part of the Flash D protocol; the general idea is to begin with an excessive VM, which is removed gradually in a controlled fashion over the next two stages.

In the X Coil, we started with five shots of alternating polarity but equal amplitude [$= 2000$ A/m ($2510 \mu\text{T}$)] reducing to 0 A/m in steps of 100 A/m. The first shot opposed the direction of the small initial longitudinal magnetic moment of the tube. At the completion of the X Coil shot sequence, the current in the Z Coil was reduced to zero; thus, the vertical bias field was the vertical EBF [$H_b = 36$ A/m ($45 \mu\text{T}$) vertical up]. This situation remained throughout the shots of Stages 2 and 3, though, wherever measurement of the tube's magnetization was necessary, the current in the X and Z Coils was again set so the applied fields counteracted EBF and therefore the effect of induced magnetization was removed.

2) *Stage 2*: This stage involved pairs of longitudinal field shots with equal amplitude but opposite directions. Successive shot pairs increased in field strength. The polarity and magnitude of these shots were calculated as follows: two pairs of initial shots, with the first shot of the pair 1 being opposed to the last shot of Stage 1. Shots of pair 1 had a field strength of 200 A/m ($251 \mu\text{T}$), pair 2 had field strength of 300 A/m ($377 \mu\text{T}$).

After each shot, a measurement was made of the tube's VM at 2-cm intervals along the magnetometer array, and after every n th complete pair, the data from both shots in a pair were used to obtain the value VM_n . This was derived graphically from plots of VM versus longitudinal displacement corresponding to each shot in a given pair (see Fig. 5). During this stage, the tube may essentially be considered a longitudinal dipole with a relatively small VM ($LM/VM > 10$). If the tube were a purely longitudinal dipole, then we would expect the plot of VM on the longitudinal axis to pass through the origin in Fig. 5. The origin corresponds to the point on the magnetometer array directly underneath the geometric middle of the dipole (tube) and a zero value for VM. Where there is a small VM, the same plot will be elevated above the origin. Looking at the intersection of the VM plots for both shots in a pair, we extracted a measure of VM_n . This value, together with the value for the preceding

Fig. 6. Initial magnetization curve for CU200T-G steel tube as a function of applied field in the vertical direction. Gradient of the linear fitted curve $\chi_i = 12.1$.

shot pair, VM_{n-1} was used to calculate the current amplitude (and therefore the applied field) in the X Coil for the $(n+1)$ th pair. This is the reason why there were initially two shot pairs of predetermined field strength that provided an arbitrary starting point for Stage 2.

If the target vertical magnetization for Stage 2 (VM_t) was not reached after a given pair, then the X Coil current for the next pair was calculated using the following formula [5]:

$$I_{n+1} = I_n + \left(\frac{VM_t - VM_n}{VM_{n-1} - VM_n} \right) \times (I_{n-1} - I_n) \times 0.5. \quad (1)$$

The target vertical magnetization, $VM_t = 500$ A/m ($628 \mu\text{T}$). This figure is equal to the sum of the final desired vertical magnetization, VM_f and the expected depreciation of VM during Stage 3, VM_d

$$VM_t = VM_f + VM_d. \quad (2)$$

In our case, the VM_f is 0 A/m and the allowance for change of vertical magnetization in Stage 3 is given by [5]

$$VM_d = 1.4\chi_i^2 EBF \quad (3)$$

where χ_i is the vertical initial magnetic susceptibility and EBF in the vertical direction $= 36$ A/m ($45 \mu\text{T}$). χ_i was found experimentally using the deperm apparatus with applied vertical field values in the range 0–400 A/m.

3) *Stage 3*: This stage consisted of linearly decreasing X Coil shots of alternating polarity in decrements of 25 A/m ($31 \mu\text{T}$). The first shot had a direction and magnitude the same as the last shot of Stage 2.

III. RESULTS

Results for the initial vertical magnetization curve of the tube at low fields (< 400 A/m) are presented in Fig. 6. A linear fit to this data provided a value for the initial susceptibility, $\chi_i = 12.1$ in the vertical direction across the tube. This is used in (3) to determine VM_d .

Normalized results are shown in Fig. 7 for both dc deperm techniques. Notice that for larger step decrements, the results

Fig. 7. Comparison of normalized final (a) LM and (b) VM results after the Flash D deperm and various grades of anhysteretic deperm. The normalizing function used is shown below, where σ is the standard deviation and μ is the mean magnetization. $N(M) = (1/\sigma\sqrt{2\pi})e^{-((M-\mu)^2/2\sigma^2)}$.

for the anhysteretic deperms polarize in the longitudinal direction depending on the direction of the last step. This is inherently different from a normal distribution, but the normalization curves shown are not meant to be a rigorous statistical analysis. That would assume variation in the data follows a normal distribution, which may or may not be the case. The graphs do, however, demonstrate the qualitative difference between the reliability of the deperm techniques: those with a narrower distribution are more reproducible.

A more detailed examination is shown in Fig. 8. These plots show the standard deviation (σ) of final magnetization as a function of the number of steps required for each demagnetization technique. A trend emerges in the data from the anhysteretic deperms; the greater the number of steps used, the less the variation in the final VM and LM results. This is displayed in the curves fitted to the data using a power law. We stress that these curves have no theoretical basis and are included only to demonstrate the general trends.

Fig. 8(a) also shows the disparity between σ for VM_f with the Flash D technique, and that for the anhysteretic deperm with a comparable number of steps. The difference in variation for the

Fig. 8. Standard deviation (σ) of (a) final VM and (b) final VM results with respect to the number of steps used in different deperm methods. Curves have been fitted (according to a power law) to the data for anhysteretic demagnetization (shown by circles). Deperms with larger step decrements correspond to deperms with a smaller number of total steps. The average number of steps was calculated and used for the Flash D deperm datum (shown by a square).

final longitudinal magnetization, as shown in Fig. 8(b), is not as pronounced.

IV. CONCLUSION

The construction of the apparatus and the methods used in this investigation were designed to simulate, on the small scale, two stepwise deperm techniques intended for deperming large scale ferromagnetic bodies; specifically for use on ships and submarines.

We have found that the anhysteretic deperm method is practicable and there is an advantage in using a stepped anhysteretic method instead of the Flash D deperm in terms of minimizing the variation in final vertical magnetization for a CU200T-G steel tube. We interpret this as an improvement in reproducibility over conventional deperm techniques.

An anhysteretic deperm with the same number of steps (i.e., taking approximately the same time) as a Flash D deperm, will have a standard deviation of the final VM that is significantly less than that for the Flash D deperm. There is no such economy in using an anhysteretic deperm to improve the stability of the

LM outcome. Flash D and the anhysteretic method produce comparable variations in the final LM.

The advantage of using the anhysteretic deperm method lies not in reducing the number of steps needed, but in increasing the reliability of the final VM. To maintain the quality of the final LM result, a similar number of steps would be required whether we use an anhysteretic or a Flash D deperm. However, with an anhysteretic deperm there is the possibility of applying established theoretical analyses of anhysteretic processes to anticipate the deperm result. There are outstanding problems in this area, but Bi and Jiles [10] have recently investigated the effect of orthogonal bias fields on hysteresis curves. Although they did not consider anhysteretic magnetization in the orthogonal direction, their quantitative analysis may provide a useful starting point for describing longitudinal and vertical magnetization in deperm subjects. Whilst these problems are left to a future publication, it is noted that there is no current theory for predicting Flash D deperm outcomes and any such method is unlikely to be as simple as that for anhysteretic deperms.

APPENDIX

CU200T-G cold-rolled or temper-rolled steel is suitable for general fabrication and welding. Typical applications include tubing and pressing as per Australian Standard AS1365 [8].

Mechanical Properties.

Transverse tensile Yield Strength: 200 MPa.

Elongation on 80 mm: 28%.

Hardness (HRB): 65.

Chemical Composition.

0.15% Carbon.

0.04% Phosphorous.

0.6% Manganese.

0.04% Sulfur.

0.005–0.010% Silicon.

0.03–0.05% Aluminum.

0.001–0.005% Nitrogen.

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