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# Validation of Closed Loop Degaussing System for Double Hull Submarines

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**Abstract** — This paper presents last DCNS development on Closed Loop Degaussing System dedicated to high performance electromagnetic silent warship.

This paper focuses on an evolution of the CLDG algorithm for degaussed warship. Developed in cooperation with Grenoble Electrical Engineering Lab, this genuine method allows to determine the hull unknown magnetization components, thus the predicted signature, based on real time magnetic measurements from sensors located very close to hull. The inverse problem is solved leading to the determination of the complete magnetic model of the ship. A large and complex double hull submarine mock-up has been designed and produced. The new developed method has been successfully validated on this mock up, and the interest of the CLDG system has been confirmed. In conclusion, DCNS-G2ELAB roadmap for full scale CLDG completion is presented.

## I. INTRODUCTION

Most parts of submarines are made of steel. One of the drawbacks of using such a material is that steel is ferromagnetic. The hull of the submarine, placed in the earth's magnetic field and subjected to high pressure effects, get a static magnetization. This magnetization effect is added to the induced magnetization.

$$\mathbf{M}_{\text{overall}} = \mathbf{M}_{\text{induced}} + \mathbf{M}_{\text{Remanent}} \quad (1)$$

The overall magnetization creates a local static magnetic anomaly around the submarine and can lead to its detection or localization by magnetic sensors embedded in airplanes or even worse in mines. Therefore, for decades, worldwide navies are looking at ways of reducing this magnetic anomaly by setting up large coils in the whole ship fed with appropriate currents (Fig.1.).

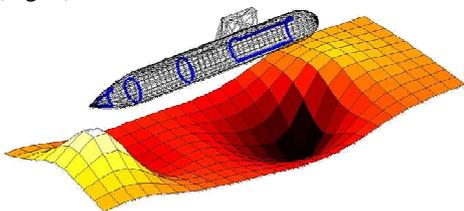


Fig 1: Examples of the Magnetic Anomaly and Degaussing Coils in a submarine.

One of the most efficient ways to ensure the magnetic discretion of a vessel would consist in setting up a closed loop degaussing system on board. The principle of the Close Loop Degaussing System (CLDG) is based on a real-time anomaly evaluation by using internal magnetic sensors. As a result, the current in degaussing coils can be adjusted to compensate for any change in magnetization.

Before reducing the anomaly, it is necessary for the ship to evaluate its own magnetic anomaly. The more important part

of such system concerns the identification of the ship's hull magnetization. This problem is quite difficult to solve. Indeed, the magnetization can be divided in two parts: an induced one, due to the reversible reaction of the material in the inductor field, and a remanent one due to the magnetic history of the material (which depends on hysteresis, mechanical and thermal constraints). The computation of the induced magnetization is now a documented issue [1]. However, the remanent part is impossible to evaluate with a deterministic calculation; we have no access to the magnetic past of the material and sensors can't extract directly the remanent magnetization from the induced one. Moreover, even if we had such a knowledge, existing models would be too complex to be applied to 3D geometries. It is therefore necessary to use magnetic measurements to determine the total magnetization of the hull. Thus, the main goal is to solve an inverse problem (i.e. determination of the sources by knowing the effects) with magnetic sensors placed in the air region closed to the hull.

This problem has already been studied and the magnetization identification has already been achieved when sensors could be located far enough from the sheets and with a simplified mock-up of a surface ship [2], [3]. Some of the main results recorded will be given below. However, this method has not been tested yet on a realistic mock-up of a double-hull submarine with a significant number of magnetic sensors number placed between the two hulls, i.e. close to the magnetic sources. This is one of the main goals of the project presented in this paper.

## II. BACKGROUND THEORY

### A. Forward modeling

Let us consider a device made up of a ferromagnetic sheet  $S$  with a thickness  $e$  and placed in an inductor magnetic field  $\mathbf{H}_0$  (the earth's magnetic field, for instance). This sheet has an unknown static magnetization  $\mathbf{M}$  which contributes to the overall magnetic field. Therefore, field  $\mathbf{H}$  is the sum of the inductor field and the field created by the shell itself:

$$\mathbf{H} = \mathbf{H}_0 + \mathbf{H}_{\text{shell}} \quad (2)$$

The field generated by the ferromagnetic material is directly linked to its magnetization by a conventional volume integral equation. For a sheet configuration, it is standard practice to assume that the magnetization is tangential to the shell and constant through it, its permeability being high and its thickness  $e$  being low in comparison with other dimensions. Therefore, the integral equation can be written as:

$$\mathbf{H} = \mathbf{H}_0 + \frac{e}{4\pi} \nabla \int_s \frac{\mathbf{M}_i \cdot \mathbf{r}}{r^3} dS \quad (3)$$

where:  $\mathbf{r}$  is the vector between the point where  $\mathbf{H}$  is expressed and the integration point on the  $S$  surface of the shell.

For complicated geometries, this equation has, of course, no analytical solution, it is then necessary to discretize it to get a numerical expression. Considering that this surface  $S$  is meshed into  $n$  surface patches with a uniform magnetization  $\mathbf{M}_i$  associated to each of them. Equation (3) becomes:

$$\mathbf{H} = \mathbf{H}_0 + \frac{e_i}{4\pi} \sum_{i=0}^n \nabla \int_s \frac{\mathbf{M}_i \cdot \mathbf{r}}{r^3} dS_i \quad (4)$$

This equation is a vector one and depends linearly from the  $\mathbf{M}_i$  values. Let us remember that the magnetization is tangential to the surface  $S$ . Each patches magnetization has then two degrees of freedom. Therefore, equation (4) can be represented as a system of equations:

$$[\mathbf{H}] = [\mathbf{H}_0] + [\mathbf{A}][\mathbf{M}] \quad (5)$$

where  $\mathbf{H}_0$  and  $\mathbf{H}$  are vectors of 3 components (each component of the inductor and total field),  $\mathbf{A}$  is a  $3 \times 2n$  matrix which represents the interaction linking the sources to the field and  $\mathbf{M}$  is the  $2n$  magnetization vector (2 components per meshed element).

### B. Inverse modeling

Let us now imagine that we want to determine  $\mathbf{M}$  vector (an image of the magnetization of the sheet projected on its mesh). A solution is to place magnetic sensors around the shell to have a measurement of  $\mathbf{H}$  at a given point of the air region. Let us consider that  $m$  tri-axis magnetic sensors are placed around the shell, (3) leads to a Matrix system where  $\mathbf{H}$  is measured,  $\mathbf{H}_0$  is known (the position of the device in the earth's magnetic field is known),  $\mathbf{A}$  is a  $3m \times 2n$  matrix (the coefficient of the matrix can be computed with numerical integration techniques) and  $\mathbf{M}$  is the searched value. To get  $\mathbf{M}$ , we have to solve this system. Unfortunately, this task is not so simple and several aspects can lead to very uneasy resolution process:

*-The system is underdetermined:*

If the shell geometry is complicated and the magnetization has significant local variations, a very fine mesh is needed to accurately represent the real device. However, the number of sensors is often limited, and only few measurement equations are available. Therefore, we are faced with a linear system with fewer equations than unknowns.

*-The system has a poor condition number:*

This mathematical property leads to an unstable solution. In fact, the measurement vector is associated with a non negligible range of noise and a poor condition number will amplify it during the resolution process to give a divergent solution.

This Inverse problem is said to be ill-posed. In order to solve it, [2] proposes to add others equations representative of the magnetic behavior of the shell. In our case, it enables to write  $2n$  additional equations and to add them to the previous system. The dimension of the research space is therefore considerably reduced and a standard single value breakdown,

which returns the solution with the minimal norm generally, succeeds. Let us note that this approach is efficient if sensors are located sufficiently far enough to ensure a global magnetic observation of the whole device. However, in a real naval application, magnetic sensors have to be placed very close to the hull to get a sufficient signal level and to avoid magnetic disturbance. In this configuration, the solution proposed by [2] failed, returning a non satisfying solution. It is then necessary to use additional a-priori information to select the good solution. It is done by combining the conventional approach to a 0-order regularization method as proposed in [4]. This kind of method ensures the stability of the solution and improves the magnetization identification process.

### III. DOUBLE HULL SUBMARINE SPECIFICITIES AND EXPERIMENTAL SET-UP

We focus on the specific double hull submarine structure: the internal hull is dedicated to the pressure effects and the role of the external one has to do with hydrodynamics.

Both hulls are made of ferromagnetic materials. The space, between them, seems to be an interesting location for our magnetic sensors, enabling a good observing position of the sources. Moreover, the internal hull will shield the disturbing magnetic fields created by internal sources (i.e. electrical machines or ferromagnetic sources).

Considering, this shielding effect, internal magnetic sources are not taken into account in our approach which makes it possible to define and use a simpler model or mock-up. In our approach, sensors have to be placed onboard close to the ferromagnetic hull. Due to the proximity of the steel, measurements will not be limited on local magnetization or reaction of the steel. We have to dispose of the overall magnetization.

The project was organized in two parts:

- First, a numerical design and modeling,
- Secondly, an experimental validation.

#### A. Numerical design and modeling

First of all a mock-up with realistic geometry has been defined with the help of DCNS. It is made up of two hulls separated by a 4 cm gap (Fig. 2):

- Internal hull (Thickness: 3mm,  $\varnothing = 30$ cm, Length: 3m),
- External hull (Thickness: 1mm,  $\varnothing = 38$ cm, Length: 3.45m).

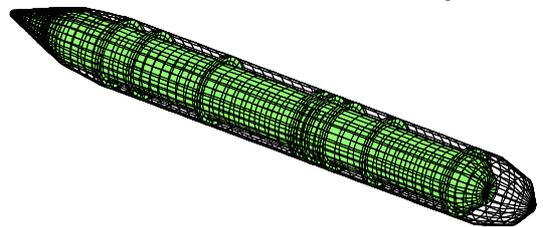


Fig 2: Double Hull Submarine Mock-up.

The first approach led to a numerical design. This step was very important as it made it possible for us:

- To determine the range of magnetic field between the two hulls for different kinds of mock-up magnetization (induced, remanent or induced + remanent).
- To specify the Magnetization behaviour of the submarine.

- To determine the best possible locations for sensors in order to correctly follow evolutions in the submarine magnetization.

Using FLUX [5] as FEM electromagnetic reference software, this step allows us to test and improve our toolboxes based on moment method to solve forward problem. Then, the best sensor positions to extract hulls magnetization were defined. Thus, virtual measurement has been generated and used as input to test inverse problem resolution. This methodology helped us to test and improve the efficiency of the inverse problem algorithm.

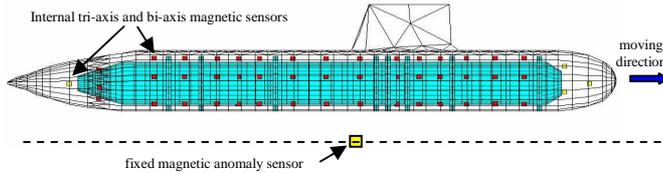


Fig 3: Numerical mock-up of a double hull submarine with the mesh, internal fluxgates sensors (bi-axis in red and tri-axis in yellow) and anomaly measurement line.

A numerical validation has been made. Using a forward problem, an overall hulls magnetization (Fig.4.) can be generated and the signature along a line under the submarine obtained too. Then, virtual measurements will be calculated on dedicated positions.

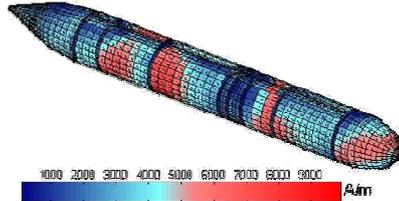


Fig 4: Reference Magnetization for Numerical Validation (forward problem).

Knowing the induced field, from these virtual measurements an inverse problem is solved in order to predict the submarine magnetization (Fig.5.) and its signature (Fig.6.).

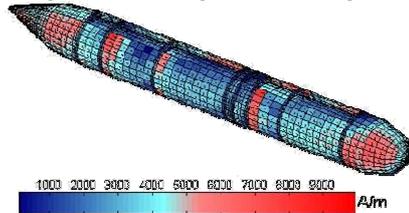


Fig 5: Identified Magnetization obtained by Inverse Problem resolution.

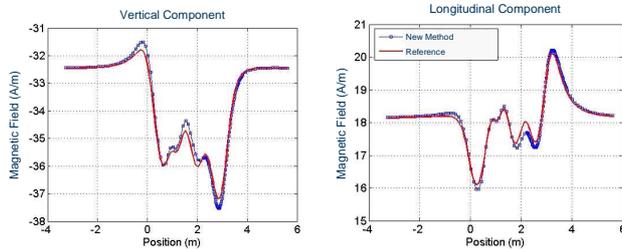


Fig.6: Comparison between reference (forward problem) and CLDG inverse problem signature prediction.

The results shown in figure 6 between the two signatures obtained by forward or identification are a good match.

## B. Experimental Validation

The mock-up has been made by DCNS. This was done taking into account a lot of troubles encountered in observing the required dimension (Fig.7.).



Fig.7: Initial Mock-up

## C. Experimental Setup

**Coils System:** A longitudinal coils system around the internal hull was put up. It is used for the deperring and the polarization. Some of the coils can be used as degaussing coils.



Fig 8: Coils system around the internal hull (between the 2 hulls).

**Sensor's Characterization:** Before the implementation of the sensor on the mock-up, each sensor has been characterized, thus, to verify its specifications (sensitivity, nonlinearity, drifts) and establish a correction matrix.

**Mock-up Set-up:** The submarine mock-up has been placed on a railway in a field simulator in the LMMCF (Low Magnetic Field Facility) [7] (Fig.9). 75 bi-axis and 5 tri-axis fluxgate sensors have been used to instrument the mock-up.

Below the mock-up, another fluxgate sensor has been placed (Fig.9, Fig.10, and Fig.11). By moving the submarine over it, we get a measurement of the magnetic anomaly which can be compared to the predicted one. Then, the accuracy of the inversion process can be evaluated.



Fig 9: Low Magnetic Field Facility.



Fig 10: Sensor Signature



Fig 11: Submarine Mock-up placed on the railway in the LMMCF

The experimental set-up makes it possible to take measurements with an accuracy exceeding a few hundreds of

nanoTeslas. The mock-up has been placed in a realistic magnetic condition with a strong permanent magnetization.

#### D. Experimental Validation

The whole geometry of the mock-up is meshed into more than 4000 surface elements. So, about 8000 unknowns, fully describing the magnetization, have to be determined. From sensors; 165 measurement equations are obtained, the system is then highly under-determined. To reduce the size of the research space, 4000 equations, representative of the intrinsic magnetic material behaviour; are added [2],[5]. However, a physical and acceptable solution is still difficult to obtain. It is therefore necessary to use a 0-order regularization approach to finally get a magnetization distribution which seems to be satisfactory (Fig.12.). From this magnetization distribution, it is possible, by applying a matrix relation similar to (4) to compute a predicted field on a reference line located outside the submarine. As it is shown on figure 13, the predicted and the measured fields show a very good adequacy.

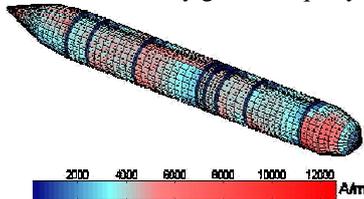


Fig 12: Reconstructed hull magnetization

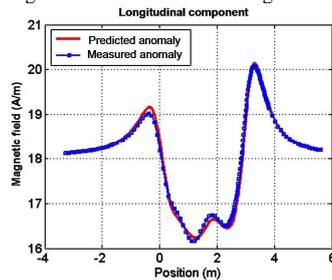


Fig 13: Results of the experimental set-up: Comparison between Measured and predicted signatures.

#### E. CLDG Application on a double hull submarine

To confirm the accuracy of the CLDG and test the efficiency of our algorithm, a simple degaussing system has been built and validated on the double hull submarine. It is made up of 7 longitudinal coils and only 3 vertical coils. For each coil, its effect has been calculated and tested experimentally.

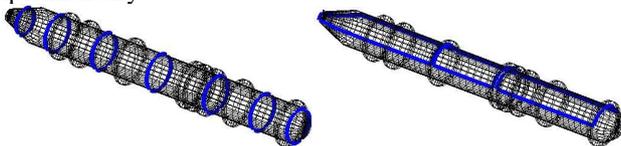


Fig. 14: Basic degaussing Coils Set Up for CLDG. (Long and Vertical)

The submarine has been placed in a realistic magnetic condition. It presents, for the internal hull, a vertical stabilization combined with an athwarship one. Moreover some local anomalies for the internal and the external hull have been added. The whole is placed in an induced longitudinal field.

As §D the magnetization of the submarine is identified and the signature predicted. In order to minimize this anomaly,

degaussing coils are energized. The current through them is adjusted and optimized by a least square algorithm. The mock-up with Active CLDG is verified and results are presented in figure 15.

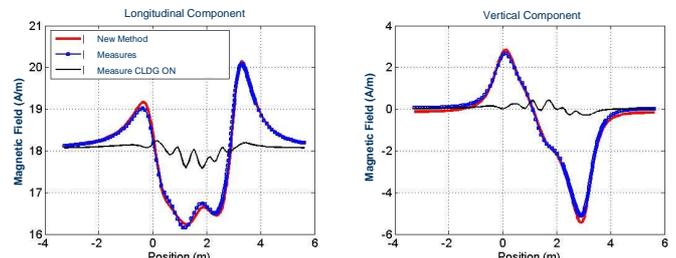


Fig. 15: Results of the experimental set-up (measured, predicted and reduced magnetic fields)

The efficiency of the anomaly reduction is obvious. The initial anomaly is around 4.99 A/m and the compensated system makes it possible to obtain a final anomaly of 0.47 A/m. This is essentially due to the good magnetic behaviour identification. This application confirms previous results and the validity of the CLDG-

#### IV. CONCLUSION

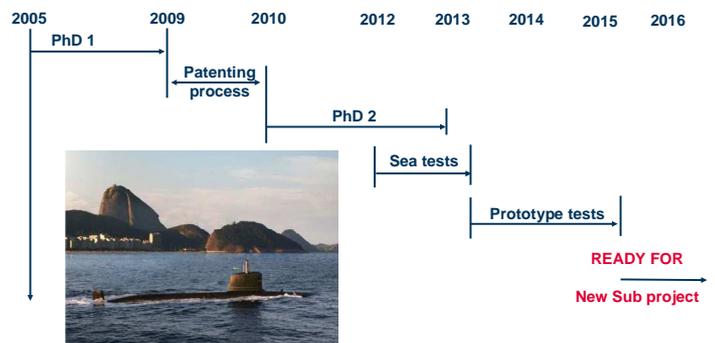
An already known identification method combined with a 0-order regularisation process has been established enabling the determination of unknown magnetization from static near field measurements.

It can be used to determine the magnetic anomaly created by double hull submarine with internal magnetic measurement realized very close to the hull. It has been fully validated on a realistic mock-up of a submarine.

A real Closed Loop Degaussing System has shown its efficiency by reducing the anomaly and minimizing the signature. It is based on a good prediction and identification of the magnetic behaviour of the submarine. Validation on a simple hull submarine has been done too.

The first important step results makes it possible to conduct a second step with a more complex physical mock-up.

Methodology is under process for being patented. DCNS/G2ELAB will shortly begin a three years PhD work in order to improve algorithms robustness and efficiency. And we are now working to offer, in the best conditions, full scale sea trials and prototyping.



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