ANALYSIS OF MODEL ACCURACY AND MAGNETIC SIGNATURE OF A SHIP SCALE MODEL

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The paper describes the analysis of a naval ship permanent magnetization by employing a physical scale model. The experimental setup consists in a shielded room of non-ferromagnetic materials surrounded by a triaxial Helmholtz coil system, an automatic compensation system, and a mobile platform moving horizontally. There were performed several triaxial measurements of magnetic signature, in horizontal planes below the model hull. The paper illustrates the model magnetic field at normal measurement depth. Part of the obtained results were compared to a set of measurements of vertical magnetic signature on the original ship.

1. INTRODUCTION

The issue of reducing the ship magnetic presence in the underwater environment is generated by various types of weapons therein, exploiting the ship’s magnetic signature, particularly the naval mine. Modern magnetic mines incorporate vectorial magnetometers of fluxgate type [1, pp. 64–94; 2, pp. 7–8]. The most important source of ship magnetic signature is given by the magnetization of ferromagnetic steel in the ship’s hull, internal structure, and equipment [1, pp. 127–131]. The magnetic signature is acquired during ship construction – the permanent magnetization, and also during ship operation in the Earth’s magnetic field – induced magnetization. Since measuring the ship’s magnetic signature is extremely laborious and costly, requiring a large number of sensors [3], there can be used instead physical scale models of the respective ship [4, pp. 38–43]. For the analysis of the permanent magnetization of a naval ship, a physical scale model of the vessel was employed [4, pp. 38–42]. The model was constructed at scale 1 : 100 [5, pp. 180–202; 6]. Part of the model measurement results was compared to a set of measurements performed on the ship itself at reference depth[7].

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2. CONSIDERATIONS REGARDING THE SHIP MODEL AND MAGNETIC SIGNATURE

For analysis there was chosen a naval ship, with main dimensions: length \( L = 60 \) m, width \( l = 10 \) m, draft \( T = 3 \) m, height \( D = 5 \) m. The ship hull is built of high strength naval steel, sheet thickness 12 mm, relative magnetic permeability \( \mu_r = 180 \) and electrical conductivity \( \sigma = 4.8 \) MS/m [8, pp. 10]. The scale model in Fig. 1, is made of galvanized steel sheet, thickness 0.4 mm, reproducing the ship hull and superstructure, leaving aside the vessel equipment. The model hull material has relative magnetic permeability \( \mu' = 285 \) and electrical conductivity \( \sigma' = 5.2 \) MS/m [9, pp. 97, 200–208]. The material magnetic permeability is considered constant because the external magnetic field it was exposed to, is low – the local geomagnetic field is approximately 48.000 nT [2, pp. 17–29].

Geometric similarity is ensured by the compliance of body shape and maintaining the ratio between the vessel and model dimensions. In this case, the scaling factor is \( m = 100 \). It is difficult however, to ensure the same ratio for the vessel and model hull thickness. The physical similarity relies on Maxwell's equations in magnetostatic form [4, pp. 5–7]:

\[
\nabla \times \mathbf{H} = \mathbf{J}, \quad (1)
\]

\[
\nabla \cdot \mathbf{B} = 0, \quad (2)
\]

where \( \mathbf{H} \) is the magnetic field strength, \( \mathbf{B} \) is the magnetic induction, \( \mathbf{J} \) is the current density, and \( \nabla \) is the Nabla operator. Achieving physical similarity is difficult, requiring the use of materials with electric and magnetic properties very different from the original system, so as to take into account the proportionality of sheet thickness. Therefore, the chosen model is not an exact reproduction of the ship magnetic behavior, in terms of order of magnitude.

However, it is extremely useful in the analysis of signature variance on its three components, the hull shape playing an important part in developing the signature components. From the practice of magnetic signature measurements, a few considerations on its aspect have emerged [1, pp. 128–131]. The variation form of the ship signature components is described by the number of half-waves.

A half-wave is defined as the signature portion of same polarity. For the vertical component, the number of half-waves \( n_z \) is 2 or 3, depending on the aspect...
ratio of the vessel. It has been established experimentally that the number of half-waves of the longitudinal component, denoted by $n_x$, is larger by 1 than the number of half-waves of the vertical component $n_z$. The number of half-waves of the transverse component $n_y$ is twice the number of half-waves of the vertical component $n_z$.

3. DESCRIPTION OF THE MEASUREMENT INSTALLATION

The measurements occurred in the Laboratory of Bioelectromagnetism within the Faculty of Medical Bioengineering, Iași. The measurement system, illustrated in Fig. 2, consists of a shielded room made entirely of non-ferromagnetic materials, a triaxial Helmholtz coil system surrounding the shielded room, magnetic field automatic compensation and control system, and horizontal platform made of non-ferromagnetic materials [10–11].

![Fig. 2 – Shielded chamber – outside view (left) and measurement set-up inside the shielded chamber (right).](image)

The acquisition system is schematically drawn in Fig. 3 and consists of a triaxial fluxgate magnetometer, an optical encoder, a data acquisition board, LabView software, and a calibrated ruler. The model is fastened to an aluminum beam connected to the mobile platform. The magnetometer is mounted on a transversal wooden beam independent to the mobile platform. The magnetometer is placed in the center of the shielded room and the Helmholtz system, between the mobile platform and the analyzed model.

The Helmholtz coil system is surrounding a cubic volume of side 4 m. The rectangular coils are situated in Helmholtz condition. The field they generate presents non-uniformity of order $10^{-4}$ from the field in the coils center, for a 48 cm distance from the coils center [10, 12].

The mobile system slides on the longitudinal axis Ox, each measurement line on this axis representing a series of points at 1 cm from each other. After the
measurement line is performed, the system is then moved along the Oy axis at fixed distance. Thus there are performed a set of runs on the longitudinal axis, generating a matrix of measurement points [13].

One end of the longitudinal axis was fitted with a fixed optical sensor generating a square wave for each measurement point determined by the ruler. The ruler is graded every centimeter. Gradations consist of black and white areas. The white areas reflect the light infrared emission to a receiver, who is generating a square wave signal of maximum 5 V, used by the acquisition system to trigger measurement. The measurement points are determined by the encoder signal transition from maximum to minimum value. Signal acquisition rate was set at 1000 samples per second, exceeding the rate of change of the magnetometer analog signals. A LabVIEW program allows the simultaneous acquisition on four channels: three analog channels corresponding to the three axes of the magnetometer and a digital channel of the encoder, the latter being used as trigger.

Fig. 3 – Simplified scheme of the model magnetic signature measurement installation.

The model magnetic signature measurements were performed prior to any magnetic treatment, in a local external field of approximately 48.000 nT [2, pp. 17–29]. Through the means of the triaxial Helmholtz coil system and the compensation control system, the Earth’s magnetic field was automatically compensated inside the shielded room [10, 11].

In order to eliminate the effect of local variations of the Earth’s magnetic field, the magnetic measurements were performed in the afternoon, in a period of magnetic calm [14; 15, pp. 351–354].

There was adopted the rectangular coordinate system Oxyz, coinciding with the coordinate system of the model ship hull, as follows:
- the Oy axis coincides with the longitudinal axis of the ship, being oriented towards the bow, therefore coinciding with the heading direction of measurements,
- the Oy axis is oriented towards starboard (on the right side of the measurement heading direction),
- the axis Oz is directed vertically downward.
5. MEASUREMENT RESULTS AND DISCUSSION

The three components of the magnetic signature at the reference depth are illustrated in Fig. 4–6. The results are given in nT. In the longitudinal plane, there are 103 measurement points, numbered upwards from bow to stern. The distance between two consecutive points is 1 cm, covering nearly twice the ship model length. The results describe the permanent magnetic signature components, without any influence from external fields.

Shown in Fig. 4, the longitudinal component \( B_x \) has three half-waves of alternating polarity. The half-waves of positive polarity are located approximately at the fore-aft extremities of the model, with maximum values of approximately 2.61 nT, whereas the half-wave of negative polarity corresponds to the astern part of the model, with the extreme value of 1.24 nT.

The vertical component \( B_z \) has two half-waves of opposite polarity, the positive one is situated in the foremost part of the longitudinal distance, with a maximum of 5.27 nT, while the opposite polarity half-wave is in the second part of the measurement distance, with the extreme value of 2.84 nT.

The aspect of the longitudinal and vertical components comply with the theoretical form of the tangential and the normal component, respectively, of the magnetic dipole, since measurements were performed at a sufficiently high depth from the model ship hull [7]. It is noted that the extreme values are reached in the vicinity of bow - stern extremities of the model.

Since the transversal component \( B_y \) presents symmetry to the longitudinal axis of measurements, with the corresponding ordinate of \( y = 29 \) cm, the following comments will be made only on the transversal component values in one of the half-planes.

The two half-waves of the transversal component have the extreme values lying in the longitudinal plane, near the forward – stern extremities of the model, at transversal distance of about 1–1.5 widths of the model ship, corresponding to the theoretical indications.

Of the three components, the vertical one \( B_z \) is the dominant, reaching values in the range of 2.84 – 5.27 nT, due to the model ship magnetization in the Earth’s magnetic field, which also has as dominant component the vertical one in the geographical area the model ship was constructed [2, pp.17–29]. The longitudinal component \( B_x \) ranges from 1.24 nT to 2.61 nT, while the transversal component \( B_y \) is low, compared to the other two.

Number of half-waves of the vertical, longitudinal and transverse components, are \( n_z = 2 \), \( n_x = 3 \), and \( n_y = 4 \), respectively. This is in full compliance with ship signature aspect considerations [1, pp. 128–130]. This proves that the model ship is viable in terms of magnetic components variation and relative size, although their values are much lower compared to the magnetic signature components of the original system – the actual ship [16].
Fig. 4 – Longitudinal component $B_x$ of the model ship magnetic signature at $z = 7$ cm and representation of the model ship, as reference.

Fig. 5 – Vertical component $B_z$ of the model ship magnetic signature at $z = 7$ cm.

Fig. 6 – Transverse component $B_y$ of the model ship magnetic signature at $z = 7$ cm.
7. COMPARING MAGNETIC SIGNATURES OF THE SHIP AND MODEL

For the original system ship, there is available a set of measurements of the magnetic signature vertical component, under the keel of the ship, at normal measurement depth [7, 16]. The set of measurements is shown in Fig. 7 – the line with triangular markers. The longitudinal plane of the actual ship is represented above the chart, as reference for the measurement points.

Fig. 7 – The vertical component of the magnetic signature of the model and the ship.

The 1 m distances between the ship measuring points next to the ship frames were converted and associated with longitudinal points abscissas from the measurements performed on the model.

The vertical component of the magnetic field strength was measured in mOe, and included the vertical components of the ship permanent and induced magnetization, and the local geomagnetic field, of 410 mOe. The geomagnetic field was then subtracted, and values were converted into subunits of magnetic flux density, resulting the quantity denoted $B_z_{\text{nava}}$, expressed in nT. Measurements of the ship vertical magnetic signature were then normalized, in order to be comparable to the values of the vertical component of the model ship magnetic field – quantity denoted $B_z_{\text{model}}$, represented by the line with square markers in Fig. 7.

There was determined a lower order of magnitude for the model ship magnetic signature, partly determined by lack of similitude in terms of material
properties, and sheet thickness scaling. This large difference is mainly determined by dissimilarity in measurement conditions for the ship and model. For the latter, there was obtained solely the permanent magnetization of the model. In the case of ship vertical magnetic field measurements, the values include both the permanent and the induced magnetization.

![Scatterplot of measurements performed on the actual ship and model.](image)

Fig. 8 – Scatterplot of measurements performed on the actual ship and model.

On the other hand, there appears to be a high correlation between these values. The correlation renders obvious in the scatterplot in Fig. 8. This illustrates the datasets $B_{z\_nava}$ and $B_{z\_model}$, recorded in the corresponding positions $x = 20 \div 66$. The differences between model and ship signature shape can be explained by the existing shipboard installations and equipment generating magnetic field, particularly in the afore part of the ship.

9. CONCLUSIONS

The paper object is an extensive analysis on a scale model of a naval ship. The model was built to a scale of 1:100, respecting the proportionality between the main dimensions, but not including the hull thickness scaling, nor the similitude of material properties. Based on the analysis of permanent magnetization components of the model ship, some conclusions regarding their shape can be drawn. The longitudinal component ($B_x$) has three half-waves, the vertical one ($B_z$) – two half-
waves, and transversal component ($B_y$) presents two half-waves. All these shapes correspond to the theoretical and experimental data regarding the ship's magnetic signature.

The vertical component $B_z$ is dominant, due to prior magnetization in the Earth’s magnetic field, which also has as dominant component the vertical one. The longitudinal component $B_x$ has an order of magnitude two to three times smaller than the vertical one, while the transversal component $B_y$ is low, compared to the first two components. The order of magnitude of the longitudinal component is due to the elongated shape of the hull, which can be approximated with an elongated ellipsoid. The aspect of the magnetic signature components for the scale model fully complies with the general characteristics regarding the ship’s magnetic signature shape and relative order of magnitude of components.

The measurement data of the model signature vertical component was compared to a corresponding set of measurements carried out on the vessel itself. The data sets presented different orders of magnitude, due to dissimilarity in measurement conditions, but in terms of shape, there appeared a high correlation between the two sets of measurements.

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