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ANALITICAL AND PHYSICAL MODELING OF THE NAVAL MAGNETIC SIGNATURE

BY

OCTAVIAN BALTAG[1] and GEORGIANA ROȘU[2,*]

[1]"Alexandru Ioan Cuza" University of Iași,
Faculty of Physics
[2]Military Technical Academy of Bucharest

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Abstract. The paper presents the theoretical and experimental results regarding one of the ship's physical fields: the magnetic signature and its interaction with the Earth's magnetic field. The analytical modeling is based on a simplified model, valid at a certain distance from the ship hull, determined by the ship's own disruptive field value and its temporal evolution caused by ship dynamics in the marine environment. The national theoretical and experimental research stage is presented, and compared to international research. There is described the simplified ellipsoidal shell model, and magnetic signature of an ellipsoidal ferromagnetic layer is computed. The theoretical results are compared to the measurements performed on a real ship modeled through the ellipsoidal shell, and the physical model of the same ship, obtained by applying similarity criteria. There is noticed a good correlation and concordance among magnetic field results obtained through theoretical and experimental models and real ship measurements.

Keywords: ship magnetism; deperming; degaussing.

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[*] Corresponding author; *e-mail*: georgianamarin01@gmail.com

1. Introduction

The naval magnetic signature represents the ship's magnetic field distribution in the underwater environment, characterized by uniqueness and developed mainly by the Earth's magnetic field acting upon the ship's ferromagnetic hull. The ship magnetization can be produced during its construction and also during its exploitation.

The ship magnetization during construction is called permanent magnetization, has relatively constant value, without reaching the saturation of the ferromagnetic masses, is stable in time, and is characteristic to each type of ship. The ship magnetization during exploitation is called induced magnetization, having a variable character, with the magnitude and direction depending also on the ship type.

The permanent magnetism depends upon:

– the ratio between the ship's main dimensions;

– the ship's secondary ferromagnetic masses – their shape, placement, and ferromagnetic properties;

– the ship berth orientation and the geographic latitude of the naval shipyard;

– the ship construction technology.

The induced magnetism depends upon:

– the ratio between the ship's main dimensions: length, width, draft;

– the geographic latitude of the ship position;

– the ship's heading – its direction relative to the meridian;

– the magnetic properties of the materials used in the ship's hull and its secondary equipment, as well as their distribution along the ship.

Knowing these two fields is important, being connected to danger level to which the ship is exposed during exploitation. For this purpose, the ship is subjected to diagnosis operations in specialized naval ranges, in order to determine the ship's magnetic field components and for applying magnetic signature reduction techniques (Baltag 2003, Holmes 2006).

The research of magnetic signature employs both experimental and theoretical methods: experimental techniques for the ship magnetic characterization in magnetic ranges or through physical models, and theoretical methods for modeling and virtual simulation. The magnetic signature modeling initially used simplified analytical models: the dipoles array, magnetic charges, and magnetic moments methods, along with the physical modeling of the ship at a small scale. Common current methods employ dedicated numerical models capable of generating a magnetic signature specific to each type of ship.

Most methods use the finite element technique, due to its flexibility and adaptability to complex geometries of the naval architecture: FEMM, ANSYS, COMSOL, FLUX3D, etc. In order to minimize the surface ships and submarines vulnerability, there have been developed magnetometric techniques for the control of magnetic fields generated by electromagnetic installations and systems onboard the ship, and for those related to static and dynamic signature characteristic to the ferromagnetic hull ship (Roșu, 2015).

2. The Magnetic Field Mathematical Model

According to the classical approach, the ship magnetic field is stationary, thus Maxwell's equations are reduced to the magnetostatic form (Bansal, 2004):

$$\nabla x \overline{H} = 0 \tag{1}$$

$$\nabla \circ \overline{B} = 0 \tag{2}$$

It is considered that the field sources are located on the hull or inside it, and there are not taken into count the circuits with circulating electric currents.

The model closest to reality and the most convenient representation of the ship, is the ellipsoidal shell model (Aird, 2000), in which the ship is approximated by an ellipsoid body bounded inside and outside by two ellipsoidal surfaces, with the major axis along the ellipsoid's symmetry axis, and minor axis perpendicular to it – as represented in Fig. 1. The ellipsoid is laying in magnetic field oriented at a particular angle to the ship's major axis.

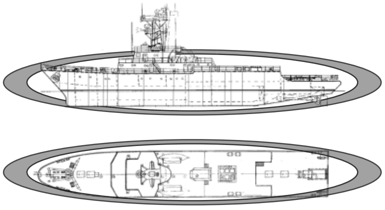

Fig. 1 − The ship representation and its ellipsoidal shell model.

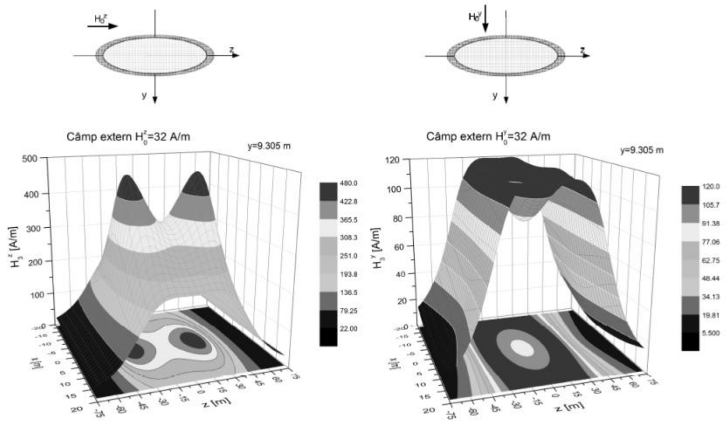

Fig. 2 – The ellipsoidal shell magnetic field distribution, induced by an external field oriented parallel and perpendicular to the ellipsoid's major axis, respectively.

The ship's magnetic field is obtained from the magnetic potential gradient (Roșu, 2015), expressed in ellipsoidal coordinates:

$$\nabla\Phi = \vec{\xi}\frac{1}{c}\sqrt{\frac{\xi^2-1}{\xi^2-\eta^2}}\frac{\partial\Phi}{\partial\xi} + \vec{\eta}\frac{1}{c}\sqrt{\frac{1-\eta^2}{\xi^2-\eta^2}}\frac{\partial\Phi}{\partial\eta} + \vec{\phi}\frac{1}{c}\frac{1}{\sqrt{\left(\xi^2-1\right)\left(1-\eta^2\right)}}\frac{\partial\Phi}{\partial\phi} \tag{3}$$

Fig. 2 describes the magnetic field distribution below the ellipsoidal shell, for an external field of 32 A/m, in two situations. Based on the magnetic field representation, its gradient can be determined. A significantly higher induced magnetic field is obtained for the external field oriented along the major axis of the ellipsoid, as compared to the case of vertical external field, proving that the ellipsoidal geometry tends to magnetize on its major axis.

3. The Physical Scale Model and Magnetic Signature Analysis

Physical scale modeling of ships constitutes a less laborious and less expensive solution for the magnetic characterization of the ship. The study was conducted by respecting the geometrical and physical similarity criteria corrected by factors determined by the magnetic properties of the material used for the simulated ship. There was selected a particular ship for analysis, having the following characteristics: length L = 60 m, width B = 10 m, draft T = 3 m, height D = 5 m. The ship hull is built from high strength naval steel, of 12 mm thickness, relative magnetic permeability μ = 180, and electrical conductivity σ = 4.8 MS/m. The similarity criteria applied to the model refer to geometrical and physical similitude (Kunes, 2012). The geometrical similarity is ensured by following the hull geometry and maintaining constant ratio between the ship and the model main dimensions, according to:

$$\frac{L}{L^{'}} = \frac{B}{B^{'}} = \frac{h_k}{h_k^{'}} = m \tag{4}$$

where h is the depth from the ship keel to the measurement plane, and m denotes the model scaling factor. The two criteria of physical similarity are (Constantinescu, 2010):

$$\Pi_1 = \frac{\sigma_0\mu_0 I_o^2}{T} \tag{5}$$

$$\Pi_2 = \frac{\varepsilon_0}{\sigma_o T} \tag{6}$$

By neglecting the displacement currents, only the first similarity criterion should be ensured. Since the ship's own magnetic field varies slowly in time, it is considered that the magnetic field variation has the same period *T* for both ship and model, and therefore neglected.

Practically, there are two scales for modeling the ship: one scale for the main dimensions, and another for the sheet thickness. If the sheet thickness and the magnetic permeability of the physical scale model are denoted by *d*' and μ', respectively, then their product can be computed through: $d'\mu' = d\mu/m$. The simultaneous fulfillment of two conditions needs to be taken into account, obtained from the first criterion and the condition of proportionality of the thickness and permeability product, thus producing the third similarity criteria:

$$\Pi_3 = \sigma_0 d_0^2 \mu_0^3 \tag{7}$$

This final similarity criterion refers to the proportionality of magnetic properties, main dimensions and sheet thickness of the ship and model, respectively (Roșu, 2014).

4. Comparison of Models to the Real Ship Signature

There was used for comparison a set of magnetic field measurements of the ship for which the scale model was built. The measurements recorded the vertical component of the magnetic signature, below the ship keel, at normal measurement depth, ranging from bow to stern, as represented in Fig. 3. Measurements performed on the vessel Bz_nava were then normalized to be compared with the vertical component values Bz_model, registered under the model keel. The scaling factor used for the ship model 1:100, was also employed for scaling the measurement depth.

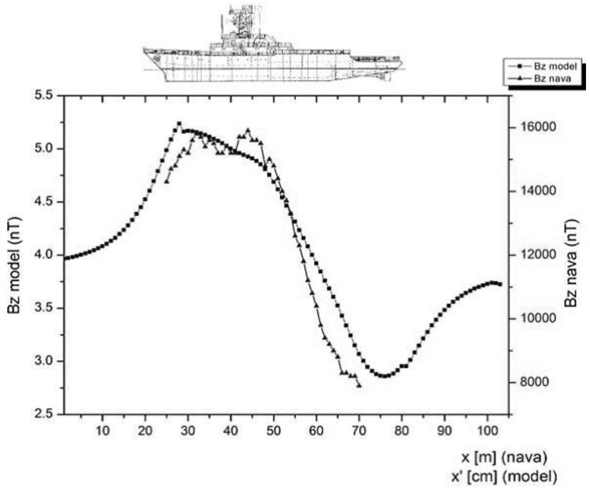

Fig. 3 – The magnetic signature vertical component of the model and the ship, respectively.

There is noticed a high correlation between the values of the vertical magnetic signature of the physical model and that of the ship. Differences can be explained by the presence of installations and equipment generating magnetic field onboard the ship, which was not reproduced in the scale model.

Table 1

Comparison Between the Analytical Model Results - Signature Measurements

Quantity	Ellipsoidal shell model	Real ship
Main dimensions	length: $2a_0$ = 74.4 m width: $2b_0$ = 12.4 m semi-height: b_0 = 6.2 m	L = 60 m, Width: l = 10 m T = 3 m, Depth: D = 5 m
Measurement / Computation depth	$h_{computed}$ = 6.2 m below ellipsoidal shell	$h_{measure}$ = 7 m below ship keel
External field	Vertical field 32 A/m ≈ 400 mOe (Fig. 2 and Fig. 4)	Total geomagnetic field, with dominant vertical component 32 A/m ≈ 400 mOe
Measured / computed values	Total magnetic field	vertical component of the geomagnetic field (40000 nT), plus the ship permanent and induced magnetization
Field values range (external field included)	5.5 A/m … 120 A/m	42,435 nT … 50,439 nT

In Table 1 there are shown for comparative purposes the analytically computed and the measured field values, below the longitudinal axis of the model, and the ship, respectively, at the specified depths.

5. Conclusions

This paper describes the theoretical and experimental research of the naval magnetic signature, performed by using an ellipsoidal shell model and a physical scale model of a particular ship. For the theoretical model of an ellipsoidal shell, there is computed the magnetization induced by an external field oriented parallel with and perpendicular to the main axis of the chosen ellipsoid, thus revealing the dominant effect of the field component oriented parallel to principal axis of the ellipsoid. For the experimental research, a physical model was built to a scale of 1:100, respecting the proportionality between the main dimensions. The data sets measured for both the actual ship and the physical model, presented different orders of magnitude, but in terms of shape, there appeared a high correlation between the two sets of measurements.

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MODELAREA ANALITICĂ ȘI FIZICĂ A AMPRENTEI MAGNETICE NAVALE

(Rezumat)

Lucrarea prezintă rezultatele unui studiu teoretic și experimental privind unul din câmpurile fizice specifice navelor: câmpul magnetic al navei și interacțiunea navei cu câmpul magnetic terestru. În modelarea analitică se folosește un model simplificat, valabil la o distanță de interes față de corpul navei, interes determinat de valoarea câmpului propriu perturbator și evoluția sa temporală determinată de dinamica navei în mediul acvatic. Se prezintă stadiul cercetărilor teoretice și experimentale în plan intern, comparativ cu cele mondiale. Se prezintă modelul de înveliș elipsoidal simplificat al navei și se calculează amprenta magnetică pentru un model de strat feromagnetic elipsoidal. Se constată o bună corelare și concordanța rezultatelor obținute prin modelarea teoretică, experimentală și cele măsurate pe nava reală.