Detection of ferromagnetic objects by using scalar magnetometers

Kazimierz Jakubiuk, Mirosław Wołoszyn
Gdansk University of Technology
80-233 Gdańsk, ul. Narutowicza 11/12, e-mail: {k.jakubiuk, m.woloszyn}@ely.pg.gda.pl

The paper presents the results of the analysis of the possibility of detecting ferromagnetic objects (ships, submarines, mines, etc.) by using two scalar magnetometers. By using two magnetometers of high sensitivity (in the order of magnitude of $pT/Hz^{0,5}$) placed at a distance from each other and operating in a differential system, it is possible to detect ferromagnetic objects from a distance. It is necessary to compensate for the error code to synchronize the work of the two magnetometers. Ferromagnetic object's detection by using two magnetometers requires proper configuration of the devices.

KEYWORDS: magnetic field, magnetization of ferromagnetic object, measurements of magnetic field, scalar magnetometers, detection of ferromagnetic object

1. Introduction

Every object built of ferromagnetic materials which is located in the Earth's magnetic field, disturb the uniformity of this field. Modern optically pumped magnetometers, further referred to as scalar magnetometers, allow to measure the magnetic induction module with the sensitivity of $4\,pT/Hz^{0,5}$[1]. Considering the necessity of compensation while taking measurements of directional error [2] of the magnetometers, the actual sensitivity of the magnetometers installed on the moving platforms amounts to less than 100 pT [3, 4, 5, 6, 7]. This paper presents the results of the analysis of the disturbance of the Earth's magnetic field in relation to the detection of a ferromagnetic object by using two scalar magnetometers operating in a differential configuration.

2. Model of the object's magnetic field

Disturbance in the Earth's magnetic field caused by a ferromagnetic object, further referred to as the object's magnetic field is a complicated function of its shape, dimensions, and orientation in relation to the Earth's magnetic induction vector and magnetic properties of the material of which the object is built. The analysis of the disturbance in the Earth's magnetic field by a ferromagnetic object is a complicated task, which for the actual shapes of the ferromagnetic objects can be performed by using numerical methods.

In case of modelling of the object's magnetic field, it is necessary to make appropriate simplifying assumptions. A submarine of average dimensions was chosen as a ferromagnetic object for the purpose of this study. The analysis of the submarine's magnetic field was performed by finite-element method. The shape of the submarine for mathematical modelling is shown in Fig.1. The chosen submarine is 50 m long and its diameter is 5 m.

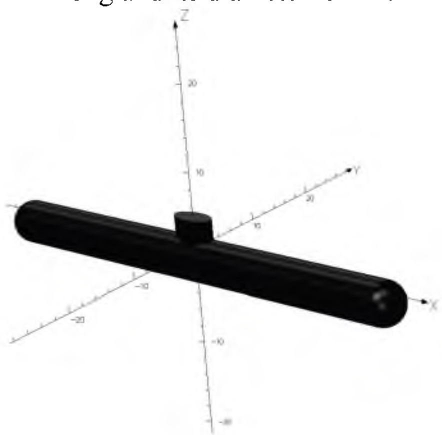


Fig. 1. The shape of a submarine model

Four layers of steel in the hull of the total thickness of 8 mm and relative magnetic permeability of $\mu_w = 200$ (Fig. 2) were introduced. The assumed number of layers results from the need to generate an appropriate number of finite elements in a layer of the submarine hull. The model was placed in an area of the shape of a cuboid of relative magnetic permeability of $\mu_w = 200$. After setting the test parameters of the external magnetic field and appropriate boundary conditions, calculations of the submarine model magnetic field were performed for its various courses by finite-element method in the OPERA 3D package (the number of nodes – 6,4 million, the number of equations – 5,8 million, the estimated error of the calculations < 2%, the time of calculations 5 hours). It was assumed that the submarine hull had only induced magnetization.

Scalar magnetometers are used to measure the magnetic induction module. In the performed analysis of disturbance in the Earth's magnetic field caused by a submarine, it was assumed that the magnetic induction module of this disturbance, later referred to as anomalous magnetic induction of the submarine is calculated using the formula:

$$B_a = |\mathbf{B}_w| - |\mathbf{B}_E| \tag{1}$$

where: $\mathbf{B}_w$ – resultant magnetic induction in the neighbourhood of the object, $\mathbf{B}_E$ - the Earth's magnetic induction , B_a - anomalous magnetic induction of the submarine.

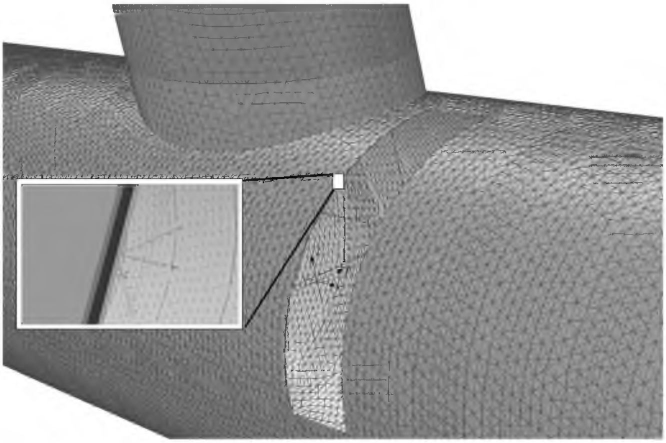


Fig. 2. Layers of a part of the ship hull model

3. Analysis of the object's magnetic field

The analysis of a ferromagnetic object model's magnetic field allows for an appropriate selection of configuration of magnetic sensors in order to guarantee highly effective detection of objects. The distributions of the submarine's magnetic field for its various orientations in relation to the Earth's magnetic induction vector and for various distances between the sensor and the submarine in the vertical axis, result in limitations in the submarine detection range when two magnetic sensors are used. Several chosen examples of the submarine model magnetic field are presented below.

Fig. 3 shows the distribution of anomalous magnetic induction of the submarine model for the course 0° and the distance between the magnetic sensor and the submarine in the vertical axis z_p=100 m, further referred to as measurement depth. For other dimensions of the submarine of proportions retained in relation to the assumed submarine model dimensions, a non-dimensional coefficient k was introduced, which is expressed as the dependence:

$$k = \frac{L_{do}}{L_o} \tag{2}$$

where: L_o – the length of the submarine model used in the analysis, L_{do} – the length of another submarine model.

The so-called measurement depth z_b and non-dimensional distances from the centre of the coordinate system in the horizontal plane x_b and y_b are defined as follows:

$$z_b = \frac{z_p}{L_o} \qquad x_b = \frac{x}{L_o} \qquad y_b = \frac{y}{L_o} \tag{3}$$

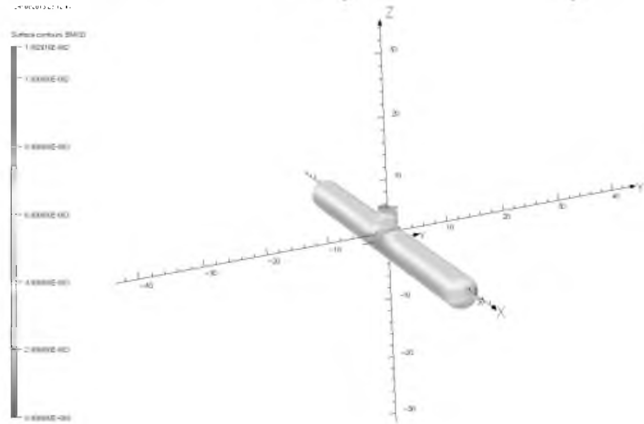
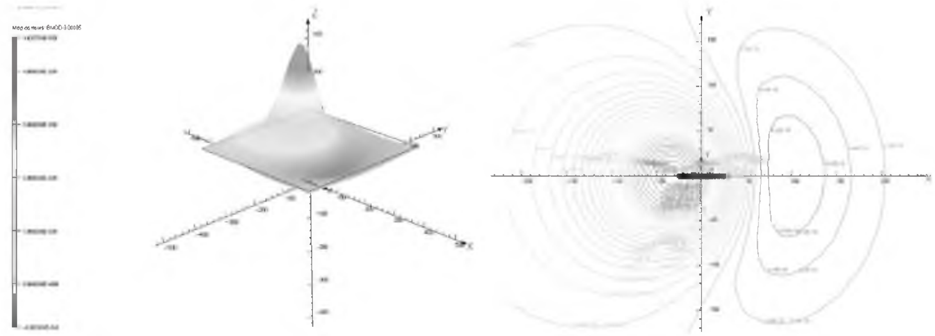


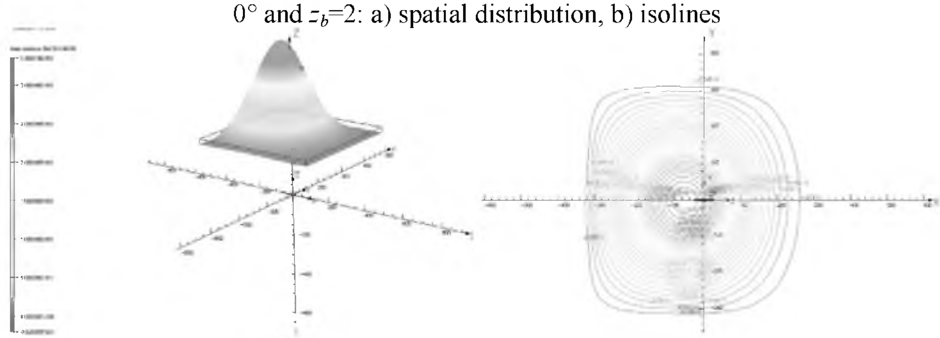
Fig. 3. Distribution of the anomalous magnetic induction module on the submarine model hull surface for the course 0°

For the course 0° the submarine's induced magnetization in the direction of its axis is biggest. The anomalous magnetic induction of the submarine achieves its biggest values for this course. The maximum value of the anomalous magnetic induction of the submarine for this course is about 4.6 nT (for the non-dimensional measurement depth z_b = 2). However, already for the non-dimensional distance y_b = 2 in the submarine's plane the value of the anomalous magnetic induction decreases to about 500 pT (Fig. 4), whereas for the non-dimensional measurement depth z_b = 6 the maximum value the anomalous magnetic induction is only 320 pT (Fig. 5). The spatial distribution of the anomalous induction is more "elongated" in comparison to the distribution for a smaller measurement depth. For y_b = 2 the value of the anomalous magnetic induction is about 240 pT. Therefore, for bigger values of the measurement depth, the changes in the magnetic induction are much smaller. It means that the difference in the Earth's magnetic induction measurement results obtained with the use of two sensors will be smaller too. Fig. 6 shows the distribution of the anomalous magnetic induction for the submarine course 90°. For this course the submarine shows the smallest values of induced magnetization. The value of the maximum anomalous magnetic induction of the submarine for this course is about 4.2 nT. For the measurement depth z_b = 6 the maximum value of the anomalous magnetic induction is about 300 pT. For the remaining submarine model courses, for example 45° and 315°, the values of the anomalous magnetic induction are similar, but have a different spatial distribution, which is a mirror reflection in relation to the coordinate x (Fig. 7 and Fig. 8).



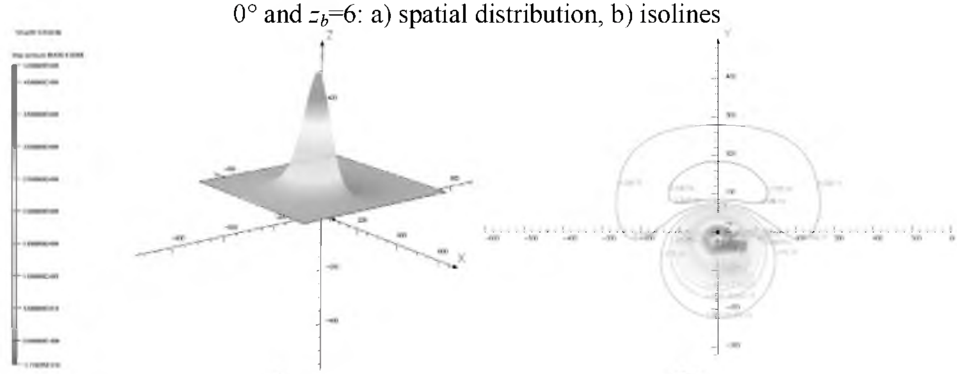
a) b)

Fig. 4. Distribution of anomalous magnetic induction of the submarine for the course 0° and z_b=2: a) spatial distribution, b) isolines



a) b)

Fig. 5. Distributions of anomalous magnetic induction of the submarine for the course 0° and z_b=6: a) spatial distribution, b) isolines



a) b)

Fig. 6. Distributions of anomalous magnetic induction of the submarine for the course 90° and z_b=2: a) spatial distribution, b) isolines

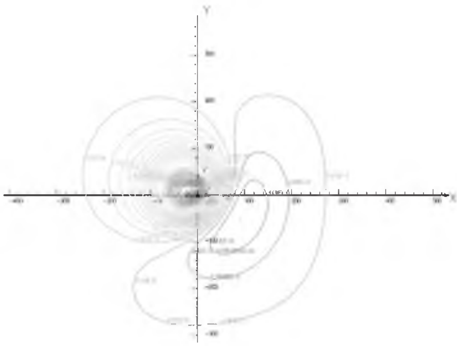


Fig. 7. Distributions of the isolines of the anomalous magnetic induction for the course 45° and z_b=2

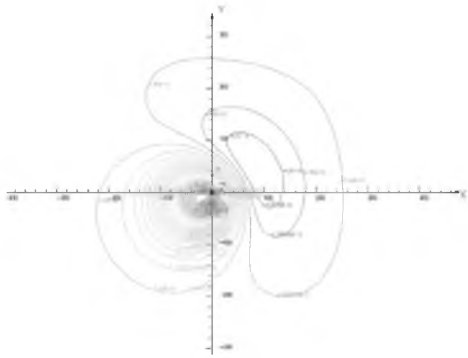


Fig. 8. Distributions of the isolines of the anomalous magnetic induction for the course 315° and z_b=2

4. Configuration of magnetic sensors

Configuration of the magnetic sensors of the magnetometric system should ensure the highest possible sensitivity of measurement. The distance between the sensors cannot be too large due to the risk of non-detecting the object between the sensors nor too small due to the little difference in the magnetic induction module. As a result of the performed distributions' analysis of the anomalous magnetic induction of the submarine model, a conclusion was drawn that the magnetic sensors should move at the same height. The magnetic sensor located higher could not detect the object's presence. There are three possible configurations of the sensors in case when they are located in the same plane (Fig. 9÷11).

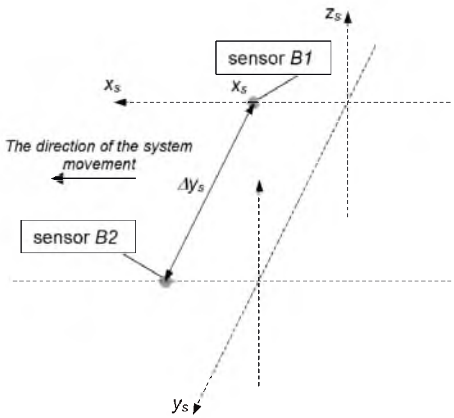


Fig. 9. Configuration of sensors - alternative no. 1

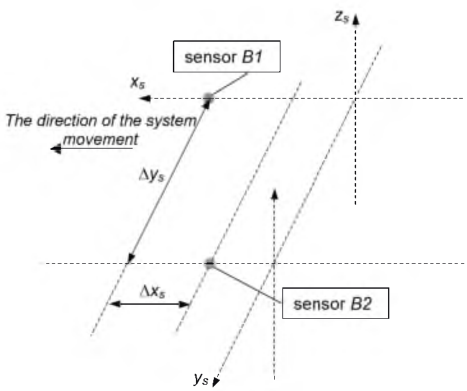


Fig. 10. Configuration of sensors - alternative no. 2

For the assumed coordinates system of helicopters (x_s, y_s, z_s), the distance between the sensors is Δx_s Δy_s. The alternative no. 3. of the magnetic sensors' configuration was rejected as poorly effective due to the limited range of the object detection (narrowed object detection band). Two first alternatives of sensor's configuration were thoroughly analyzed. For both alternatives computer simulations were performed aimed at showing the maximum achievable differences in the measurement results for the magnetic induction module.

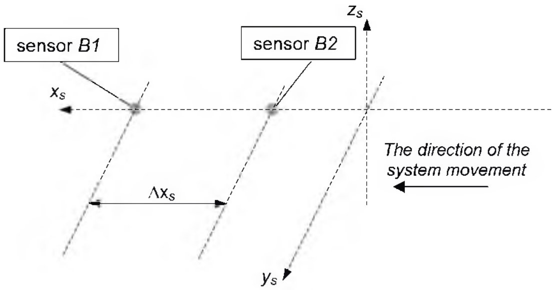


Fig. 11. Configuration of sensors – alternative no. 3

The preformed analysis led to the conclusion that the sensors' configuration as in the alternative no. 1 is not advantageous in terms of ferromagnetic object detection. The reason being that it is likely that the object will be located between the two sensors. In such a particular situation the magnetic sensors can be moved along the straight line which crosses the isolines of the magnetic induction module (the lines of the same value of the magnetic induction module). Fig. 12 presents the example of such a situation for $z_b = 4$.

It can be seen in the Fig. 12 that despite the sensor *B1* moving, for the non-dimensional distance $y_b = 1$ on the right side of the submarine and the sensor *B2* $y_b = 1$ on the left side of the submarine, the difference between the magnetic induction modules is approximately equal to zero (--$\Delta y_{s2} = 2$, --ΔB_2 - Fig. 13). On the basis of the performed numerical analysis of numerous configurations and the positions of the magnetic sensors in relation to the flight directions above the object model, a conclusion was drawn that the configuration as in the alternative no. 2 is most advantageous for an effective detection of submarines.

Taking into consideration various possible submarine's submersion depth and various directions in which the sensors move above the examined area, it can be concluded that unequivocal values of the distances between the sensors Δx_s and Δy_s, for which the measured difference between the magnetic induction modules reaches the largest values, do not exist. The performed analysis led to the conclusion that the non-dimensional distances between the sensors Δx_s and Δy_s should reach the values in the range of $1 \div 3$.

sensors should be included in the range of values 1÷3. The possible ferromagnetic objects' detection range by differential method is $z_b = 6$.

The performed numerical calculations for the selected ferromagnetic object model allow to formulate the following conclusions:

– the maximal values of the anomalous magnetic induction for the non-dimensional measurement depth $z_b > 2$ reach several nT, and for $z_b > 6$ these values amount to 300 pT,
– the values of the anomalous magnetic induction for the non-dimensional measurement depth $z_b > 6$, along the line of the South North direction at the distance equal to the double length of the object are only slightly higher than 100 pT,
– the larger the non-dimensional measurement depth is, the smaller the changes in the anomalous magnetic induction occur. The gradients of the anomalous magnetic induction are, therefore, increasingly smaller,
– for the object model of the dimensions *k* times larger than the ones assumed for the purpose of the performed analysis, the values of the anomalous magnetic induction are the same at the non-dimensional measurement depth *k* times larger.

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