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Stationary Magnetic Field of an Electric Circuit Laid out on the Floatation of a Ship

This paper presents the calculus algorithm of the intensity of the magnetic field for a maritime ship. The following have been analyzed: the magnetic field created by a live oriented right line segment and the magnetic field created by oriented circuit segments positioned across in the floating plane from a ship side to the other. The spreading of the magnetic field has been calculated for a ship with a view to compensate the vertical component of the terrestrial magnetic field.

Keywords: *stationary electromagnetic field, electric circuit, ship de-magnetization, impulse method*

1. Introduction

Main latitude winding (PL), horizontal winding of the ship (OD), horizontal rolling winding (OR – used to compensate the vertical component of the earth's magnetic field and reverse the direction of the ship's field in the process of general degaussing of the ship by pulse method), main adjusting winding (PA dedicated to the compensation of the residual magnetic field after the magnetic processing of the ship) are laid out on the ship' floatations. No matter the winding destination, the ship's floatation is approximated by line segments, each segment being part of the relative winding.[1,2,3,4,5,6,]

In order to conclude the calculation algorithm of the magnetic field intensity, two circuit segments, laid out on floatation, evenly in relation to the sheer plan (PD) of the ship (figure 1).

2. The magnetic field created by the live oriented line segment $\overrightarrow{A_k A_{k+1}}$

The coordinates that define the line segment are:

$$A_k(x_k, y_k, z_k),\ A_{k+1}(x_{k+1}, y_{k+1}, z_{k+1}). \tag{1}$$

According to figure 1, the following vector relations are set:

$$\overrightarrow{OA_k} = x_k\vec{i} + y_k\vec{j} + z_k\vec{k}\ , \tag{2}$$

$$\overrightarrow{OA_{k+1}} = x_{k+1}\vec{i} + y_{k+1}\vec{j} + z_k\vec{k}\ , \tag{3}$$

$$\overrightarrow{OQ} = x\vec{i} + y\vec{j} + z\vec{k}\ , \tag{4}$$

$$\overrightarrow{OP} = \overrightarrow{OA_k} + u(\overrightarrow{OA_{k+1}} - \overrightarrow{OA_k}),\ u \in [0,1], \tag{5}$$

$$\vec{R} = \overrightarrow{OQ} - \overrightarrow{OP}, \tag{6}$$

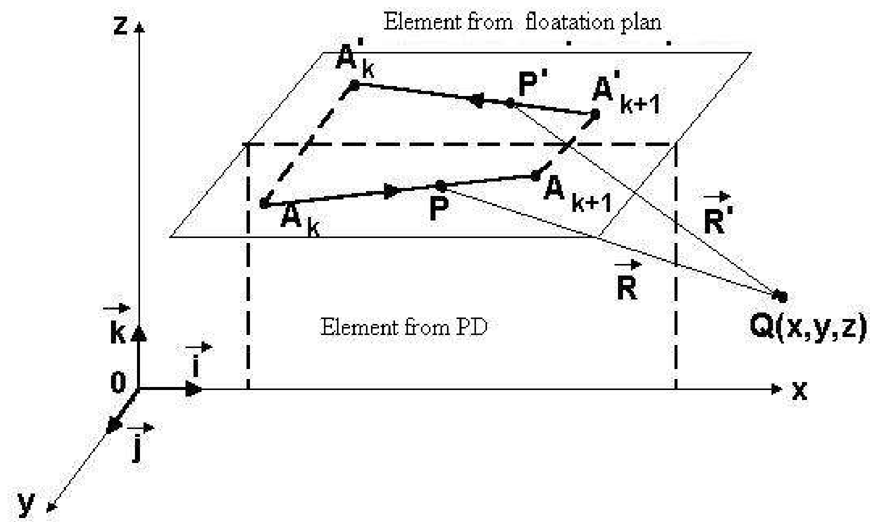

Figure 1. Arrangement of line segment on ship's floatation

In the above relations, z is the depth of the safety plan, and $z_k = z_{k+1}$ is the vertical coordinate of the floatation plan. The coordinate system corresponds to the system in which the lines are designed.[8]

Using the notations:

$$\begin{aligned} \Delta x &= x - x_k\ , \\ \Delta y &= y - y_k\ , \\ \Delta z &= z - z_k\ , \end{aligned} \tag{7}$$

$$\Delta x_k = x_{k+1} - x_k\ ,$$

$$\Delta y_k = y_{k+1} - y_k\ ,$$

it results:

$$\vec{R} = (\Delta x - u\Delta x_k)\vec{i} + (\Delta y - u\Delta y_k)\vec{j} + \Delta z\vec{k} \,, \tag{8}$$

$$R = \sqrt{\alpha u^2 - 2\beta u + \gamma} \,, \tag{9}$$

where:

$$\alpha = (\Delta x_k)^2 + (\Delta y_k)^2 \,, \tag{10}$$

$$\beta = \Delta x \Delta x_k + \Delta y \Delta y_k \,, \tag{11}$$

$$\gamma = (\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2 \,, \tag{12}$$

Elementary vector $\vec{dl}$, as proximity of point *P*, is calculated as it follows:

$$\vec{dl} = d(OP) = (\overrightarrow{OA}_{k+1} - \overrightarrow{OA_k})du = \left(\Delta x_k \vec{i} + \Delta y_k \vec{j}\right)du \,, \tag{13}$$

Having the expressions for $\vec{dl}$ and $\vec{R}$, the cross product is calculated:

$$\vec{dl} \times \vec{R} = \left[-\Delta y_k \Delta z\vec{i} + \Delta x_k \Delta z\vec{j} + (\Delta x \Delta y_k - \Delta x_k \Delta y)\vec{k}\right]du \,, \tag{14}$$

Introducing expressions (9) and (14) in Biot-Savart-Laplace formula and considering the integration limits imposed to parameter *u*, it results:[4,5,7,9]

$$\vec{H}_{k,k+1}(x,y,z) = \frac{I}{4\pi}\int_0^1 \frac{\vec{dl} \times \vec{R}}{\sqrt{\left(\alpha u^2 - 2\beta u + \gamma\right)^3}} \,, \tag{15}$$

and respectively:

$$\vec{H}_{k,k+1}(x,y,z) = \frac{I}{4\pi}\left[-\Delta y_k \Delta z\vec{i} + \Delta x_k \Delta z\vec{j} + (\Delta x \Delta y_k - \Delta x_k \Delta y)\vec{k}\right] \cdot$$

$$\cdot \frac{1}{\alpha\gamma - \beta^2}\left(\frac{\alpha - \beta}{\sqrt{\alpha - 2\beta + \gamma}} + \frac{\beta}{\sqrt{\gamma}}\right) =$$

$$= \vec{i} H_{x,k,k+1}(x,y,z) + \vec{j} H_{y,k,k+1}(x,y,z) + \vec{k} H_{z,k,k+1}(x,y,z) \,. \tag{16}$$

3. The magnetic field created by the oriented line segment $\overrightarrow{A'_{k+1}A'_k}$

The points coordinates that define the circuit segment are: $A'_k(x_k, -y_k, z_k)$, $A'_{k+1}(x_{k+1}, -y_{k+1}, z_k)$.

Corresponding to the figure 1, the following relations are established:

$$\overrightarrow{OA'_k} = x_k\vec{i} - y_k\vec{j} + z_k\vec{k} \,, \tag{17}$$

$$\overrightarrow{OA'_{k+1}} = x_{k+1}\vec{i} - y_{k+1}\vec{j} + z_k\vec{k} \,, \tag{18}$$

$$\overrightarrow{OP'} = \overrightarrow{OA'_k} - u(\overrightarrow{OA'_k} - \overrightarrow{OA'_{k+1}}), \quad u \in [0,1], \tag{19}$$

$$\overrightarrow{R'} = \overrightarrow{OQ} - \overrightarrow{OP'} . \quad (20)$$

With notations set up by relation (7), the expression of the intensity of the magnetic field created by the oriented circuit segment is:

$$\vec{H}_{k+1,k}(x,y,z) = \frac{I}{4\pi}\left[\Delta y_k \Delta z \vec{i} + \Delta x_k \Delta z \vec{j} - (\Delta x \Delta y_k + \Delta x_k \Delta y + 2\Delta x_k y_k)\vec{k}\right] \cdot$$

$$\cdot \frac{1}{\alpha'\gamma' - (\beta')^2}\left[-\frac{\alpha' - \beta'}{\left(\alpha' - 2\beta' + \gamma'\right)^{1/2}} - \frac{\beta'}{\left(\gamma'\right)^{1/2}}\right], \quad (21)$$

where:

$$\begin{aligned} \alpha' &= (\Delta x_k)^2 + (\Delta y_k)^2 = \alpha; \\ \beta' &= \beta - 2\Delta y \Delta y_k - 2 y_k \Delta y_k ; \\ \gamma' &= \gamma + 4 y_k^2 + 4 y_k \Delta y. \end{aligned} \quad (22)$$

In relation (22) the magnetic field intensity components can be highlighted in relation to the coordinate's axis:

$$\vec{H}_{k+1,k}(x,y,z) = \vec{i} H_{x,k+1,k}(x,y,z) + \\ + \vec{j} H_{y,k+1,k}(x,y,z) + \vec{k} H_{z,k+1,k}(x,y,z), \quad (23)$$

$$\vec{H}_{x,k+1,k}(x,y,z) = \frac{I}{4\pi} \cdot \frac{\Delta y_k \Delta z}{\alpha'\gamma' - (\beta')^2}\left[-\frac{\alpha' - \beta'}{\left(\alpha' - 2\beta' + \gamma'\right)^{1/2}} - \frac{\beta'}{\left(\gamma'\right)^{1/2}}\right],$$

$$\vec{H}_{y,k+1,k}(x,y,z) = \frac{I}{4\pi} \cdot \frac{\Delta x_k \Delta z}{\alpha'\gamma' - (\beta')^2}\left[-\frac{\alpha' - \beta'}{\left(\alpha' - 2\beta' + \gamma'\right)^{1/2}} - \frac{\beta'}{\left(\gamma'\right)^{1/2}}\right],$$

$$\vec{H}_{z,k+1,k}(x,y,z) = \frac{I}{4\pi} \cdot \frac{-(\Delta x \Delta y_k + \Delta x_k \Delta y + 2\Delta x_k y_k)}{\alpha'\gamma' - (\beta')^2}$$

$$\left[-\frac{\alpha' - \beta'}{\left(\alpha' - 2\beta' + \gamma'\right)^{1/2}} - \frac{\beta'}{\left(\gamma'\right)^{1/2}}\right].$$

For example, the line segments defined by the points having the following coordinates have been chosen:

$A'_{10}(0, 4.888, 3.432)$, $A'_{11}(3.879, 4.888, 3.432)$,

$A'_{10}(0, -4.888, 3.432)$, $A'_{11}(3.879, -4.888, 3.432)$.

The points coordinates that define the line segments that approximated this floatation, in the starboard, are presented in Table 1.

Table 1

Point	x(m)	y(m)	z(m)	Point	x(m)	y(m)	z(m)
A_0	-38,79	2,55	3,432	A_{11}	3,879	4,88	3,432
A_1	-34,911	3,50	3,432	A_{12}	7,758	4,65	3,432
A_2	-31,032	4,05	3,432	A_{13}	11,637	4,40	3,432
A_3	-27,153	4,40	3,432	A_{14}	15,516	3,95	3,432
A_4	-23,274	4,70	3,432	A_{15}	19,395	3,37	3,432
A_5	-19,395	4,88	3,432	A_{16}	23,274	2,80	3,432
A_6	-15,516	4,88	3,432	A_{17}	27,153	2,45	3,432
A_7	-11,637	4,88	3,432	A_{18}	31,032	1,20	3,432
A_8	-7,758	4,88	3,432	A_{19}	34,911	0,35	3,432
A_9	-3,879	4,88	3,432	A_{20}	38,79	0	3,432
A_{10}	0	4,88	3,432	-	-	-	-

In figure 2 is presented the 3D chart of the coordinate function distribution $h_z(x,y,z) = h_{z,10,11}(x,y,z) + h_{z,11,10}(x,y,z)$ in the measurement plan (z =-4,3888m), and in figure 3, the 3D chart of function $h_y(x,y,z) = h_{y,10,11}(x,y,z) + h_{y,11,10}(x,y,z)$ in the same plan.

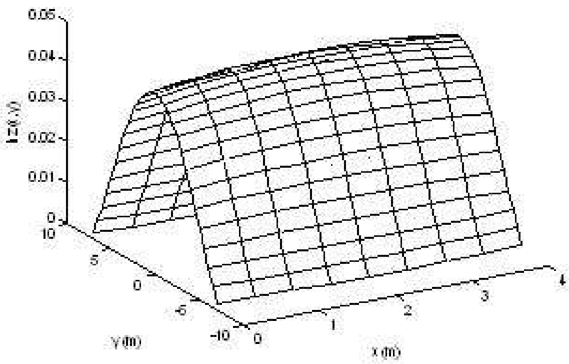

Figure 2.

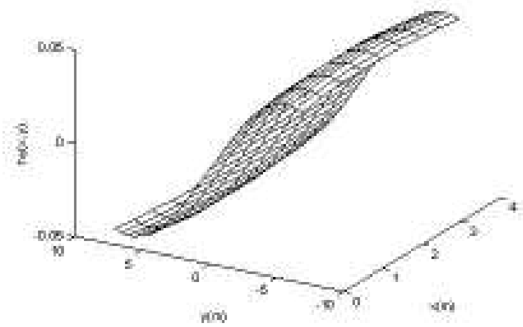

Figure 3.

4. The magnetic field created by oriented circuit segments laid out thwart ships in the floatation plan, from side to side

The points coordinates that define the oriented line segment $\overrightarrow{A_k A_k^{'}}$ are:

$$A_k(x_k, y_k, z_k),\ \ A_k^{'}(x_k, -y_k, z_k). \tag{24}$$

Acting like in previous cases, for the intensity of the magnetic field created by the oriented $\overrightarrow{A_k A_k^{'}}$ the following relation is obtained:

$$\vec{H}_{k,k'}(x,y,z)=\frac{I}{4\pi}\left(2y_k\Delta z\vec{i}-2y_k\Delta x\vec{k}\right)\frac{1}{ac-b^2}\left(\frac{a+b}{\sqrt{a+2b+c}}-\frac{b}{\sqrt{c}}\right) \quad (25)$$

where:

$$a=4y_k^2\ ;\ b=2\Delta y\Delta y_k\ ;\ c=(\Delta x)^2+(\Delta y)^2+(\Delta z)^2, \quad (26)$$

and Δx, Δy, Δz, Δy_k have the same meaning as in (27).

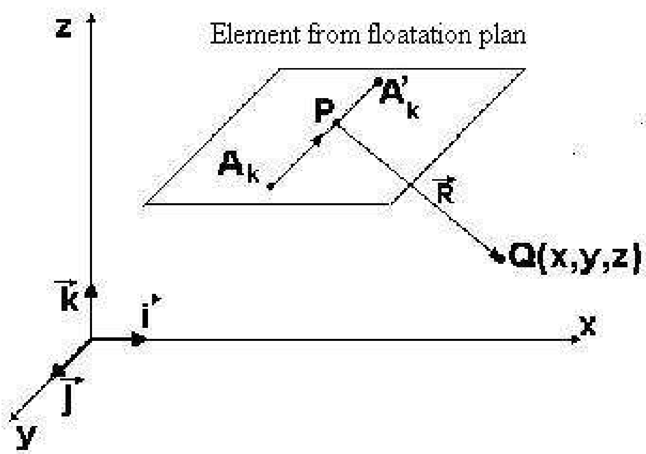

Figure 4. Transversal circuit segment in the floatation plan

For each segment, the components of the magnetic field intensity can be expressed so that the terms in the right member exclusively represent functions of coordinates:

$$\frac{H_{m,k,k+1}4\pi}{I}=h_{m,k,k+1}(x,y,z),\quad m=x,y,z,$$

$$\frac{H_{m,k+1,k}4\pi}{I}=h_{m,k+1,k}(x,y,z),\quad m=x,y,z, \quad (27)$$

$$\frac{H_{m,k,k'}4\pi}{I}=h_{m,k,k'}(x,y,z),\quad m=x,z\ ,$$

and, respectively, for the considered floatation:

$$\frac{H_x\cdot 4\pi}{I}=h_x(x,y,z), \quad (28)$$

$$\frac{H_y \cdot 4\pi}{I} = h_y(x, y, z), \qquad (29)$$

$$\frac{H_z \cdot 4\pi}{I} = h_z(x, y, z), \qquad (30)$$

where:

$$h_x(x, y, z) = \sum_{\kappa=1}^{p-1} \left[h_{x,\kappa,\kappa+1}(x, y, z) + h_{x,\kappa+1,\kappa}(x, y, z) \right], \qquad (31)$$

$$h_y(x, y, z) = \sum_{\kappa=1}^{p-1} \left[h_{y,\kappa,\kappa+1}(x, y, z) + h_{y,\kappa+1,\kappa}(x, y, z) \right], \qquad (32)$$

$$h_z(x, y, z) = \sum_{\kappa=1}^{p-1} \left[h_{z,\kappa,\kappa+1}(x, y, z) + h_{z,\kappa+1,\kappa}(x, y, z) \right]. \qquad (33)$$

Figure 5 represents the 3D chart of field $h_z(x,y,z)$. It can be noticed that the field distribution presents a high uniformity rate in order to compensate the vertical component of the terrestrial magnetic field.

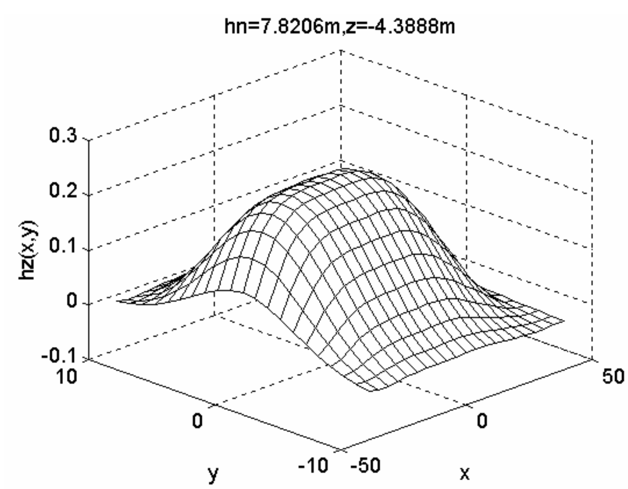

Figure 5. The $h_z(x,y,z)$ field distribution in the measurement plan for the winding laid out on the ship's floatation

5. Conclusion

For the considered ship having Δ_m=1240 dwt, L_{CWL}=77,584 m, B_{max}=9,776 m, T=3,432 m, D=5,408 m, z_k=3,432m and z=-4,3888m (measurement depth in relation to ship's keel), the vertical component of the magnetic field intensity has been calculated, expressed as a coordinate function, for the case in which the ship has a single winding laid out on the floatation above the waterline with 0,1B_{max}. This kind of winding is used as a horizontal rolling winding (general degaussing of the ship by pulse method).For this ship, the number of stations is n=20, and the distance between two consecutive station plans is λ_x =3,879 m. According to the lines, for the distance λ_x the floatation was approximated by 20 line segments, in each board

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