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Model of the relationship of residual magnetization and the elastic stress of ship's hulls during cargo and ballast operations

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Summary. The mathematical model of the relationship of residual magnetization and the acting elastic stresses of ship's hulls during cargo and ballast operations is determined. The validation of adequacy of the approximating model by Fisher criterion and the experimental check of adequacy approximating model are carried out.

Key words. The mathematical model, the residual magnetization, the elastic stresses, ship's hull.

INTRODUCTION

Cargo and ballast operations on the dry cargo ship has always belonged to the category of the most demanding. Typically, a long-term effect of constantly changing the mechanical elastic stresses accompany to the maintenance of the ship's hull. The nature and values of this stresses vary and depend on sailing conditions, correct loading and unloading, ballasting and deballasting of ship and other factors [20]. In some negative cases, individual components of the ship's hull are overloaded. Because of this, there are risks of occurrence of excessive permanent deformation and local destruction, which in turn can lead to an accident – disruption or loss of the general hull strength. Therefore, today the control of the ship's hulls during cargo and ballast operations in conditions of uncertainty as to the actual (instantaneous) state of the ship's hull remains topical, which would apply principally new methods of control, taking into account all the features of operation of bulk carriers.

ANALYSIS OF PUBLICATIONS

The research in [1, 3, 8, 9, 17] show that to estimate the elastic stresses are widely used magnetic methods of non-destructive testing (NDT), which are based on the relationship of the magnetic and mechanical properties of ferromagnetic materials. Among these magnetic values are: initial χ_a and reversible χ_r magnetic susceptibility, coercive force H_c, magneto-elastic increase of magnetization $\Delta M_\sigma(H_i, \sigma_0)$ (H_i – the internal magnetic field), residual magnetization M_r.

Made analysis of literary sources allows to state that most of the control methods of elastic stresses are special occasions (the construction made of a particular grade of steel with specific structural and magnetic state). At the same time, applying the mentioned methods, it is difficult to determine the sign of acting elastic stresses in ferromagnetic structures, so they could not get wide distribution in practice.

However, an exception is the ability to estimate the elastic stresses on the value of residual magnetization, that is connected with a very large range of changes M_r during the transition from tension to compression [3].

THE PURPOSE OF ARTICLE

Get the adequate mathematical model of the relationship of residual magnetization and the acting elastic stresses in the ship's hulls during cargo and ballast operations.

MATERIALS AND RESEARCH RESULTS

A special interest is the determination of the relationship residual magnetization and the mechanical stresses in structural steels, which including used for the manufacture of ship's hulls. The relatively low carbon content not exceeding usually 0.3-0.4% and a low content of alloying elements is characteristic for this type of steel (St3S, 09G2S, 10ChsND etc).

1. Approximation of the dependence of the residual magnetization of mechanical stresses in ferromagnetic steel constructions. During the carried out analysis of magnetic characteristics shown that in magnetic method of NDT magnetic parameter such as residual magnetization essentially depends on the elastic compression and tensile stresses. The experimental results of measurements of the values of plastic deformations ε and true stresses $\sigma_{true} = F/S$ (where F – the load, S – cross-sectional area of the sample at a given value ε) during modes «slow» and «fast» loading on samples of steel St3S are obtained in research work [10]. The value M_r is measured by the ballistic method, while the residual magnetization measurement error was 3%. On the Fig. 1 it is shows the experimentally the obtained dependence [10] the residual magnetization M_r of the tensile and compressive stresses in the elastic diapason: $-\sigma_T \le \sigma \le \sigma_T$.

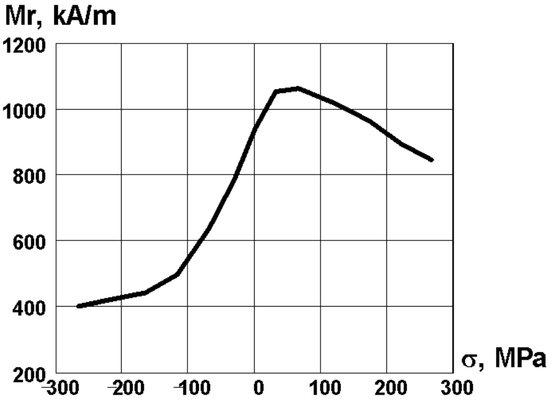
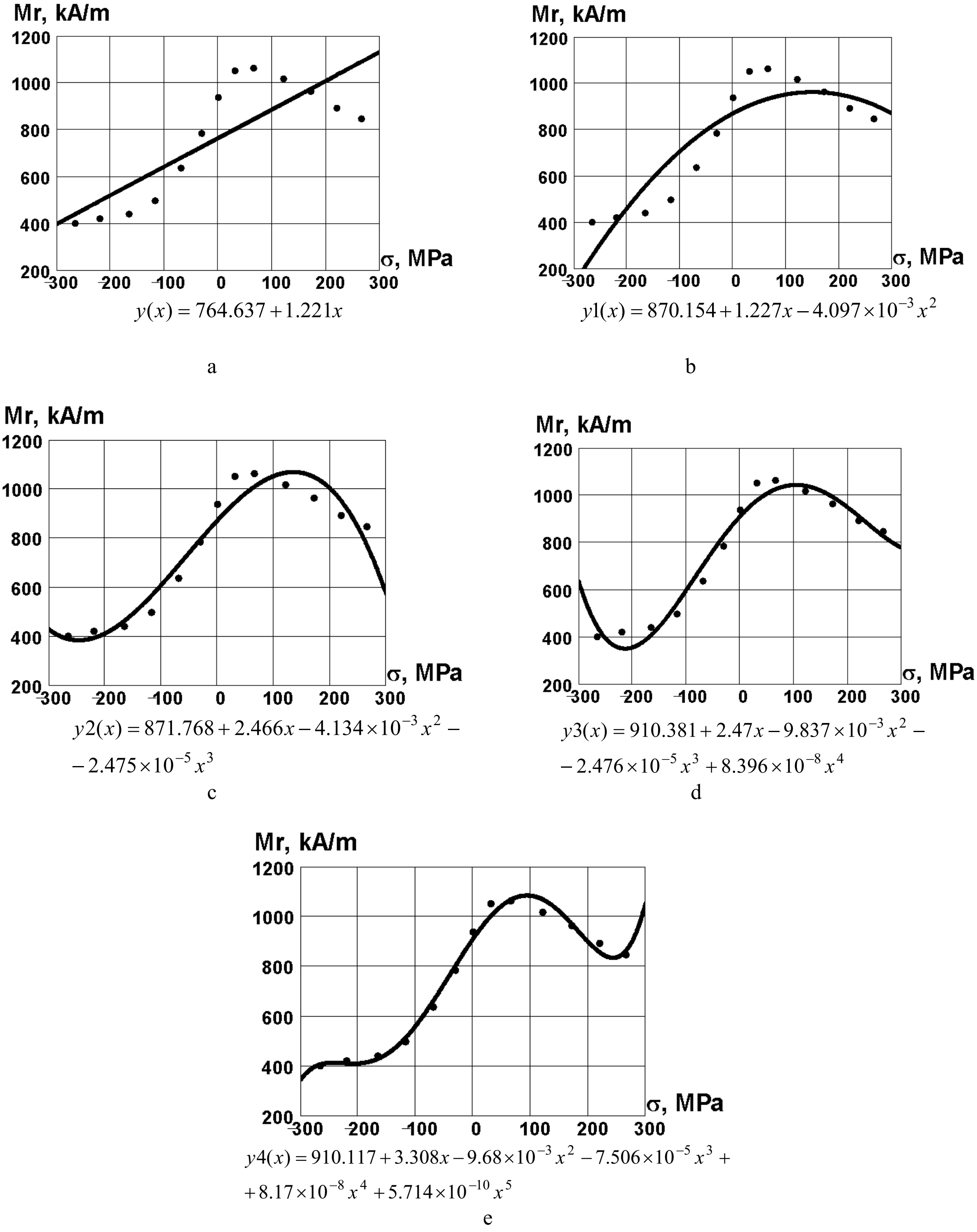


Fig. 1. The residual magnetization – tensile and compressive stresses relation in the elastic diapason: $-\sigma_T \le \sigma \le \sigma_T$ for steel St3S

The experiment was carried out on samples of steel St3S after annealing at 650 ºC for 2 hours duration (cooling oven) in order to eliminate differences in the initial crystallographic and magnetic structures. By its nature, the shown relations (Fig. 1) is exactly the same as the dependencies for a large number of ferromagnetic steel (40H, 30HGSA etc.) in other research work [8-10]. The difference from each other is only in the numerical data.

At the same time dependence shows an extremely large diapason of changes M_r during the transition from tension to compression: $M_r(+\sigma) - M_r(-\sigma) \approx 450\ kA/m$, that once again confirms the effectiveness of application of function $M_r(\sigma)$ to the NDT stresses in ferromagnetic steel structures.

The experimentally obtained the residual magnetization M_r - tensile and compressive stresses relation for steel St3S [10] is approximated by a linear dependence, as well as polynomials of the second, third, fourth and fifth degree. One of the most effective way of approximating the specified models is the application of the program Mathcad 11 with using polynomial regression function: *«regress»*. The obtained graphics and the corresponding regression equation of mentioned approximating models are shown in Fig. 2.



$y(x) = 764.637 + 1.221x$

a

$y1(x) = 870.154 + 1.227x - 4.097\times10^{-3}x^2$

b

$y2(x) = 871.768 + 2.466x - 4.134\times10^{-3}x^2 - 2.475\times10^{-5}x^3$

c

$y3(x) = 910.381 + 2.47x - 9.837\times10^{-3}x^2 - 2.476\times10^{-5}x^3 + 8.396\times10^{-8}x^4$

d

$y4(x) = 910.117 + 3.308x - 9.68\times10^{-3}x^2 - 7.506\times10^{-5}x^3 + 8.17\times10^{-8}x^4 + 5.714\times10^{-10}x^5$

e

Fig. 2. Graphics of approximation of the dependence of residual magnetization M_r of the tensile and compressive stresses in the elastic diapason: $-\sigma_T \le \sigma \le \sigma_T$ for steel St3S: a – a linear relationship, b – the second degree polynomial, c – the third-degree polynomial, d – the fourth degree polynomial, e – the fifth degree polynomial

Relying on the results of the foregoing analysis of residual magnetization - tensile and compressive stresses relation is justified to take that as a kind of mathematical model for approximating function is the most appropriate model of a third-order polynomial.

2. Construction of a mathematical model of the relationship of residual magnetization and elastic stresses in ferromagnetic steel *construction.* The obtained above approximating dependence $f = M_r(\sigma)$ makes sense in case of change only of acting in the ferromagnetic structure (ship's hull) elastic stresses. In reality, the situation is somewhat different. The experimental measurements were carried out on the researched vessel at various points on the surface of the horizontal plate of hatch coaming as the upper plane of equivalent girder [12]. Here solid coaming of cargo holds (Fig. 3) is one of the most important carrying longitudinal connections and is therefore used as a control object of elastic stresses in the ship's hull during cargo and ballast operations.

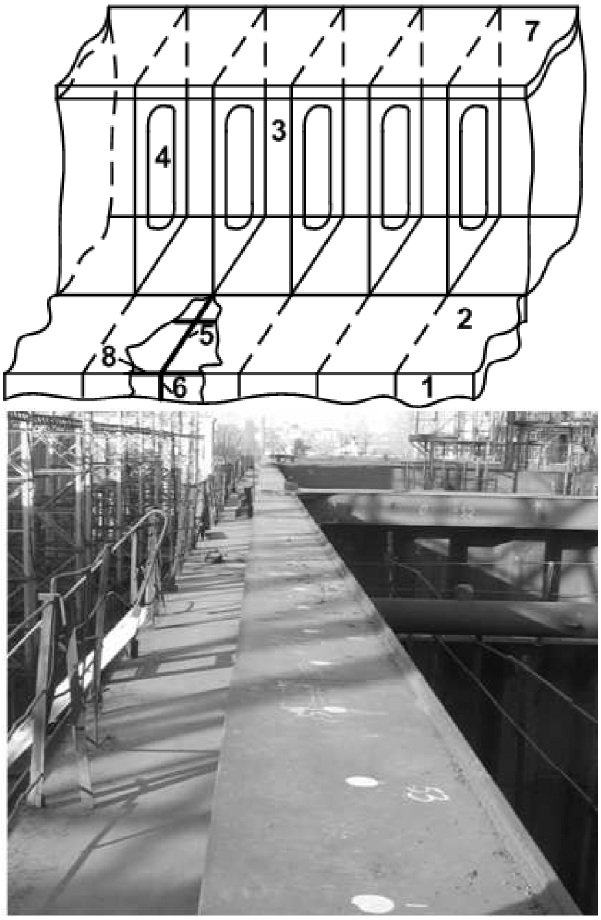


Fig. 3. Hatch coaming: 1 – ship's side (sheer-strake), 2 – deck plate, 3 – hatch coaming, 4 – coaming stay, 5 – beam, 6 – frame, 7 – coaming's horizontal plate, 8 – deck stringer

Therefore, in practice, in the course of the measurements, it was found that the obtained values of the residual magnetization depend on many different factors: the elastic stresses in ferromagnetic steel construction (ship's hull) during its operation (σ), size of the gap between the controlled surface of the coaming and transmitter (δ), the coercive force of material of coaming (H_c), which in the course of the experiment was measured previously by coercimeter, the normal and tangential vector component of the magnetic field strength of Earth, depending on the spatial orientation of the ship's hull (H_r, H_x), the geometric dimensions of the field of control in view of the edge effect (a, b, c) (Fig. 4).

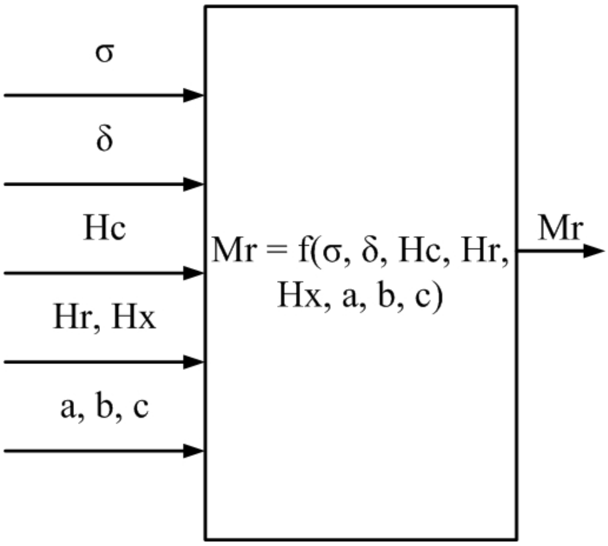


Fig. 4. The structure of the system of mathematical model of residual magnetization relation M_r.

The approximating model of the relationship of the residual magnetization and the considered above parameters was obtained by the mathematical theory of experimental design [2, 4, 6]. The effectiveness of the method experimental design is that it allows to build a approximating model of a certain value in the form of a polynomial of n-th order depending on a number of arguments – the factors on the basis of data obtained by carrying out experiments in a given set of points. Furthermore, based on the obtained by the method experimental design function, it is possible to evaluate the effect of each factor on the test parameter value, in this case – the residual magnetization.

All set basic requirements, according to the method of experimental design for the response function (M_r) and the factors discussed above are satisfied in full. That is, the create of a mathematical model approximating dependence of residual magnetization of the influencing factors in the form of a second order polynomial based on the theory experimental design is hypothetically possible.

In such a way, it is required to establish the relationship of residual magnetization and the three selected on the basis of a priori information the most important factors: the elastic stresses in the structure σ, the coercive force of the material of the coaming H_c and the gap size between the coaming and transmitter δ.

Relationship $M_r(\sigma, H_c, \delta)$ can be approximated by a polynomial of the second degree. The experiment was carried out on the program planning of the central composite rotatable the second order [4, 6]. Planning is called a rotatable [2], if it is invariant to rotation of the coordinate system. It means that the information contained in the regression equation to be equally distributed over the hypersphere. When planning is rotatable the predicted values of optimization parameter have a minimum dispersion in a different points of the factor space, that is determined with minimal errors in all directions at the same distance from the center plane.

The main advantage of rotatable plan is to ensure the same accuracy of predicted value in all directions at the same distance from the center of the plan.

The intervals variation and natural levels of: the elastic stresses σ and the coercive force H_c are taken in accordance with relevant mechanical and magnetic characteristics of the material coaming ship's hull [15], as well as on the basis of experimental data [10]. But varying intervals and natural levels of the gap size between the coaming and transmitter have been determined taking into account the coaming surface unevenness (roughness, rust, etc.).

Selected in the research the levels and intervals varying factors are listed in a Table 1, in which the following notation: 0 – ground level, 1 – upper level, -1 – lower level, 1.682 – maximum value, -1.682 – the minimum value of the independent variable.

Table 1. Calculated planning matrix

Factors	Code designation	The varying intervals	Natural levels of factors corresponding to coded factors				
			+1.682	+1	0	-1	-1.682
σ, MPa	x_1	210	265	210	0	-210	-265
H_c, kA/m	x_2	0.15	0.68	0.6	0.45	0.3	0.29
δ, m	x_3	$0.75\times\times10^{-3}$	$3.5\times\times10^{-3}$	$3\times\times10^{3}$	2.25×10^{-3}	$1.5\times\times10^{-3}$	$1\times\times10^{-3}$

Compiled the central composite rotatable the second order plan for the three factors consists of the full factorial experiment plan of type 2^3, the six experiments in the «star points» and the six experiments in the center of the plan.

Based on the results of experiments carried out in accordance with the plan of the experiment it can be estimated the coefficients of the regression equation of the form:

$$\begin{aligned} y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + \\ + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2. \end{aligned} \quad (1)$$

Using the formulas [2, 4, 6], coefficients of the regression equation were determined: $b_0 = 772{,}37$, $b_1 = 99{,}82$, $b_2 = -101{,}1$, $b_3 = 43{,}02$, $b_{12} = 17{,}16$, $b_{13} = 0{,}48$, $b_{23} = -45{,}07$, $b_{11} = -69{,}88$, $b_{22} = 9{,}59$, $b_{33} = -18{,}1$.

The obtained regression equation is of the form:

$$\begin{aligned} y = 772{,}37 + 99{,}82x_1 - 101{,}1x_2 + 43{,}02x_3 + \\ + 17{,}16x_1x_2 + 0{,}48x_1x_3 - 45{,}07x_2x_3 - \\ - 69{,}88x_1^2 + 9{,}59x_2^2 - 18{,}1x_3^2. \end{aligned} \quad (2)$$

Passing from a coded value of factors (x_1, x_2, x_3) to natural factors (σ, H_c, δ), and after the necessary transformations, the dependence $M_r(\sigma, H_c, \delta)$ was obtained:

$$\begin{gathered} M_r(\sigma, H_c, \delta) = 464 + 0{,}22\sigma - 156 H_c + \\ + 3{,}82 \cdot 10^5 \delta + 0{,}55\sigma H_c + 3{,}05\sigma\delta - 4{,}01 \cdot 10^5 H_c \delta - \\ - 1{,}58 \cdot 10^{-3} \sigma^2 + 426 H_c^2 - 3{,}22 \cdot 10^7 \delta^2. \end{gathered} \tag{3}$$

3. *Verification of the accuracy and adequacy of the obtained approximating model* of *the relationship of residual magnetization and the influencing factors.* Response function approximated by a polynomial could not correspond to (to be inadequate) the observed values of magnitude y. So, before you use the obtained mathematical model to validate its adequacy to the experimental data. According to [2] for a rotatable plans, the validation of adequacy of the mathematical model is carried out in several stages.

Stage 1. The dispersion of reproducibility S_r^2 is calculated, which is defined in this case by the results of experiments in the center of the design according to the expression:

$$S_r^2 = \frac{\sum\limits_{U=1}^{n_0} (y_U - \bar{y})^2}{n_0 - 1}, \tag{4}$$

where: n_0 − number of experiments in the center of the plan, $\bar{y}$ − the average value of the parameter y_U from n_0 measurements at the center of the plan, then $S_r^2 = 1369\ kA/m$.

Stage 2. The dispersion characterizing errors in the determination of the coefficients of the regression equation is calculated according to the formulas [2]:

$$S_{b0}^2 = \frac{2A\lambda^2 (k+2)}{N} S_r^2, \tag{5}$$

$$S_{bi}^2 = \frac{c}{N} S_r^2, \tag{6}$$

$$S_{bil}^2 = \frac{c^2}{N\lambda} S_r^2, \tag{7}$$

$$S_{bii}^2 = \frac{Ac^2 \left[(k+1)\lambda + (k-1) \right]}{N} S_r^2, \tag{8}$$

where: $A = \frac{1}{2\lambda \left[(k+2)\lambda - k \right]}$, $c = \frac{N}{\sum\limits_{j=1}^{N} x_{ij}^2}$, $\lambda = \frac{k(n_0 + n_\Pi)}{(k+2) n_\Pi}$, N − number of experiments in the matrix, k − number of factors, y_j − the value of the response function in the *j-th* experiment, x_{ij}, x_{lj} − the coded values of *i-th* and *l-th* factor in the *j-th* experiment, $n_\Pi = N - n_0$.

Then the dispersions of coefficients of the obtained regression equation will be: $S_{b0}^2 = 228{,}09$, $S_{bi}^2 = 100{,}2$, $S_{bil}^2 = 171{,}2$, $S_{bii}^2 = 95{,}11$.

Stage 3. The confidence intervals are calculated for the coefficients of the regression equation:

$$\begin{aligned} \Delta b_0 &= \pm t S_{b0}^2 = \pm 38{,}81, \\ \Delta b_i &= \pm t S_{bi}^2 = \pm 25{,}73, \\ \Delta b_{il} &= \pm t S_{bil}^2 = \pm 33{,}63, \\ \Delta b_{ii} &= \pm t S_{bii}^2 = 25{,}06, \end{aligned} \tag{9}$$

where: $t = 2.57$ − a table value of Student criterion at the 5% significance level and degrees of freedom $f = 5$.

Stage 4. Dispersion of adequacy S_{ad}^2 is determined by the formula:

$$S_{ad}^2 = \frac{S_R - S_E}{f}, \tag{10}$$

where: S_R − the sum of squared deviations of the empirical values y_j of the response function from its values $\hat{y}_j$, calculated by the model at all points of the plan, $S_E = \sum\limits_{U=1}^{n_0} (y_U - \bar{y})^2$, f − number of degrees of freedom, $f = N - k' - (n_0 - 1)$, k' − the number of coefficients of the approximating polynomial, then $S_{ad}^2 = 6550\ kA/m$.

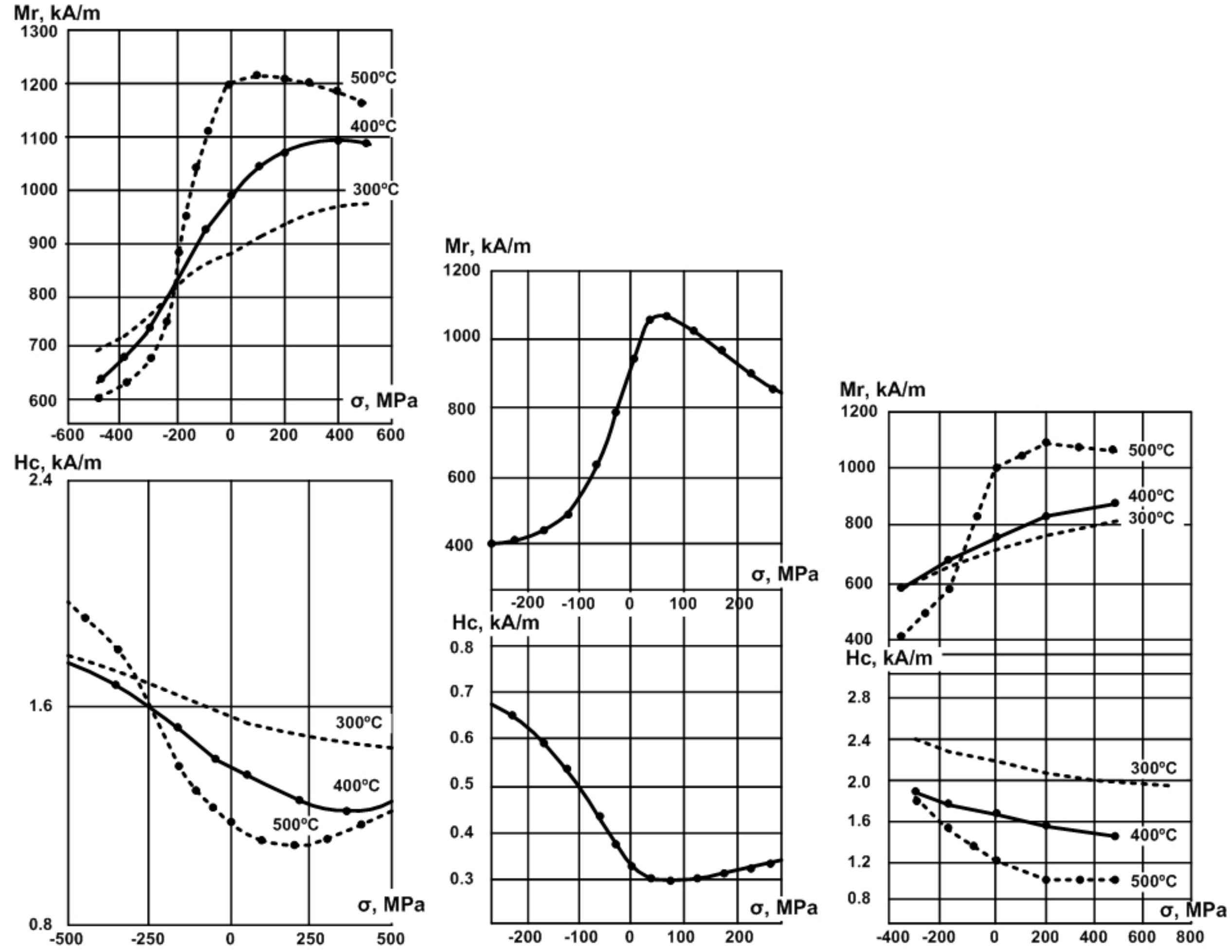
Stage 5. The adequacy of the regression equation is tested by the Fisher criterion:

$$F_{\exp} = \frac{S_{ad}^2}{S_r^2}, \quad F_{\exp} = 4{,}78. \tag{11}$$

The founded value of adequacy is less than the table value [2] ($F = 5{,}1$) when adopted 5% significance level and the corresponding number of degrees of freedom ($f = 5$), so the hypothesis of adequacy of the calculated model is adopted.

Defined by means of experiment and from equation (2) the values of the residual magnetization M_r are of the same character as the values obtained M_r for a large number of ferromagnetic steel (40H, St3S, 30HGSA) in other investigations [5, 7, 8, 10]. The difference from each other is only in the numerical data that proves the curves shown in Fig. 5. Here, the families of curves are for different temperatures are tempering.

4. The experimental check of adequacy the obtained approximating model of the relationship of residual magnetization and the acting elastic stresses. To test adequacy the obtained model was also carried out an experiment on a sample of steel St3S with size: 240 mm x 69 mm x 10.25 mm (Fig. 6).



Steel grade: 40H
($H_c = 0{,}95$ kA/m)
a

Steel grade: St3S
($H_c = 0{,}3$ kA/m)
b

Steel grade: 30HGSA
($H_c = 1{,}0$ kA/m)
c

Fig. 5. The experimental dependences of the residual magnetization and coercive force of elastic stresses for different steel grades

Fig. 6. Experimental samples of steel St3S

The sample was deformed by stretching at the tensile machine ZIM GMS-100A (Fig. 7). The coercive force was determined under load using structurescope – coercimeter CRM-C-K2M.

Fig. 7. The tensile machine ZIM GMS-100A

By the magnetization curve for St3S [16], the values of magnetic induction B, corresponding to the measured values of the coercive force, were determined. Assuming that the test sample is a directly (rod) core with a rectangular cross section, the value of the magnetic permeability μ [18] was determined by the formula:

$$\mu = \frac{\pi l^2}{4S\left(\ln\frac{kl}{a+b}-1\right)}, \tag{12}$$

where: l − sample length, S − cross-sectional area of the sample, a, b − transverse dimensions of the sample, k − coefficient, depending on the shape of the sample [18].

Further from the well-known expression for the magnetic permeability according to [18], the values of the magnetic field strength H were founded:

$$H = \frac{\mathrm{B}}{\mu\mu_0}, \tag{13}$$

where: $\mu_0 = 4\pi \times 10^{-7}$ − the magnetic permeability of vacuum.

According to expression:

$$M_r = \chi H, \tag{14}$$

where: χ − the magnetic susceptibility, the values of the residual magnetization M_r were founded.

In the Table 2 values of the residual magnetization, calculated from the above the obtained approximating model $M_r(\sigma, H_c, \delta)$ (Eq. 3), and the values M_r, obtained from the tests of the sample St3S, are presented. Error of calculation totaled 10-12%.

Table 2. The comparative table of experimental verification of the adequacy of the obtained mathematical model and by Fisher criterion

Experiment №	σ, MPa	Hc, kA/m	B, Tesla	H, kA/m	Mr, kA/m	Mr*, kA/m
1.	0	0.277	0.346	5.985	269.5	708.29
2.	141.4	0.27	0.338	5.847	263.3	711.43
3.	212.1	0.27	0.338	5.847	263.3	966.31
4.	282.8	0.31	0.388	6.711	302.2	789.17
5.	339.5	0.35	0.438	7.642	341.1	473.37
6.	386.8	0.36	0.45	7.424	350.9	478.43
7.	407.4	0.38	0.475	7.871	370.3	800.03
8.	451.9	0.40	0.5	7.837	390.3	624.81
9.	496.2	0.43	0.534	7.933	417.2	742.57
10.	782.8	0.785	0.889	7.918	699.9	406.77
11.	–	–	–	–	–	629.45
12.	–	–	–	–	–	969.55
13.	–	–	–	–	–	793.52
14.	–	–	–	–	–	648.80
15.	–	–	–	–	–	772.37
16.	–	–	–	–	–	772.37
17.	–	–	–	–	–	772.37
18.	–	–	–	–	–	772.37
19.	–	–	–	–	–	772.37
20.	–	–	–	–	–	772.37

Mr* – a values of the response function $M_r(\sigma, H_c, \delta)$ at the points of factorial design

CONCLUSIONS

1. As a result of carried out analysis of the magnetic characteristics of the ferromagnetic steels changing under the influence of elastic stresses, it was found that the change of residual magnetization M_r of the mechanical stresses occurs in a sufficiently large range during the transition from compression to tension, therefore estimate the acting elastic stresses in the ferromagnetic structures can be made in magnitude of residual magnetization.
2. The mathematical model of the relationship of residual magnetization and the acting elastic stresses of ship's hulls during cargo and ballast operations was defined by the mathematical theory experimental design.
3. The dependence $M_r(\sigma, H_c, \delta)$ is approximated by a polynomial of the second degree. The obtained mathematical model is adequate to the experimental data that proves check of adequacy regression equation by the Fisher criterion.
4. The experimental check of adequacy approximating model of the relationship of residual magnetization and the acting elastic stresses was carried out.
5. The error of calculations of the acting mechanical stresses by the obtained mathematical model does not exceed 10-12%.
6. In such a way, it can pass to residual magnetization [13, 14] by measuring the magnetic field strength on the surface of the control object – hatch coaming (eg, fluxgate magnetometer), and from it by a numerical method using the resulting model it can determine the value of the acting mechanical stresses in the ship's ferromagnetic constructions.

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МОДЕЛЬ ВЗАИМОСВЯЗИ ОСТАТОЧНОЙ НАМАГНИЧЕННОСТИ И УПРУГИХ НАПРЯЖЕНИЙ КОРПУСОВ МОРСКИХ СУДОВ В ПРОЦЕССЕ ГРУЗОВЫХ И БАЛЛАСТНЫХ ОПЕРАЦИЙ

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Аннотация. Определена математическая модель взаимосвязи остаточной намагниченности и действующих упругих напряжений в корпусах морских судов в процессе грузовых и балластных операций. Выполнена проверка адекватности аппроксимирующей модели по критерию Фишера, а также экспериментальная проверка.

Ключевые слова: математическая модель, остаточная намагниченность, упругие напряжения, корпус судна.