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Research Article

COMPARISON OF MODELS OF MAGNETIZATION CURVES AND HYSTERESIS LOOPS ACCORDING TO THE GILES-ATHERTON MODEL FOR SOFT MAGNETIC AMORPHOUS ALLOYS

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ABSTRACT

The subject of research in the article is ferromagnetic soft magnetic amorphous materials and alloys, which are used in power sources of automated control systems, and in vehicle electrical installations. The aim of the work is an objective comparison of two magnetization models for soft magnetic amorphous alloys - the main magnetization curve using approximation functions and the Giles-Atherton hysteresis loop model. In the study, the least squares method was used to optimize the main magnetization curve and the Giles-Atherton hysteresis loop optimization method with the aim of its maximum coincidence with the experimentally obtained loop. Experimental and reference data for common types of magnetically soft amorphous alloys were used for modeling. As a criterion of model accuracy for both modeling methods, the relative error in determining the magnetic induction value was chosen, and the experimental value obtained from the real hysteresis loop of a magnetically soft amorphous alloy was taken as its exact value, and the approximate value was taken from calculations of the magnetic induction value using the methods of approximating the magnetization curve and simulation of the hysteresis loop using the Giles-Atherton method. As a result of the research, it was revealed that both models of magnetization of magnetically soft amorphous materials give simulation results similar in accuracy. The obtained results of the study can be used to select an appropriate magnetization model for the mathematical description of ferromagnetic devices using magnetically soft amorphous metals and alloys. The final conclusion about the advantages of a particular model can only be made on the basis of the ultimate goals of the analysis.

Keywords

Vehicle power supply, magnetization curve, approximating function, Giles-Atherton hysteresis model, method error.

Introduction

Among the means of technical, mathematical, linguistic and other types of support for automated control systems (ACS), the technical support that ensures the functioning of various technical devices of the system due to their various power sources is of particular importance. Especially effective is the use of soft magnetic amorphous alloys in transformer power supplies, the energy efficiency of which is 70-85% higher compared to similar transformers using ordinary electrical steel. Since the devices for supplying automatic control systems usually operate in a continuous mode, the use of transformers with low losses for magnetization reversal and hysteresis can significantly save the consumed electrical energy. As the cost of electricity increases, the use of soft magnetic amorphous alloys becomes justified in power distribution networks, where transformers with a power of up to 1600 kVA are used. For this reason, the use of a suitable magnetization model for amorphous materials, which arises in the calculation of the cores of ferromagnetic devices, in particular transformers, is an urgent scientific problem.

To approximate the hysteresis loop in ferromagnetic materials, the Giles-Atherton [4, 5, 6, 7, 10], Chan [8, 9, 10, 11, 14, 15] and other models are most often used. However, if the ferromagnetic elements in these devices operate at high values of magnetic induction, then in this case the main magnetization curve is used, which is approximated by a suitable algebraic expression. Most often, to approximate the magnetization curve, the hyperbolic sinus, arc tangent, complete and incomplete polynomials of the n-th degree, where n is an odd integer [1, 2, 3, 17, 18], are used. The use of one or another method for creating mathematical models of ferromagnetic devices depends on the goals set and the depth of study of the processes occurring in them.

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In the qualitative analysis of ferromagnetic devices, the requirement of simplicity of analytical transformations is decisive; in this case, an analytical description of the magnetization curve is usually used. However, with a deeper study of the ongoing processes, for example, when studying the quantitative parameters of the device operation, it may be necessary to describe the magnetization process using one of the existing models of the hysteresis loop. Therefore, of significant scientific interest is a comparative analysis of the description of magnetization using magnetization curves and using hysteresis loops, in order to identify the optimal method for a particular problem being solved, as well as an objective assessment of the error when using both methods of mathematical description of hysteresis.

Research methods. As models for the study, cores made of magnetically soft amorphous steels and amorphous iron-based alloys were used, the experimental magnetization curve of which was recorded at an alternating current with a frequency of 50 Hz according to the methods described in [1, 2], in particular, for the AMAG 492 alloy, for other amorphous alloys, data on magnetization are taken from the literature [12, 13]. The appearance of the main magnetization curves is shown in fig. 1. It can be seen from the curves that for the majority of soft magnetic amorphous alloys, saturation occurs already at low values of the magnetic field intension compared to cold-rolled electrical steel, for which the saturation strength is , which indicates a high value of relative magnetic permeability for amorphous alloys.

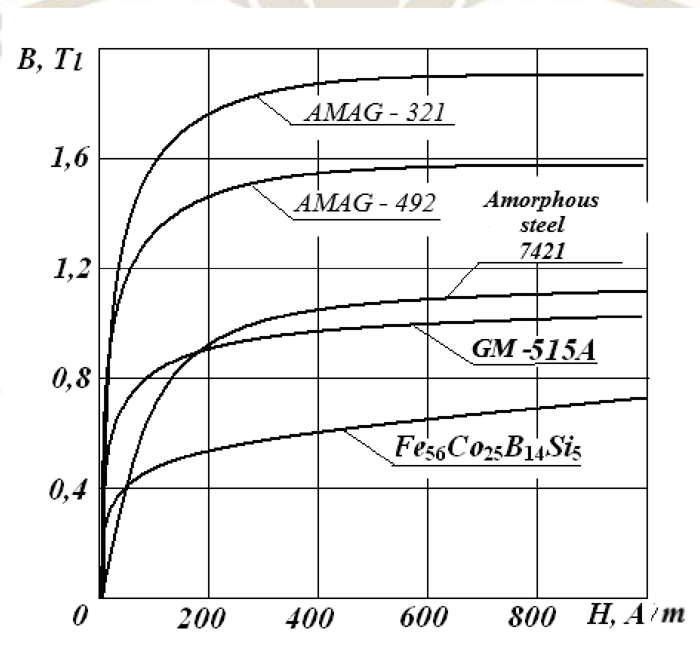

Figure 1. Magnetization curves of common types of amorphous steels and alloys

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The linear coefficients in the approximating expressions were calculated based on the minimum total quadratic error using the least squares method, the transition from nonlinear to linear functions was carried out using the appropriate substitutions [16, 20] and using the expression

$$k = \frac{\sum_{i=1}^{N} B_i^n \cdot \sum_{i=1}^{N} H_i - N\sum_{i=1}^{N} B_i^n \cdot H_i}{\left(\sum_{i=1}^{N} B_i^n\right)^2 - N\sum_{i=1}^{N} B_i^{2n}},$$ modified for the condition of passing the curve through the origin,

where is N - the number of experimental points on the magnetization curve; i – point number; B_i, H_i - are the experimental values of the magnetic induction and the magnetic field intension at the i-th point, respectively. For cores made of a soft amorphous alloy based on iron grade AMAG 492 in the range of inductions from 0 to 1.6 T (saturation induction), the following approximating expressions were obtained:

–hyperbolic sinus $H = 1{,}892 \cdot 10^{-5} sh(11{,}552 \cdot B)$;

–arc tangent $B = 1{,}022 \cdot arctg(0{,}049 \cdot H)$;

–incomplete polynomial of the ninth degree $H = 14{,}66B^9$

–incomplete polynomial of the eleventh degree $H = 5{,}22B^{11}$.

Graphs of the main curve of magnetization of the amorphous alloy AMAG 492 and functions approximating it are shown in Fig.2.

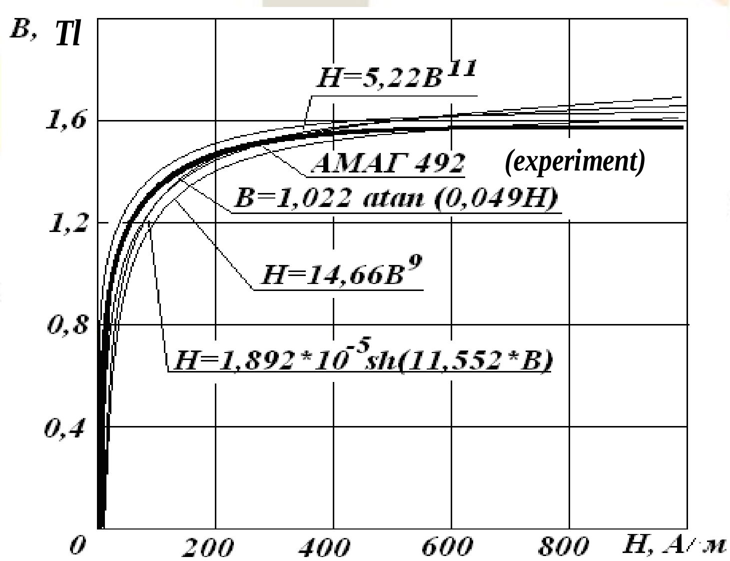

Figure 2. Magnetization curve and its approximating functions for AMAG 492 alloy

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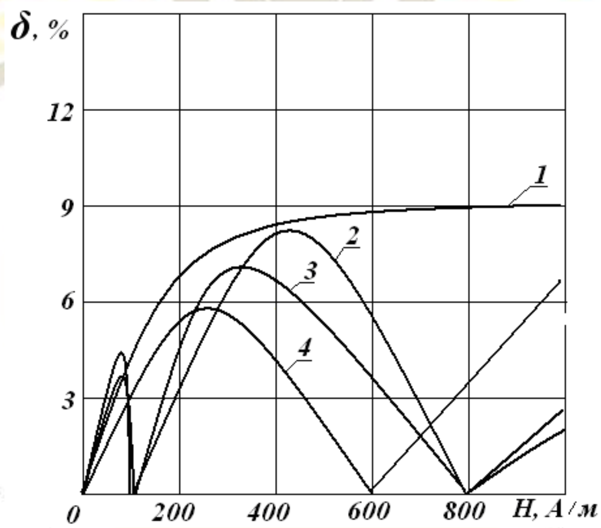
It can be seen from the graphs of the functions that, according to the accuracy criterion, all of them are sufficiently suitable for approximating the main magnetization curve of the AMAT 492 alloy. However, the expressions for the hyperbolic sine and arc tangent are inconvenient for subsequent transformations, in particular, expressions with hyperbolic functions are inconvenient for obtaining inverse dependencies (H from B or B from H), which is necessary when analyzing circuits. Obviously, the most suitable for the criterion of simplicity and accuracy is the approximation by incomplete polynomials of the ninth and eleventh degrees.

To estimate the errors, we study the nature of the change in the relative approximation error with a change in the magnetic field intension. The relative approximation error for each of the experimental points can be calculated from the expression $\delta(\%)=\left|\frac{B_i - B_{iA}}{B_i}\right|\cdot 100\%$, where B_i – is an experimental value of magnetic induction in i-th point; B_{iA} is the value of the magnetic induction calculated from the approximating function. Dependence curves $\delta(\%)= f(B)$ for incomplete polynomials of degrees from 9 to 11, as well as for the functions of the hyperbolic sine and arc tangent for the core of the AMAT 492 amorphous alloy are shown in Fig. 3.



1-incomplete polynomial of degree 11, 2-incomplete polynomial of degree 9, 3-hyperbolic sine, 4- arctangent
Figure 3. Approximation errors

It can be seen from the graphs that the errors in the approximation by polynomials with degrees of 9 and 11 give errors not exceeding 9%, which can be considered acceptable when calculating ferromagnetic elements based on amorphous alloys.

The above methods for approximating the magnetization curve are approximate, since in reality any ferromagnetic material is magnetized along a hysteresis loop. Therefore, it is of interest to mathematically describe the process of material magnetization taking into account hysteresis. For modeling, we will use the hysteresis loop of the AMAG 492 material, using the Giles-Atherton model [4, 5, 19], as the most commonly used in commercial programs for calculating ferromagnetic devices. Due to the lack of parameters of this model in the reference data, it is necessary to apply its optimization, which makes it possible to calculate the model parameters using known experimental and reference data.

The essence of the Giles-Atherton model is that the total magnetization consists of three components: hysteresis-free magnetization M_{an}, reversible (reversible) magnetization M_{rev}, irreversible magnetization M_{irr}, and the relationship between the magnetization M, magnetic field intension H and magnetic induction value B is described by the expression $B = \mu_0 (M + H)$.

Magnetization M ferromagnetic in an external magnetic field depends on the magnitude of the internal field H_e, equal to $H_e = H + \alpha M$, where α – coefficient taking into account the effect of interaction between the external and internal magnetic fields. Due to small value α, equal to $4-6 \cdot 10^{-5}$ in the sources [4] it is recommended to take it equal to zero, thus it turns out $H_e \approx H$.

The value of the hysteresis-free magnetization M_{an} can be written in the form of $M_{an} = M_s f(H)$, where M_s – saturation magnetization,, and $f(H)$ – function equal to zero at $H = 0$ and unit at H, tending to infinity. In the Giles-Atherton model, as a function $f(H)$ the Langevin function is used in the form *£(x)=coth(x)-1/x*, with considering, the hysteresis-free magnetization curve is described by the function $M_{an} = M_s \cdot \coth\left(\left(\frac{H}{A}\right) - \left(\frac{A}{H}\right)\right)$, where A – a scale factor ranging from 0.1 to 10000 is chosen according to the appearance of the hysteresis loop so that the curve M_{an} passed through the points (0,0) and (H_c, B_r) hysteresis curve, where H_c и B_r – respectively coercive force and residual magnetic induction.

It is known from [4] that the total magnetization M is the sum of two components – the irreversible magnetization M_{irr} and the reversible magnetization M_{rev}.

$$M = M_{irr} + M_{rev}. \quad (1)$$

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The derivatives with respect to H of the irreversible and reversible components are determined, respectively, by the expressions

$$\frac{dM_{irr}}{dH}=\frac{M_{an}-M_{irr}}{\frac{\delta k}{\mu_0}-\alpha(M_{an}-M_{irr})};\quad \frac{dM_{rev}}{dH}=c\left(\frac{dM_{an}}{dH}-\frac{dM}{dH}\right), \qquad (2)$$

whence, after transformations and taking into account (1), a differential equation can be obtained that describes the hysteresis in the Giles-Atherton model

$$\frac{dM}{dH}=\frac{1}{(1+c)}\cdot\frac{(M_{an}-M)}{\frac{\delta k}{\mu_0}-\alpha(M_{an}-M)}+\frac{c}{(1+c)}\frac{dM_{an}}{dH}. \qquad (3)$$

Here: δ – sign function, $\delta=1$ if $\frac{dH}{dt}\geq 0$, $\delta=-1$ if $\frac{dH}{dt}\leq 0$, $\frac{k}{\mu_0}\approx H_c$ - coefficient, approximately equal to the coercive force; c - is the weight coefficient equal to the ratio of the differential susceptibilities of the initial and hysteresis-free magnetization curves, determined experimentally by the best approximation of the calculated and experimental hysteresis curves, is in the range from 0 to 1; α – the coefficient taking into account the effect of interaction between the external and internal magnetic fields, previously its value was taken equal to zero.

With these notations, expression (3) can be rewritten as

$$\frac{dM}{dH}=\delta\frac{(1-c)\cdot(M_{an}-M)}{H_c}+c\frac{dM_{an}}{dH}. \qquad (4)$$

Integrating the left and right sides of (4) over dH, we obtain

$$M=\delta\frac{1-c}{H_c}\int(M_{an}-M)dH+c\cdot M_{an}. \qquad (5)$$

Since $M_{an}=M_s\cdot\coth\left(\left(\frac{H}{A}\right)-\left(\frac{A}{H}\right)\right)$, after substituting this expression into (5), we finally obtain

$$M=\delta\frac{1-c}{H_c}\int(M_s\cdot\coth\left(\frac{H}{A}-\frac{A}{H}\right)-M)dH+c\cdot(M_s\cdot\coth\left(\frac{H}{A}-\frac{A}{H}\right)) \qquad (6)$$

We perform the integration of equation (6) by the numerical method of Gauss-Kronrod- [16] as giving the highest algebraic accuracy with the following initial parameters characteristic of the AMAG 492 alloy, which are given in Table 1.

Tab. 1 Calculation parameters of the Giles-Atherton model for the amorphous alloy

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AMAG 492

Parameter	Size	Unit of measurement
B_s	0,75	Tl
M_s	$1,27*10^4$	А/м
H_c	8	А/м
Δ	+1, -1	-
A	32	-
c	0,58	-
α	0	-

Based on the results of numerical integration, we obtain a series of values of the magnetic field intension H and the corresponding induction B, and we will take the integral within the range of the magnetic field intension from -1000 to +1000 A/m. On fig. 4 shows plots of the hysteresis curves of dependence $B = f(H)$ for the AMAG 492 alloy, obtained experimentally and calculated from the results of solving equation (6) for a steady state at a magnetization reversal frequency of 50 Hz.

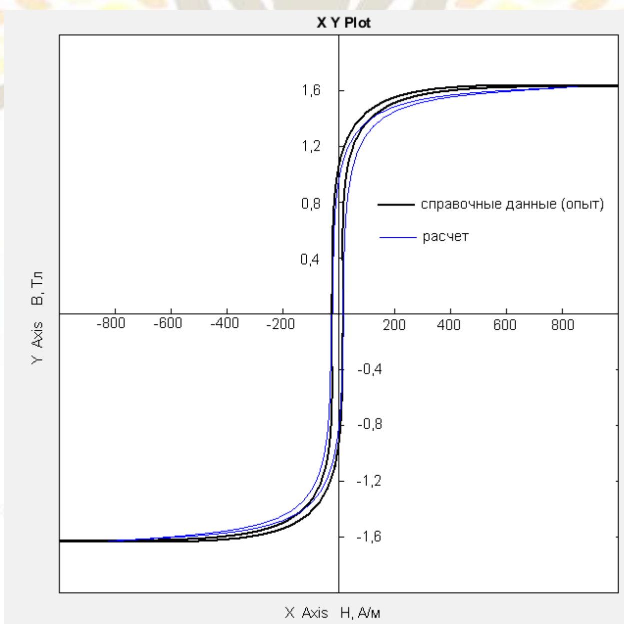

Figure 4. Calculated and experimental graphs of hysteresis curves of dependence $B = f(H)$ for AMAG 492 alloy

From those shown in Fig. 4 graphs show a good agreement between the calculated and experimental curves, which at the reference points (the exact origin of coordinates, the point

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with the coercive force H_c and the residual magnetic induction B_r and the point with the limiting value of the magnetic field intension, in our case equal to 800 A/m) coincide completely. The greatest difference between the experimental and calculated plots of hysteresis loops is observed in the area of the greatest bend in the magnetization curve. In the sections of the linear dependence of $B = f(H)$ and the saturation section of the magnetization curve, the calculation errors are minimal.

RESEARCH RESULTS

We compare the magnetization curves of amorphous materials obtained by their approximation by an algebraic expression and their hysteresis loops obtained using the Giles-Atherton model. As a comparison criterion, the value of the relative modeling error can be used, calculated by the expression

$$\delta(\%) = \left|\frac{B_i - B_{iA}}{B_i}\right| \cdot 100\%$$

, where B_i is the experimental value of the magnetic induction at the *i*-th point; B_{iA} is the value of the magnetic induction calculated from the approximating function and using the Giles-Atherton model at the same point.

On fig. Figure 5 shows the graphs of dependence *B=f(H)* for the amorphous alloy AMAG 492, constructed for various modeling methods: the experimental dependence *B=f(H),* taken on a full-scale sample, the calculated dependence *B=f(H)*, obtained by use of approximation by an incomplete polynomial of the form $H=14,66B^9$ and the calculation model of the hysteresis loop obtained from the Giles-Atherton model. It can be seen from the graphs that the adopted methods give approximately the same modeling accuracy.

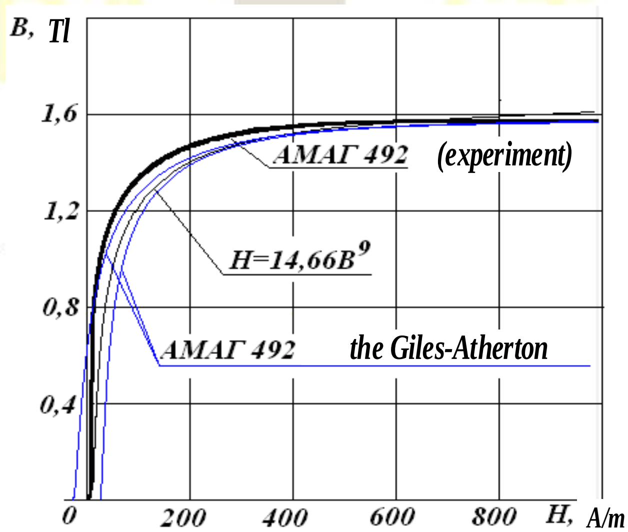

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Figure 5. Graphs of dependence *B=f(H)* with various modeling methods

On fig. 6 shows plots of the relative simulation error $\delta(\%) = f(B)$ for the AMAG 492 alloy using the simulation methods discussed above.

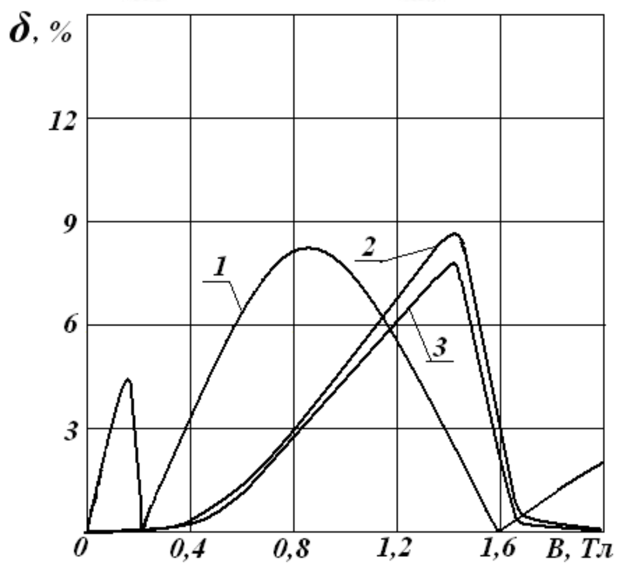

Figure. 6. Graphs of dependence $\delta(\%) = f(B)$ for alloy AMAG 492:

1 – approximation by the function $H=14{,}66B^9$, 2 – direct branch of the hysteresis loop of the Giles-Atherton model, 3 – reverse branch of the Giles-Atherton hysteresis loop model

From the graphs shown in fig. Figure 6 shows that the relative errors of approximation of the magnetization curve and the hysteresis loop of the Giles-Atherton model in their largest value differ little from each other.

From the graphs shown in fig.6 shows that the relative errors of approximation of the magnetization curve and the hysteresis loop of the Giles-Atherton model in their largest value differ little from each other.

As an example, let us consider the calculation using the models of the magnetization curve and the Giles-Atherton hysteresis loop model of the values of magnetic inductions in the stabilizer rods using the amorphous alloy AMAG 492, the scheme of which is shown in Fig. 7 [14, p.96].

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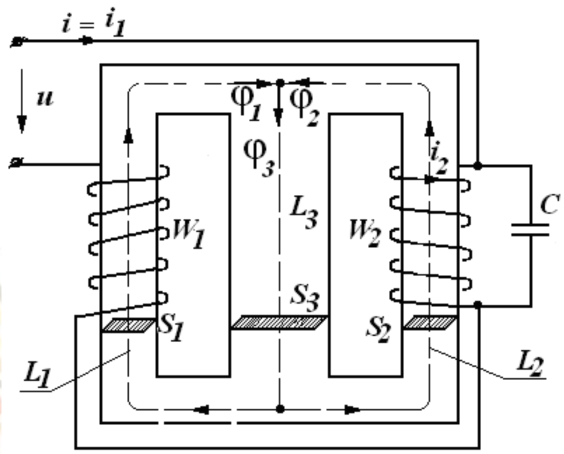

Figure 7. Model of a parametric stabilizer with an AMAG 492 amorphous alloy core

The electrical state of the stabilizer can be described by a system of algebraic equations for instantaneous values of electrical and magnetic quantities

$$\begin{cases} \varphi_1 + \varphi_2 - \varphi_3 = 0 \\ i_1 W_1 = h_1 L_1 + h_3 L_3 \\ i_2 W_2 = h_2 L_2 + h_3 L_3 \end{cases}, \qquad (7)$$

Where : *u, i* – instantaneous supply voltage and current, φ_1, φ_1, φ_1 – instantaneous values of magnetic fluxes; L_1, L_2, L_3 are the lengths of the average magnetic lines of the magnetic circuit; h_1, h_2, h_3 - are the instantaneous values of the magnetic field in the rods of the magnetic circuit; i_1, i_2 – instantaneous currents in the coils of the outermost rods of the magnetic circuit, respectively, with the number of turns W_1, W_2 ; s_1, s_2, s_3 – are the sections of the magnetic core rods; C - is the capacitance of the capacitor. We transform expression (7) in such a way that the instantaneous values of magnetic inductions become unknown, for which we use the known ratio

$$\varphi = b*s; \quad i = \frac{h*L}{W}; \quad h = \frac{b}{\mu_0} - M \quad . \qquad (8)$$

Taking into account (8) expression (7) can be rewritten in the form of

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$$\begin{cases} b_1 s_1 + b_2 s_2 - b_3 s_3 = 0 \\ h_1 * L_1 = (\frac{b_1}{\mu_0} - M)L_1 + (\frac{b_3}{\mu_0} - M)L_3 \\ h_2 * L_2 = (\frac{b_2}{\mu_0} - M)L_2 + (\frac{b_3}{\mu_0} - M)L_3 \end{cases} . \qquad (9)$$

The solution of the system of algebraic equations (9) was carried out in the following sequence:

1) by setting the values of the magnetic field intension in the range from -1000 to +1000 A / m through the value of 10 A / m, we solve the differential equation $M = \delta \frac{1-c}{H_c} \int_{-1000}^{+1000} (M_S * \coth(\frac{H}{A} - \frac{A}{H}) - M)dH + c * (M_S * \coth(\frac{H}{A} - \frac{A}{H}))$, finding the values of the magnetization M corresponding to the magnetic field intension H, Values of unknown quantities δ, c, A, H_c, M_c should be taken from Table 1;

2) after substituting the found values of M in (9), this system of equations turns into a system of equations for the instantaneous values of magnetic inductions with linear coefficients;

3) solving the system of equations (3) we find three values of magnetic induction in the extreme rods b_1 , b_2 and the middle rod b_3. After that, we set the next value of H and repeat the calculations until all calculations are completed in the range of values of the magnetic field intension H from -1000 to +1000 A/m

The results of the calculations are shown in Fig. 8, the results of calculations using the magnetization curve model and theoretical calculations are taken from [14, p. 96-108] for the model with parameters: core material - amorphous alloy AMAG 492, magnetization curve of the material – H=14,66B^9, lengths of the middle lines L_1=L_2=0,245м, L_3=0,15м, core cross-sections S_1=S_2=0,00085м^2, S_3=0,0017м^2, number of turns W_1=300, W_2=350, C=25 мкФ, current through the coil W_2 is determined from the expression $i_2 = \frac{(\frac{b_2}{\mu_0} - M)L_2 + (\frac{b_3}{\mu_0} - M)L_3}{W_2}$ – current through the capacitor C - from the expression $i_{C2} = W_2 * C_2 * S_2 * \frac{d_2 b_2}{dt^2}$, and the supply voltage with the parameters of the stabilizer is related by the

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expression $W_1 * S_1 \frac{db_1}{dt} + W_2 * S_2 \frac{db_2}{dt} = 312\sin(\omega t + \frac{\pi}{6})$, the parameters for the Giles-Atherton model are taken from Table 1.

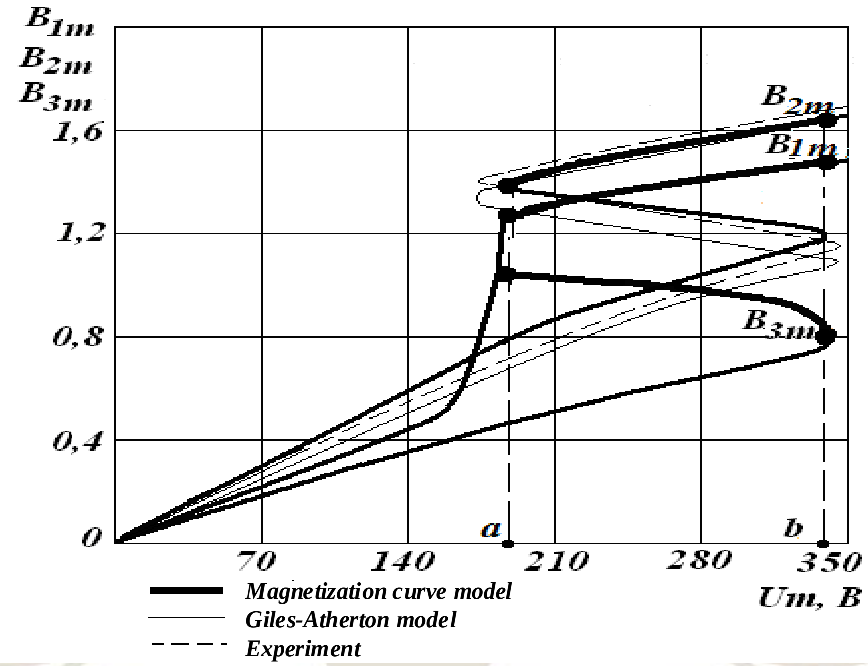

Fig. 8. Dependence of the amplitudes of inductions in the rods on the amplitude of the input voltage of the stabilizer

From the graphs in Fig. 8 it can be seen that in the zone of existence of parametric oscillations (the range of change in the amplitudes of the supply voltages is between points a and b), the deviations of the magnetic induction in rod 2 do not exceed 7-9% of the calculated values obtained from the model of the magnetization curve and the Giles-Atherton hysteresis loop model , for inductions in rods 1 and 3 (not shown on the graphs), the deviations are approximately in the same range

CONCLUSION

1. Thus, the model of the magnetization curve, obtained by approximating the magnetization curve of a ferromagnetic material, and the Giles-Atherton model can be taken to analyze devices based on magnetically soft amorphous materials, including those operating in the saturation mode, and the maximum calculation error does not exceed 7– nine%

2. The errors in the calculations of magnetic inductions obtained in the Giles-Atherton hysteresis loop model and by approximating the magnetization curve in the saturation zone of the cores have approximately the same values

3. The final conclusion about the advantages of a particular model can be made only on the basis of the final goals of the analysis.

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