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DETERMINATION OF MAGNETIC FIELD STRENGTH IN A LAYER OF ELECTROTECHNICAL STEEL

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ВИЗНАЧЕННЯ НАПРУЖЕНОСТІ МАГНІТНОГО ПОЛЯ В ШАРІ ЕЛЕКТРОТЕХНІЧНОЇ СТАЛІ

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This work is devoted to the determination of the periodic component of the magnetic field strength in a layer of electrical steel. When constructing a mathematical model, the magnetic permeability is approximated by a fractional rational function.

To calculate the magnetic field, a method of the fourth order of accuracy and two-sided method of the third order of accuracy with an explicit estimate of the leading term of the local error without additional calculations of the right side of the differential equation.

Keywords *magnetic field, equations of electrodynamics, Cauchy problem, continued fractions, bilateral approximations.*

Стаття присвячена визначенню періодичної складової напруженості магнітного поля в шарі електротехнічної сталі. При побудові математичної моделі магнітна проникність апроксимується дробовою раціональною функцією.

Для розрахунку магнітного поля використано метод четвертого порядку точності та двосторонній метод третього порядку точності з явною оцінкою головного члена локальної похибки без додаткових обчислень правої частини диференціального рівняння.

***Ключові слова**: магнітне поле, рівняння електродинаміки, задача Коші, неперервні дроби, двосторонні наближення.*

The modern development of methods for automated synthesis of MEMS at the circuit level involves the study of mathematical models for the entire class of complex systems of various nature [1]. In [2], new models were obtained for the analysis and synthesis at the circuit level of basic MEMS devices based on differential equations, which describe the oscillatory processes present in real physical systems [3].

In articles [4, 5], mathematical models are proposed for designing MEMS circuits: electrostatic and electromagnetic resonators, capacitive accelerometers of plate and counter-core structures, thermomechanical, thermopneumatic, piezoelectric and pyroelectric actuators.

When studying applied problems, it is necessary not only to find an approximate solution, but also to give a guaranteed estimate of the error of the result. The use of classical two-sided Runge-Kutta methods leads to a significant increase in the amount of computations, since the construction of the upper and lower approximations to the exact solution requires additional calculations (inversions) of the right-hand side of the differential equation and, moreover, these methods do not give an explicit estimate of the leading term of the local error [6-9]. One of the effective ways to construct such approximations is continued fractions [10]. Continued fractions can be considered as one of the main algorithms for finding Padé approximants [11, 12, 13]. Under appropriate conditions, the use of continued fractions gives a high rate of convergence of algorithms, two-sided and monotonic approximations [10]. In [14, 15, 16], using various Padé approximants, specific applied problems are investigated.

In this paper, a mathematical model is built to determine the periodic component of the magnetic field strength in a layer of electrical steel, in which the magnetic permeability is approximated by a fractional rational function. For calculations, a method of the fourth order of accuracy is proposed, as well as a two-sided method of the third order of accuracy with an estimate of the main term of the error at each point of integration. An explicit form of the principal term of the local error is written.

The method of research of mathematical models of physical systems which are directly applied at designing and the analysis of parameters of microelectromechanical systems of various configuration is developed.

To determine the magnetic field in a layer of electrotechnical steel, it is proposed to approximate the magnetic permeability $\underline{\mu}=\underline{\mu}(H)$ by a fractional rational function. The calculation of the magnetic field strength for steel E43 has been performed.

Let us consider the problem of determining the periodic component of the magnetic field strength in a layer of electrotechnical steel, on the surface $\underline{z}=0$ of which the strength $\overline{H}^{(0)}=\{0, H_0\sin(2\pi\nu\underline{t}), 0\}$ is maintained, where ν is the frequency, $\underline{z}$ is the thickness coordinate, $\underline{t}$ is the time.

We will proceed from Maxwell's equations neglecting the displacement currents. Then we get the equation [17, 18]

$$\sigma\underline{\mu}(H)\frac{\partial H}{\partial \underline{t}}=\frac{\partial^2 H}{\partial \underline{z}^2}, \qquad (1)$$

where $\underline{\mu}(H)=\frac{dB(H)}{dH}$, $B=B(H)$ is the magnetic field induction, $\sigma-$ electroconductivity coefficient with boundary conditions

$$H(0,\underline{t}) = H_0 \sin(2\pi \nu \underline{t}),\ H(l,\underline{t}) = 0, \tag{2}$$

and also with periodicity condition

$$H(\underline{z},\underline{t}+T) = H(\underline{z},\underline{t}). \tag{3}$$

Here $T = 1/\nu$ is the oscillation period of the electromagnetic wave, l is the layer thickness. Dependencies $B = B(H)$ and $\underline{\mu} = \underline{\mu}(H)$ are non-linear. For steel E43, they are shown by solid lines on Fig.1 and Fig.2.

However, this does not always accurately reflect the qualitative nature of function $\underline{\mu} = \underline{\mu}(H)$ changes. When solving problem (1)-(3), we will approximate the dependence $\underline{\mu} = \underline{\mu}(H)$ by fractionally rational function of the form

$$\underline{\mu}(H) = \mu_0 \mu_{init} \frac{1 + A_1 H^2}{1 + A_2 H^2 + A_3 H^4}. \tag{4}$$

The constants $A_i\ (i = 1,2,3)$ in relation (4) are determined from the conditions

$$\underline{\mu}(H_m) = \mu_{\max}\mu_0,\ \frac{d\underline{\mu}(H_m)}{dH} = 0\ ,$$

$$\underline{\mu}\frac{d^2\underline{\mu}(H_m)}{dH^2} < 0,\ \lim_{H\to\infty} B(H) = B_S, \tag{5}$$

which determine the features of the experimental dependences $\underline{\mu} = \underline{\mu}(H)$ and $B = B(H)$. Here μ_0 is the magnetic constant, μ_{init} and $\mu_{\max}$ are respectively, the initial and maximum relative magnetic permeabilities of the material, H_m is the value of the magnetic field for the maximum magnetic permeability, B_S is the saturation induction. We will obtain

$$A_1 = \frac{\sqrt{K^2 - \alpha^2 G} - K}{\alpha^2}, \qquad A_2 = \frac{\mu_{init}\left(A_1 H_m^2 + 2\right) - 2\mu_{\max}}{\mu_{\max} H_m^2},$$

$$A_3 = \frac{\mu_{\max} - \mu_{init}}{\mu_{\max} H_m^4}, \tag{6}$$

where

$$K = \alpha^2\sqrt{A_3} - \frac{A_3}{2M}, \qquad G = A_3\left(\alpha^2 - 2\sqrt{A_3} + 2H_m^2 A_3\right),$$

$$\alpha = \frac{\pi\mu_0\mu_{init}}{2B_S}, \qquad M = \frac{\mu_{\max}}{\mu_{init}}.$$

Note that in the case of large values of the magnetic field strength, approximation (4) can be approximately written in the form

$$\underline{\mu}(H) = \frac{\mu_{init}^{*}\mu_0}{1 + AH^2}. \tag{7}$$

For this case, the dependence of the magnetic field induction on the strength will be the Mueller dependence formula well known in the literature [18]

$$B = \beta \arctan \sqrt{A} H, \tag{8}$$

and the approximation coefficients will take the form:

$$\beta = \mu_{init}^{*} \mu_0 \sqrt{A}, \qquad A = \frac{A_3}{A_2}, \qquad \mu_{init}^{*} = \frac{A_1}{A_2} \mu_{init}.$$

The graph of the function $\underline{\mu}(H)$, which is determined by the formula (7) for steel E43, is shown in Fig. 2 by a dashed line.

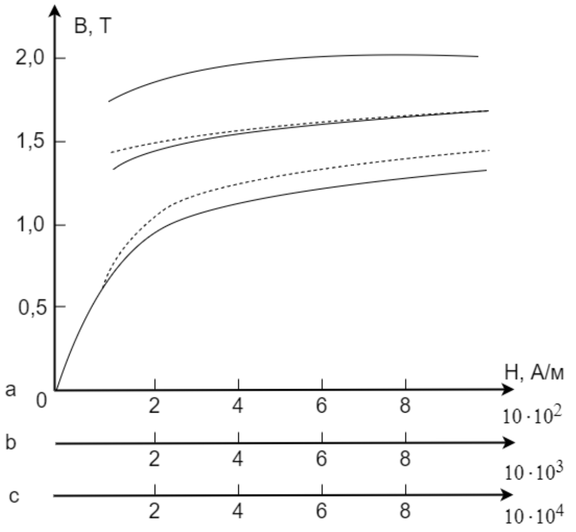

Fig. 1. Dependences of magnetic field induction determined by formula (7) and experimental data for steel E43.

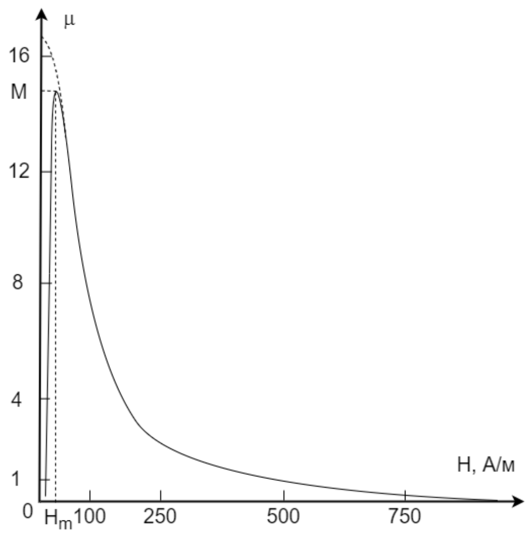

Fig. 2. Dependences of magnetic field strength determined by formula (6) and experimental data for steel E43

Let us pass in problem (1)-(3) to dimensionless quantities:

$$t=\omega \underline{t}\,,\qquad z=\frac{\underline{z}}{l}\,,\qquad u=\frac{H}{H_0}\,,$$

$$b=\frac{B}{\mu_0\mu_{init}H_0}\,,\qquad \mu(u)=\frac{\underline{\mu}(H)}{\mu_0\mu_{init}}\,.$$

Then the original equation (1) takes the form

$$2\gamma^2\mu(u)\frac{\partial u}{\partial t}=\frac{\partial^2 u}{\partial z^2}\,, \tag{9}$$

where

$$\mu(u)=\begin{cases}\dfrac{1+a_1\varepsilon u^2}{1+a_2\varepsilon u^2+a_4\varepsilon^2u^4}\,, in\ dependance\ of\ (4)\\[2mm] \dfrac{a_1}{a_2+a_3\varepsilon u^2}\,, for\ dependance\ (7)\end{cases} \tag{10}$$

The boundary conditions and the periodicity condition take the form

$$u(0,t)=\sin(t),\quad u(1,t)=0, \tag{11}$$

$$u(z,t+2\pi)=u(z,t). \tag{12}$$

Here

$$a_1=\frac{A_1}{\alpha^2}\,,\ a_2=\frac{A_2}{\alpha^2}\,,\qquad a_3=\frac{A_3}{\alpha^4}\,,$$

$$\varepsilon=(\alpha H_0)^2,\qquad \gamma^2=\pi\sigma\mu_{init}\mu_0\nu l^2\,. \tag{13}$$

After discretizing with respect to the spatial variable, we reduce problem (9), (11), (12) to a system of ordinary differential equations:

$$\frac{du_i(t)}{dt}=\begin{cases}\dfrac{1+a_2\varepsilon u_i^2(t)+a_3\varepsilon^2u_i^4(t)}{1+a_1\varepsilon u_i^2(t)}, for\,(4)\\[2mm] \dfrac{a_2+a_3\varepsilon u_i^2(t)}{a_1}, for\,(7)\end{cases} \tag{14}$$

with the initial condition

$$u_0(t)=\sin(t),\ u_i(0)=0\ ,\ i=\overline{1,N-1},\ u_N(t)=0, \tag{15}$$

where N is the number of splitting points of the interval [0, 1].

Let us consider problem (14)-(15) in a more general setting, namely, as a system of nonlinear differential equations of the first order:

$$\overline{y}'(x)=\overline{f}(x,\overline{y}),\ \overline{y}(x_0)=\overline{y}_0\,,\ x\in[x_0,x_0+L], \tag{16}$$

where

$$[x_0,x_0+L]\subset R,\ y(x)\in R^S\,,\ \ \overline{f}:[x_0\,,x_0+L]\times R^S\to R,$$

and the function $\bar{f}$ has the necessary smoothness for calculations. To reduce the cumbersomeness of the records, we present approximate solutions of problem (16) in the scalar case, since they are transferred to systems of differential equations componentwise. Using the theory of construction of Runge-Kutta methods [19], we look for the approximate solution of problem (16) in the form of a continued fraction [20, 21]:

$$y_{n+1}^{[k,l]} = y_n \big/ Q_n^{[k,l]} \qquad (17)$$

where

$$Q_n^{[k,l]} = \sum_{i=0}^{k-1} q_{i,0} + \cfrac{q_{k,0}}{1+\cfrac{q_{k,1}}{1+\ddots+\cfrac{q_{k,l-1}}{1+q_{k,l}}}}$$

Expressions for $q_{k,l}$ in case $k+l=1(1)4$ ($k=1(1)4;\ l=0(1)3$) are

$$q_{0,0}=1,\quad q_{i,0}=-\sum_{m=1}^{i} q_{i-m,0}\cdot\frac{\sigma_m}{y_n},\quad i=1(1)4,\quad y_n\neq 0,$$

$$q_{\nu,1}=-\frac{q_{\nu+1,0}}{q_{\nu,0}},\quad \nu=1,2,3,\quad q_{\mu,2}=q_{\mu+1,1}-q_{\mu,1},\quad \mu=1,2,$$

$$q_{1,3}=q_{1,2}\frac{q_{2,2}}{q_{1,2}},\quad \sigma_m=h\sum_{i=1}^{4} c_{mi}k_i,\quad m=1(1)4, \qquad (18)$$

$$k_i = f\left(x_n+\alpha_i h,\ y_n+h\sum_{j=1}^{i-1}\beta_{ij}k_j\right),\quad \alpha_i=\sum_{j=1}^{i-1}\beta_{ij}.$$

The method of the fourth order of accuracy

At different values of k and l $(k+l=4; k=1(1)4,\ l=0(1)3)$, methods of the fourth order of accuracy are constructed.

We give one set of values. If $\alpha_2=\alpha_3$, we have

$$\alpha_2=\alpha_3=\frac{1}{2},\quad \alpha_4=1,\quad \beta_{21}=\frac{1}{2},\quad \beta_{31}=\frac{1}{2}-\frac{1}{2\beta_{43}},$$

$$\beta_{32}=\frac{1}{2\beta_{43}},\quad \beta_{41}=0,\quad \beta_{42}=1-\beta_{43}, \qquad (19)$$

$$c_{11}=1,\quad c_{21}=-1,\quad c_{22}=1,\quad c_{31}=\frac{1}{6},$$

$$c_{32}=-\frac{1+\beta_{43}}{3},\quad c_{33}=\frac{\beta_{43}}{3},\quad c_{34}=\frac{1}{6},\quad (c_{1j}=0,\ j=2,3,4; c_{23}=c_{24}=0; c_{4i}=0,\ i=1(1)4),$$

where β_{43} – the parameter is different from zero.

When put $\beta_{43}=1$, we get the specific values of the parameters c_{ij}, α_i, β_{ii-1}:

$$\alpha_2 = 1/2, \quad \alpha_3 = 1/2, \quad \alpha_4 = 1, \quad \beta_{21} = 1/2,$$
$$\beta_{31} = 0, \quad \beta_{32} = 1/2, \quad \beta_{41} = 0, \quad \beta_{42} = 0,$$
$$\beta_{43} = 1, \quad c_{11} = 1, \quad c_{12} = c_{13} = c_{14} = 0,$$
$$c_{21} = -1, \quad c_{22} = 1, \quad c_{31} = 1/6, \quad c_{32} = -2/3, \qquad (20)$$
$$c_{33} = 1/3, \quad c_{34} = 1/6, \quad c_{4j} = 0, \ (j = 1(1)4).$$

Two-sided methods of the third order of accuracy

Many scientific works is devoted to the construction and study of bilateral methods of various accuracy. At the same time this leads to the complexity of the algorithm and, accordingly, to an increase in the amount of computation. For example, for the implementation of two-sided third-order accuracy methods, at least 6 (six) calls to the right-hand side of the differential equation at each nodal point are necessary [7, 8, 9].

These calculation formulas are constructed so that the local errors in the circuit at each node point:

$$y(x_{n+1}) - y_{n+1}^{[k,l]} = \omega h^p KF(f) + O(h^{p+1}),$$

where $y(x_{n+1})$ and $y_{n+1}^{[k,l]}$ is the exact and approximate solution of the problem (16), h is the integration step, $F(f)$ is a certain differential operator, calculated at the point (x_n, y_n), K is a constant, and p is the accuracy order, ω is a two-sided parameter. Here is the value of the parameters for $\alpha_2 = \alpha_3$:

$$\alpha_2 = \alpha_3 = \frac{1}{2}, \quad \beta_{21} = \frac{1}{2}, \quad \beta_{31} = \frac{1}{2} - \frac{1}{2\beta_{43}},$$
$$\beta_{32} = \frac{1}{2\beta_{43}}, \quad \alpha_4 = 1, \quad \beta_{41} = 0, \quad \beta_{42} = 1 - \beta_{43},$$
$$\tilde{c}_{11} = 1, \quad \tilde{c}_{12} = \tilde{c}_{13} = \tilde{c}_{14} = 0, \quad \tilde{c}_{21} = -1, \quad \tilde{c}_{22} = 1,$$
$$\tilde{c}_{23} = \tilde{c}_{24} = 0, \quad \tilde{c}_{31} = \frac{1}{6} + 2\omega, \qquad (21)$$
$$\tilde{c}_{32} = 2\omega(\beta_{43} - 2) - \frac{1}{3}(1 + \beta_{43}),$$
$$\tilde{c}_{33} = \frac{1}{3}\beta_{43}(1 - 6\omega), \quad \tilde{c}_{34} = \frac{1}{6} + 2\omega, \quad \tilde{c}_{41} = -2\omega, \quad \tilde{c}_{42} = 2\omega(2 - \beta_{43}), \quad \tilde{c}_{43} = 2\beta_{43}\omega, \quad \tilde{c}_{44} = -2\omega,$$

where β_{43} – the parameter is different from zero.

When put $\beta_{43} = 1$, we get the specific values of the parameters:

$$\alpha_2 = 1/2, \quad \alpha_3 = 1/2, \quad \alpha_4 = 1, \quad \beta_{21} = 1/2,$$
$$\beta_{31} = 0, \quad \beta_{32} = 1/2, \quad \beta_{41} = 0, \quad \beta_{42} = 0,$$
$$\beta_{43} = 1, \quad \tilde{c}_{11} = 1, \quad \tilde{c}_{12} = \tilde{c}_{13} = \tilde{c}_{14} = 0,$$

$\tilde{c}_{21} = -1, \quad \tilde{c}_{22} = 1, \quad \tilde{c}_{23} = \tilde{c}_{24} = 0, \quad \tilde{c}_{31} = \frac{1}{6} + 2\omega,$

$\tilde{c}_{32} = -\frac{2}{3} - 2\omega, \quad \tilde{c}_{33} = \frac{1}{3} - 2\omega, \quad \tilde{c}_{34} = \frac{1}{6} + 2\omega,$

$$\tilde{c}_{41} = -2\omega, \quad \tilde{c}_{42} = 2\omega, \quad \tilde{c}_{43} = 2\omega, \quad \tilde{c}_{44} = -2\omega. \qquad (22)$$

The local error estimate is as follows $(k = 4, l = 0)$:

$$y_{n+1} - y_{n+1}^{[4,0]} = h\sum_{i=1}^{4}\tilde{c}_{4i}k_i .$$

This bilateral formulas use at each step of integration less than the right-hand side of the differential equation in comparison with known two-sided methods such as Runge-Kutta. For example, for the implementation of two-sided third-order accuracy methods, at least 6 calls to the right-hand side of the differential equation at each nodal point are necessary [6-9].

The proposed formulas, using only four references to the right-hand side of a differential equation, make it possible to obtain not only a method of the fourth order of accuracy, but also bilateral formulas of the third order of accuracy.

Calculations for the magnetic field strength were carried out for E43 electrical steel, the characteristics of which are as follows [13]:

$\mu_{init} = 600,\ \mu_{\max} = 9000,\ B_S = 2{,}07,\ H_m = 30.$

Then $a_1 = 713610,\ \ a_2 = 41238{,}18,\ \ a_3 = 10752490.$

For these values $a_i\ (i = 1,2,3)$, the graph of the function $B = B(H)$, that corresponds to the dependence $\underline{\mu} = \underline{\mu}(H)$ according to formula (4) is shown in Fig.1 by a dashed line. Figure 1 shows that the proposed function with sufficient accuracy for practice approximates the dependence $B = B(H)$ for steel E43.

Based on numerical calculations, a harmonic analysis was carried out. Let us present the results of studying the distribution of the amplitudes for the magnetic field strength over the layer thickness for the chosen approximations (5), (6) for $\gamma = 6$.

In Fig. 3 and Fig. 4, solid lines show (in the case of dependence (5)) the distribution of the amplitude of the first harmonic of the magnetic field strength for $\varepsilon = 0; 0{,}0001; 0{,}001; 0{,}01; 0{,}1$ and, $\varepsilon = 0{,}2; 1; 10; 100; 1000$

respectively. As can be seen from the figures, when changing ε from 0 to $0{,}2$, the distribution of the field has a near-surface character, and the greatest is at $\varepsilon = 0{,}2$. For $\varepsilon > 0{,}2$ the degree of attenuation of the magnetic field decreases, i.e. the distribution becomes more linear.

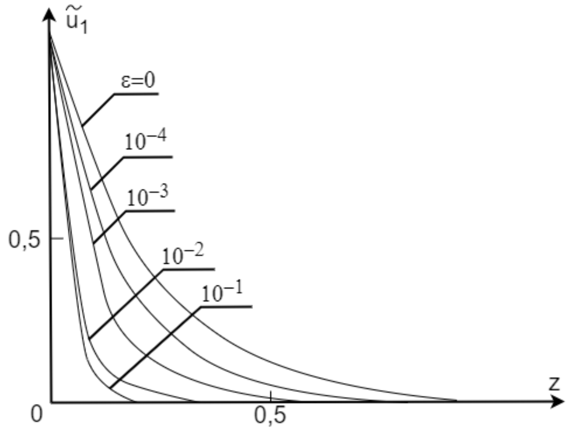

Fig. 3. Distribution of the amplitude of the first harmonic of the magnetic field strength at $\varepsilon = 0;10^{-4};10^{-3};10^{-2},10^{-1}$.

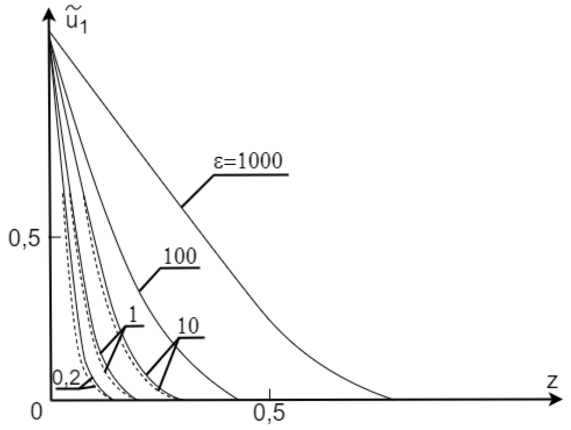

Fig. 4. Distribution of the amplitude of the first harmonic of the magnetic field strength at $\varepsilon = 0,2;1;10;10^{2};10^{3}$.

The graphs of the distribution of the amplitudes of the third harmonic of the magnetic field strength for the same parameter values are shown by solid lines in Fig. 5 and Fig. 6, respectively.

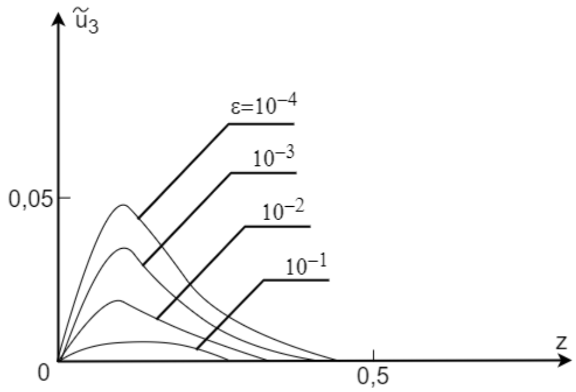

Fig. 5. Distribution of the amplitude of the third harmonic of the magnetic field strength at $\varepsilon = 0;10^{-4};10^{-3};10^{-2},10^{-1}$.

In Fig. 4 and Fig. 6, for comparison dashed lines show, the distributions of the amplitudes of the first and third harmonics of the magnetic field strength are plotted for $\varepsilon = 0,2;1;10,100;1000,$ which are found from dependence (7). Note that for $\varepsilon = 100$ and $\varepsilon = 1000$ these graphs are the same.

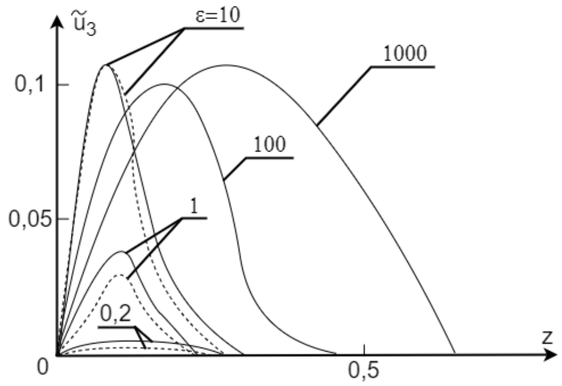

Fig. 6. Distribution of the amplitude of the third harmonic of the magnetic field strength at $\varepsilon = 0,2;1;10;10^2;10^3$.

It can be seen from the analysis of the results that the difference between the solutions of equation (9) at different $\underline{\mu}$, determined from (10) decreases with increasing ε. So, for $\varepsilon > 0,1$ it becomes less than 3%, and for $\varepsilon > 100$ – less than 1%.

This means that when determining the electromagnetic field in ferromagnetic bodies for weak fields, it is necessary to use the approximation $\underline{\mu} = \underline{\mu}(H)$ determined by formula (4). In the case of strong fields, formula (7) can be used.

V. Conclusions

A mathematical model is proposed for determining the periodic component of the magnetic field strength in a layer of electrical steel, in which the magnetic permeability is approximated by a fractional- rational function.

To study the constructed model, a method of the fourth order of accuracy is proposed, as well as a two-sided method of the third order of accuracy. In addition, explicit estimates of the main terms of the local error are written, which are obtained without additional references to the right-hand side of the differential equation.

The proposed method is a embedded [22, 23] method of order of precision 4(3) with a two-sided estimate of the error at each point of integration.

The bilateral calculation formulas allow at each integration step to reduce the number of calls to the right-hand side by 25% in comparison with the traditional two-sided Runge-Kutta methods.

The above calculation formulas at each integration point can provide several approximations to the exact solution, the comparison of which provides additional information for choosing the integration step.

The results of the work were used to construct rational modes of processing ferromagnetic elements of structures such as plates**.**

These conclusions, arising from the study of mathematical models of field distributions, must be taken into account when analyzing and synthesizing the parameters of the corresponding technological micro-electromechanical systems at the design stage.

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АВТОМАТИЗАЦІЯ ПНЕВМОПРИВОДУ ДЛЯ ПІДВИЩЕННЯ ЕНЕРГОЕФЕКТИВНОСТІ, РЕСУРСОЗБЕРЕЖЕННЯ ТА ЯКОСТІ ТЕХНОЛОГІЧНИХ ДІЙ ПРИ ВИКОНАННІ ФОРМОТВОРЕННЯ

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AUTOMATION OF PNEUMATIC ACTUATOR TO INCREASE ENERGY EFFICIENCY, RESOURCE SAVING AND QUALITY TECHNOLOGICAL ACTIONS WHEN PERFORMING SHAPING

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В роботі розглянуто які властивості взуття є визначальними для якісного формування деталей верху засобами шнурової затяжки, серед яких найбільш вагомими є: технологічне навантаження на гнучкий силовий елемент, відносне подовження матеріалу верху, коефіцієнти тертя в системі „діафрагма-матеріал-колодка”, геометричні параметри поверхні колодки, ступінь розподілу нормальних тисків з боку пружних діафрагм, швидкість зміщення затяжної кромки та інш. Зроблена спроба удосконалення обладнання з метою запобігання перевантаження обладнання для шнурової затяжки, а також для збільшення терміну його експлуатації при технологічному зусиллі на шнур, яке не повинно перевищувати 250Н. Встановлено, що при виконанні технологічної операції фрикційної шнурової затяжки заготовок верху взуття доцільно подавати тиск у пневмосистему в інтервалі 1,5÷2,0мПа з одночасним використанням гуми для діафрагм з невисоким модулем пружності. Розроблена дослідна установка для шнурової затяжки з фрикційною обтяжкою дає змогу досліджувати операції затягування та формування деталей верху взуття з достатньою точністю. При цьому здійснюється і сам процес переміщення елементарних ділянок матеріалу відповідно до отриманих зовнішніх навантажень і внутрішніх напруг, тобто відбувається формоутворення верху взуття. Для підвищення точності прилягання і забезпечення рівномірного тиску діафрагм, збільшення швидкості процесу затяжки необхідно застосувати надійний і точний механізм переміщення фрикційних рамок Запропонована нами інноваційна схема пневмоприводу, призначеного для управління роботою фрикційними рамками та здійснення ними фрикційної обтяжки заготовки. Таким чином, проаналізувавши технологічні і технічні параметри, можна стверджувати, що основними перевагами пневмопривідної системи є простота, надійність, довговічність і економічність, які обумовлені одноканальним живленням (відпрацьоване повітря випускається безпосередньо в атмосферу без відвідних трубопроводів) і дешевизною самого робочого середовища (повітря).

Ключові слова: *установка, верх взуття, діафрагма, привід, ергономічні властивості, зусилля, деформація, фрикційна шнурова затяжка, техологічні властивості, пристрій, фрикційні рамки, стиснене повітря, обладнання.*

What properties of shoe are in-process considered there is qualificatory for the quality forming of details of top facilities of the cord wearing out, among that most ponderable is : the technological loading on a flexible power element, relative lengthening of material of top, coefficients of friction in the system shoe "diaphragm-material-tree", geometrical parameters of surface of shoe tree, degree of distribution of normal pressures from the side of resilient diaphragms, speed of displacement of the protracted edge and проч. a size and direction of appendix technological loading have Especially large influence on cord, as exactly it determine size and distribution longitudinal and transversal deformation purveyance. Equipment for implementation of technological operations of the cord tightening with the friction covering, created by the improvement of pilot plant and application. Therefore this important factor must be taken into account yet on the stage of planning of