ON THE ISSUE OF USING THE DEVELOPED SOFTWARE IN THE EDUCATIONAL PROCESS FOR THE STUDY OF ACOUSTIC PATHS OF MAGNETOSTRICTIVE DISPLACEMENT TRANSDUCERS

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***Abstract*— The article is devoted to the research of the processes arising during the formation, translation and reading of information signals in the acoustic paths of magnetostrictive linear and angular displacement transducers. Mathematical models are given that make it possible to calculate the magnetic fields of annular permanent magnets and those formed by current pulses when they flow in a waveguide medium. To calculate the magnetization of the waveguide, a numerical method was developed that allows taking into account the magnetization of the waveguide material at a previous time. Mathematical models are also given to calculate the parameters of the magnetic flux of the solenoid and the output signal. Mathematical models for calculating permanent magnet magnetic fields, the developed numerical method and mathematical models for the formation of magnetic flux and output signal were implemented in the developed software used in the educational process. The developed software is of practical interest, as it allows calculating the parameters and properties of acoustic paths of magnetostrictive linear and angular displacement transducers.**

***Keywords*—** *Magnetostriction, magnetostrictive converter, software, magnetic field, educational process.*

I. INTRODUCTION

The dynamics of research and discoveries in the field of scientific research and information technology in recent years has significantly expanded the possibilities for their further study [1-12]. This became possible thanks to the successful work of not only scientists and scientific schools, but also the research of students and teachers [13-20].

The training of qualified specialists in the educational process is ineffective without visual teaching methods that allow explaining and demonstrating the basic foundations, principles of operation and design features of processes and phenomena.

Thus, to study the phenomenon of magnetostriction, as well as the processes of signal formation, translation and reading in the acoustic paths of magnetostrictive displacement transducers, software developed by the authors of the publication can be used, which allows not only to understand the principle of operation of these devices, but also to develop new elements and designs for them. One of the features of the software is the implementation of the developed numerical method for calculating the magnetization of the waveguide material. The developed and refined mathematical models allow us to calculate the values of the magnetic field strengths of a permanent magnet and the current pulses generated, the magnetic flux and the output signal generated by a solenoid with a graphical representation of the latter. The article is devoted to the theoretical foundations of the processes occurring during signal transmission in acoustic paths of magnetostrictive displacement transducers, as well as computational experiments using the developed software and experimental verification of the results obtained.

II. THEORETICAL ANALYSIS

The principle of operation of magnetostrictive devices is based on two effects, consisting in a change in the size of the waveguide material (ferromagnet) under the influence of a change in its magnetization, which leads to a change in its size at a local site and the formation of ultrasonic waves (Wiedemann effect) and the reverse effect, called the Villari effect - a change in the magnetization of the waveguide material under the influence of mechanical vibrations (ultrasonic waves).

The design of the acoustic path of the magnetostrictive displacement transducer is shown in Figure 1. In it, current pulses i entering the medium of the waveguide (pos. 1) form a magnetic field, the intensity of which on its surface can be determined according to the expression (1).

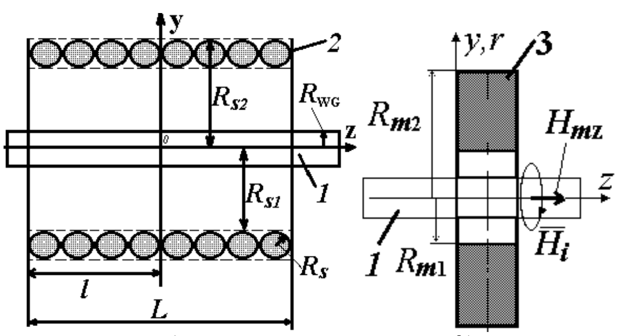
$$H_i=i/(2\cdot\pi\cdot R_{WG}) \quad (1)$$

where R_{WG} – waveguide radius.

The magnetic field created by current pulses interacts with the magnetic field of a permanent magnet (pos. 3), which leads to a change in the magnetization of the waveguide material and the formation of mechanical vibrations called ultrasonic waves. The process of calculating the change in magnetization is complex and depends on many factors and parameters. It is proposed to calculate this change more precisely using the developed numerical method.

Ultrasonic waves (acoustic signal) propagating in the waveguide medium reach the solenoid (pos. 2), that is, the element forming the output signal and are read, after which the time interval of their propagation is converted into the measured displacement values.

The principle of reciprocity can be applied to reproduce the torsion wave. Figure 1 shows a reproduction coil (solenoid) that perceives an informative parameter — the longitudinal component of the magnetic field of the ultrasonic torsion wave. In Figure 1, the following designations are adopted: R_S — the radius of the solenoid wire; $2l=L$ — length of the solenoid; z — the current coordinate measured along the 0Z axis; R_{S1} and R_{S2} — respectively the internal and external radii of the solenoid, $R_{S2}=R_{S1}+R_S$; R_{m1} and R_{m2} — internal and external the radii of the annular permanent magnet, respectively.



a) b)

Fig. 1. An explanatory drawing for further research. Image of a waveguide (position 1) and a) a single-layer solenoid (position 2) and b) an annular permanent magnet (position 3).

Knowing the distribution of the field of the solenoid $H_{CZ}(z)$, it is possible to calculate the value of the projection of its magnetic flux on the axis $0Z$ Φz through an arbitrary cross-section of the waveguide caused by the current i through the reproduction winding, since in accordance with the reciprocity theorem, the same current i, flowing around the cross-section of the waveguide surface, excites an identical flow Φ through the solenoid winding [1].

When the torsion wave moves, the sequence of magnetizations M_Z moves relative to the solenoid. Hence, $M_Z=M(z-z_0)$, where $z_0=\upsilon t$, υ is the propagation velocity of the ultrasonic torsion wave. The variable $(z-z_0)$ sets the middle line of the center of the stationary solenoid as the origin of the reference frame for M_Z. The value of t (or z) equal to zero corresponds to a certain form of magnetization located directly under the center of the solenoid. The scattering field of the $H_{col}(z)$, solenoid is fixed with respect to the z axis.

Let the magnitude of the scattering field of the solenoid be reduced to a single magnetomotive force (i.e., H is determined for $N1 = 1.0$, where N is the number of turns of the playback solenoid winding). The scattering field of the reproduction solenoid associated with the carrier consists of two components of the magnetic field H_{cz} and H_{cy} Thus, one ampere-turn of the reproduction winding will excite an infinitesimal flux through the waveguide element of radius r and thickness dy in the Cartesian coordinate system or dr in the cylindrical coordinate system will be determined according to formula (2).

$$d\Phi_Z=\mu_0 H_{CZ}\cdot 2\cdot\pi\cdot r\cdot dr \quad (2)$$

where $\mu_0=4\cdot\pi\cdot 10^{-7}$ H/m — magnetic constant.

According to the reciprocity theorem, a single current (through one turn around the element $r\ dr$) will induce a similar flow in the winding of the playback solenoid.

Since in the waveguide ultrasonic torsion waves propagate with a velocity υ and a horizontal component of magnetization $M_z(z-\upsilon t)$, the magnetic moment of the element of length dz and cross-section $r\ dr$ is equivalent to the current flowing around the element $r\ dr$. The current value is equal to $M_z(z-\upsilon t)\ dz$. This equivalent current is a scale factor that should be used in equation (3) to derive from the last actual magnetization level of the waveguide.

The total flux crossing the winding of the reproduction solenoid caused by the magnetization M_z is obtained in this case by integrating infinitesimal fluxes arising from a sequence of magnetizations along the waveguide, and is determined according to expression (3).

$$\Phi_z(z_0)=k\cdot\int_{-\infty}^{\infty}\int_{0}^{\frac{d_{WG}}{2}}\mu_0\cdot M_z(z-z_0,r)\cdot H_{cr}(z,r)\cdot 2\pi r\cdot dr\cdot dz \quad (3)$$

where d_{WG} is the diameter of the waveguide, $z_0=\upsilon t$, k is a generalized coefficient including magnetostrictive coefficients.

The playback signal is determined by the derivative of $\Phi_Z(z)$ (expression (4)).

$$u(z_0)=d\Phi_Z(z_0)/dt \quad (4)$$

The magnetization of M_z is determined by the effect on the waveguide material of a field equal to the geometric sum of the circular field H_i of the waveguide and the horizontal component of the field of the permanent magnet $Hz(r,z)$.

For an annular permanent magnet with magnetization M and with external and internal radii Rm_2 and Rm_1, respectively, the value of the magnetic field strength $Hz(r,z)$ is determined by the formula (5).

$$H_z(r,z)=H_{z2}(r,z)-H_{z1}(r,z) \quad (5)$$

where

$$H_{z2}(r,z)=\frac{1}{\pi}\cdot\int_{Rm1}^{Rm2}\left[\begin{array}{l}M\cdot\rho\cdot z\cdot E2(k2)\times\\ \times\dfrac{1}{\left[(r-\rho)^2+z^2\right]\cdot\sqrt{(r+\rho)^2+z^2}}\end{array}\right]d\rho \quad ; (6)$$

$$H_{z1}(r,z)=\frac{1}{\pi}\cdot\int_{Rm1}^{Rm2}\left(\begin{array}{l}M\cdot\rho\cdot(z-h)\cdot E2(k1)\times\\ \times\dfrac{1}{\left[(r-\rho)^2+(z-h)^2\right]}\times\\ \times\dfrac{1}{\sqrt{(r+\rho)^2+(z-h)^2}}\end{array}\right)d\rho \quad ; \quad . \quad (7)$$

According to one of the models, the field H_{CZ} on the axis of the solenoid at a point spaced at a distance z from its center is determined by the formula (8).

$$H_{cz}(z)=\frac{ni}{4(Rs2-Rs1)}\left\{\begin{array}{l}(l-z)\ln\dfrac{R_{s2}+\sqrt{R_{s2}^2+(l-z)^2}}{R_{s1}+\sqrt{R_{s1}^2+(l-z)^2}}+\\ +(l+z)\ln\dfrac{R_{s2}+\sqrt{R_{s2}^2+(l+z)^2}}{R_{s1}+\sqrt{R_{s1}^2+(l+z)^2}}\end{array}\right\} (8)$$

where $n=N/L$ is the number of turns per unit length of the solenoid, Rs_1 and Rs_2 are the internal and external radii of the solenoid, respectively, $2l=L$ is the length of the solenoid, i is the value of the current pulse, s is the cross-sectional area of the waveguide.

Using expression (5), it is possible to obtain the distribution of the longitudinal magnetization $M_Z(z)$ in the waveguide, which is determined by the functional dependence on $H_Z(r,z)$, that is, according to expression (9).

$$M_Z(z)=f(H_Z(r,z)) \quad (9)$$

To simulate the magnetization of a waveguide, it is also desirable to analytically determine the dependence, as it is presented in expression (10).

$$M_i=M(H(x_i,t),\ M(H(x_i,t-\Delta t)), \quad (10)$$

where $H(x_i,t)$ is the total field acting on the magnetic element at time t;

$M(H(x_i,t-\Delta t))$ — the magnetization of the element, determined at the previous moment in time $t-\Delta t$.

The type of this functional dependence is determined by the selected waveguide magnetization model, hysteresis loop models, and many other parameters.

Hysteresis loop is one of the properties of ferromagnets (waveguide material). It allows you to determine its magnetization by the value of the magnetic field strength and vice versa. There are many models for constructing and methods for approximating hysteresis loops, one of which used in the developed software is the polynomial approximation method [2] (expression 11) of the Nishimoto hysteresis loop model [3].

$$M(H,\alpha_1)=M_s(T)\cdot\mathrm{sign}\alpha_1+M_s\cdot\alpha_1\cdot f(H\cdot\mathrm{sign}\alpha_1) \quad (11)$$

where Ti — temperature of switchable element, $f(H)$ — function describing the limiting hysteresis loop and having the form given in formula (12) [3].

$$f(H)=\begin{cases}\dfrac{H_C-H}{H-\dfrac{H_C}{s_p}} & when\ H<H_C\\ 1-\left(\dfrac{H_C}{H}\right)^{\frac{s_p}{1-s_p}\cdot K_S} & when\ \ H>H_C\end{cases} \quad (12)$$

In this description of the hysteresis loop $s_P=Mr/Ms$, K_S — coefficient less than 1.
The graphs constructed according to formulas (11), (12) are shown in Figure 2.

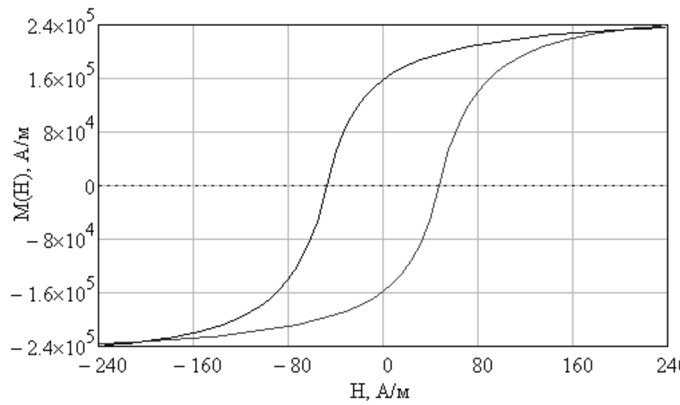


Fig. 2. Nishimoto hysteresis loop model [3]: H_C=150/π A/m, M_S=33·10^5/(4·π) A/m, s_p=0,6, M_r= s_p·M_s.

The dependence (9) was used by modeling the limiting and partial cycles of the hysteresis loop [2,3] according to formulas (10) and (11).

The loop index α_1 is determined from the conditions of equality of the magnitudes of magnetization at the return point [2] according to expression (13).

$$\alpha_1^{(k+1)}=\alpha_1^{(k)}\frac{M\left(H^{(k)},\alpha_1^{(k)}\right)+M_s\cdot\mathrm{sign}\left(\alpha_1^{(k)}\right)}{M\left(H^{(k)},-\alpha_1^{(k)}\right)+M_s\cdot\mathrm{sign}\left(\alpha_1^{(k)}\right)} \quad (13)$$

where k — sequence number of magnetization change cycle along hysteresis loop.

For calculation by formulas (11) and (12), the model also allows the use of temperature dependences $H_c(x_i)=H_c(T_i(x_i))$ and $M(x_i)=M_S(T_i(x_i))$, obtained by interpolation of experimental data.

A common disadvantage of methods for calculating the magnetization of waveguides by static hysteresis loops is the inability to take into account the influence of self-magnetizing fields in them. Their accounting is possible using the developed numerical method.

The method of self-consistent dynamic modeling (MSDM) has become widely used for modeling the recording of information on ferromagnetic media by applying a local magnetic field created, for example, by a magnetic head [4,5].

Some general provisions of this technique can also be applied to model the magnetization of waveguides of magnetostrictive devices on ultrasonic torsion waves, taking into account the peculiarities of the physics of circular field magnetization, methods for determining magnetic fields and models of the magnetization of waveguide material.

MSDM are models and methods for the approximate solution of a nonlinear problem, which, for the case of the formation of magnetization in a waveguide, have the form presented in formula (14).

$$\bar{M}(\bar{r},t) = \bar{m}_{tf}(\bar{H}_\Sigma(\bar{r},t), history\ \bar{H}_\Sigma)$$
$$\bar{H}_\Sigma(\bar{r},t) = H_{\text{external}}(\bar{r},t) + H_{\text{demagnetizing}}(\bar{r},t), \quad (14)$$

where $\bar{M}(\bar{r},t)$ — the magnetization vector at a point with a radius vector $\bar{r}$ at time t; $\bar{H}_\Sigma(\bar{r},t)$ — the intensity vector of the total magnetic field, including the sum of the external field $H_{\text{external}}(\bar{r},t)$, created by the combined action of a permanent magnet and a circular magnetic field in the absence of a magnetic waveguide, and the internal field $H_{\text{demagnetizing}}(\bar{r},t)$, existing in a magnetic material; $\bar{m}_{tf}$ — the modeling function connecting the residual magnetization of the waveguide with the magnetic field strength; $\bar{H}_{\text{demagnetizing}}(\bar{r},t)$ — the demagnetizing field is determined from Maxwell's magnetostatic equations according to expression (15).

$$\text{div}\ \bar{H}_{\text{demagnetizing}}(\bar{r},t) = -4\cdot\pi\cdot\text{div}\ \bar{M}(\bar{r},t);$$
$$H_{\text{demagnetizing}}(r\to\infty)\to 0. \quad (15)$$

Different MSDM differ in the choice of the modeling function $\bar{m}_{tf}(\bar{H}, history\,\bar{H})$ and mathematical methods of approximate solution of equations (14), (15).

It should be noted that in traditional models of magnetization formation, various models of domain formation were also used to describe the process of formation of the magnetization distribution, where the basis of consideration is the minimization of the thermodynamic potential.

Meanwhile, it is known that in most magnetic materials, including in a waveguide, the intrinsic domain structure can have dimensions much smaller than the regions that are magnetized under the action of a magnetic field. If this is the case, then these regions can be described using parameters characteristic of macro-regions, in particular, the coercive force, the squareness coefficient of the hysteresis loop, which can be easily measured and reflect the structural state of the real material. The use of these parameters makes it possible to apply to the consideration of phenomena in a waveguide some approaches developed for modeling magnetic recording by a magnetic head.

The problem of calculating the change in the magnetization of the waveguide when the magnetic field changes is solved as follows: (Figure 3).

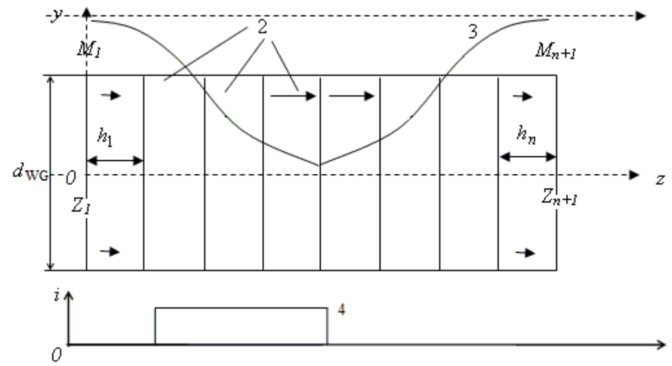


Fig. 3. Model of magnetization formation in a waveguide, where 1 is a waveguide, 2 is a waveguide partition region, 3 is the distribution of the longitudinal component of the resulting magnetic field, 4 is a current pulse in the waveguide depending on time.

To determine the magnetization and magnetic fields during the remagnetization of the waveguide, the considered waveguide region is divided into n elements of length h, bounded by nodal points Z_i. At any given time, you can set the temperature field T_i=$T(Z_i)$. When developing the model , the following assumptions are made:

1. It is assumed that in each element of the partition, the magnetization is a constant value.

2. Accordingly, each element of the partition will represent a cylindrical area with radius d_{WG} /2.

Practically, the magnetization distribution is numerically calculated using the iteration method. The generalized iterative calculation procedure is shown in Figure 4. The detailed algorithm of the developed numerical method is shown in Figure 5.

Linear interpolation is used to describe the magnetization at the previous moment between nodes Z_i and Z_{i+1} .

The total magnetic field $H_\Sigma(Z_i,t)$ is determined in accordance with the expression (16).

$$H_\Sigma(Z_i,t)=H_{\text{external}}+\Sigma\, A_{i,j}\cdot M_j(t), \quad (16)$$

where $A_{i,j}$ — an element of the matrix of form factors obtained taking into account the interpolation of magnetization in an elementary magnet by the integral solution of Maxwell's magnetostatic equations in the form of a scalar potential; i is the position of the observation point (Figure 3); j is the position of the boundary of the finite element with the magnetic material.

To calculate the total magnetic field $H_\Sigma(Z_i,t)$, described by expression (16), it is possible to use iteration methods, the most adapted to the model under consideration of which is the relaxation method. This method of solving systems of algebraic equations has a high convergence rate due to the fact that after calculating the next i–th component (k+1) of the approximation according to the formula of the Seidel method, an additional displacement of this component is produced in it.

$$H_{external} \rightarrow M_i^1 \rightarrow H_{\text{demagnetizing}_i}^1$$
$$\downarrow$$
$$(H_{external} + H_{\text{demagnetizing}_i}^1) \rightarrow M_i^2$$
$$\downarrow$$
$$B_i^2 \rightarrow H_{\text{demagnetizing}_i}^2$$
$$\downarrow$$
$$(H_{external} + H_{\text{demagnetizing}_i}^2) \rightarrow M_i^3$$
$$\downarrow$$

Fig. 4. Generalized procedure for iterative calculation of magnetization in a waveguide.

The choice of this method was also made due to the possibility of additional introduction of relaxation by induction into calculations, which increases stability.

According to this method, the value of the magnetic field strength H is determined in accordance with the expression (17).

$$H^{(k)}=H^{(k-1)}+\lambda_1(H^{(k-1)}+A(B^{(k-1)}-H^{(k-1)})), \qquad (17)$$

where λ_1 — a certain number called the coefficient of acceleration of convergence in the magnetic field strength, which determines the method of solving the expression (15). So, for $\lambda_1<1$, formula (17) is the formula of the lower relaxation method, $\lambda_1=1$ is the Seidel formula, $\lambda_1>1$ is the upper relaxation formula. $B^{(k-1)}$ is the value of the magnetic induction calculated for the (k-1)th iteration step.

As already noted, in order to increase stability, an induction relaxation is additionally introduced into the well-known MSDM calculation method, the value of which at the k-th iteration step can be determined according to the expression (18).

$$\bar{B}^{(k)} = (1-\lambda_1') \cdot \bar{B}^{(k-1)} + \lambda_1' \cdot \bar{B}(\bar{H}^{(k)}), \qquad (18)$$

where $\bar{H}^{(k)}$ —value of magnetic field strength at the k-th iteration step, determined according to expression (17), λ_1' is the coefficient of convergence acceleration by magnetic induction.

The introduction of additional relaxation by induction increases the stability of the method under consideration and is the difference between the proposed numerical method and the existing ones.

The type of the matrix of form factors depends on the orientation of the magnetization relative to the surface of the waveguide, the method of interpolation of the magnetization between the nodes of the partition elements.

The elements of the matrix of form factors are determined by the contribution of the magnetic field from the regions of the waveguide lying outside its sections bounded by the partition points Z_1 and Z_{n+1}, as well as the partition elements h_i.

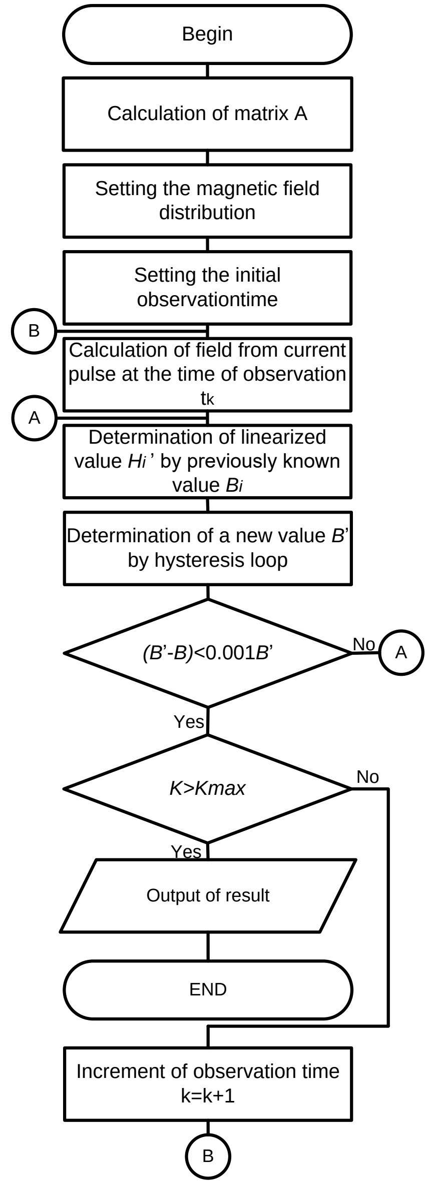


Fig. 5. Algorithm of the developed numerical method.

To determine the magnitude of the demagnetizing field, the following well-known expression is used [6].

$$H_{\text{demagnetizing}}(r) = \int(-\nabla M)\frac{(\bar{r}-\bar{\rho})dV}{\left|\bar{r}-\bar{\rho}\right|^3} + \int \bar{M}\cdot\bar{n}\frac{(\bar{r}-\bar{\rho})}{\left|\bar{r}-\bar{\rho}\right|^3}ds \qquad (19)$$

where $\bar{r}$ — radius is the vector of the observation point; $\bar{\rho}$ — radius is the vector drawn to the magnetic material; n is the unit normal to the lateral surface of the partition element; V,s are, respectively, the volume and surface of the magnet; ∇M — the magnetization.

Integration (19) allows you to determine the field from the first element of the partition in accordance with the expression (20).

$$H_1(r,z)=\frac{1}{\pi}\cdot\int_0^{d_{WG}/2}\left[\frac{M_1\cdot(z-h)\cdot E(k_1)\rho\cdot d\rho}{[(r-\rho)^2+(z-h)^2]}\times\frac{1}{[(r+\rho)^2+(z-h)^2]^{\frac{1}{2}}}\right]-$$
$$-\frac{1}{\pi}\cdot\int_0^{d_{WG}/2}\frac{M_1\cdot z\cdot E(k_2)\rho\cdot d\rho}{[(r-\rho)^2+z^2]\cdot[(r+\rho)^2+z^2]^{\frac{1}{2}}},\qquad(20)$$

where $E(k_2)=\int_0^{\frac{\pi}{2}}\sqrt{(1-k_2^2(\sin\varphi)^2)}d\varphi$ — complete elliptic integral of the second kind, $k_1^2=\frac{4\cdot r\cdot\rho}{(r+\rho)^2+(z-h)^2}$;. $k_2^2=\frac{4\cdot r\cdot\rho}{(r+\rho)^2+(z)^2}$; r — radius of the observation point measured from the selected origin, z — coordinate parallel to the direction of magnetization of the waveguide.

$$H_2(r,z)=\frac{1}{\pi}\cdot\int_0^{d_{WG}/2}\left[\frac{M_2\cdot(z-2\cdot h)\cdot E(k_1)\rho\cdot d\rho}{[(r-\rho)^2+(z-2\cdot h)^2]}\times\frac{1}{[(r+\rho)^2+(z-2\cdot h)^2]^{\frac{1}{2}}}\right]-$$
$$-\frac{1}{\pi}\cdot\int_0^{d_{WG}/2}\frac{M_2\cdot(z-h)\cdot E(k_2)\rho\cdot d\rho}{[(r-\rho)^2+(z-h)^2]\cdot[(r+\rho)^2+(z-h)^2]^{\frac{1}{2}}}\qquad(21)$$

$$H_3(r,z)=\frac{1}{\pi}\cdot\int_0^{d_{WG}/2}\left[\frac{M_3\cdot(z-3\cdot h)\cdot E(k_1)\rho\cdot d\rho}{[(r-\rho)^2+(z-3\cdot h)^2]}\times\frac{1}{[(r+\rho)^2+(z-3\cdot h)^2]^{\frac{1}{2}}}\right]-$$
$$-\frac{1}{\pi}\cdot\int_0^{d_{WG}/2}\frac{M_3\cdot(z-h)^2\cdot E(k_2)\rho\cdot d\rho}{[(r-\rho)^2+(z-2\cdot h)^2]\cdot[(r+\rho)^2+(z-2\cdot h)^2]^{\frac{1}{2}}}$$

$$H_n(r,z)=\frac{1}{\pi}\cdot\int_0^{d_{WG}/2}\left[\frac{M_n\cdot(z-n\cdot h)\cdot E(k_1)\rho\cdot d\rho}{[(r-\rho)^2+(z-n\cdot h)^2]}\times\frac{1}{[(r+\rho)^2+(z-n\cdot h)^2]^{\frac{1}{2}}}\right]-$$
$$-\frac{1}{\pi}\cdot\int_0^{d_{WG}/2}\left[\frac{M_n\cdot(z-(n-1)\cdot h)}{[(r-\rho)^2+(z-(n-1)\cdot h)^2]}\times\frac{E(k_2)\rho\cdot d\rho}{[(r+\rho)^2+(z-(n-1)\cdot h)^2]^{\frac{1}{2}}}\right]$$

where $k_1^2=\frac{4\cdot r\cdot\rho}{(r+\rho)^2+(z-n\cdot h)^2}$ and $k_2^2=\frac{4\cdot r\cdot\rho}{(r+\rho)^2+(z-(n-1)\cdot h)^2}$.

For $r=d_{WG}/2$ and $z=z_i=h\cdot i$, the coefficients of the matrix of form factors $A_{i,j}$ can be determined by the formula (22).

$$A_{i,j}=\frac{1}{\pi}\cdot\int_0^{d_{WG}/2}\left[\frac{(i\cdot h-j\cdot h)}{[(\frac{d_{WG}}{2}-\rho)^2+(i\cdot h-j\cdot h)^2]}\times\frac{E(k_1)\rho\cdot d\rho}{[(\frac{d_{WG}}{2}+\rho)^2+(i\cdot h-j\cdot h)^2]^{\frac{1}{2}}}\right]-$$
$$-\frac{1}{\pi}\cdot\int_0^{d_{WG}/2}\left[\frac{(i\cdot h-(j-1)\cdot h)}{[(\frac{d_{WG}}{2}-\rho)^2+(i\cdot h-(j-1)\cdot h)^2]}\times\frac{E(k_2)\rho\cdot d\rho}{[(\frac{d_{WG}}{2}+\rho)^2+(i\cdot h-(j-1)\cdot h)^2]^{\frac{1}{2}}}\right],\qquad(22)$$

where $k_1^2=\frac{2\cdot d_{WG}\cdot\rho}{(\frac{d_{WG}}{2}+\rho)^2+(i\cdot h-j\cdot h)^2}$ and $k_2^2=\frac{2\cdot d_{WG}\cdot\rho}{(\frac{d_{WG}}{2}+\rho)^2+(i\cdot h-(j-1)\cdot h)^2}$.

Similarly, the integration of expression (20) also allows you to determine, respectively, the field from the second, third, etc. elements by the formula (21).

The described technique makes it possible, taking into account the influence of demagnetizing fields, to determine the magnetization of the waveguide both at the local site and along the entire length of the waveguide.

The developed numerical method allows us to calculate the magnetization value of the waveguide material, the value of which, when substituted into expressions (3) and (4), allows us to find the values of the projection on the 0Z axis of the magnetic flux and the output signal generated by the solenoid.

The mathematical models presented in this section and the numerical method developed were implemented in the software used in the educational process, which will be described in more detail in the section devoted to computational experiments..

III. COMPUTING EXPERIMENT

Using the refined and developed models and numerical method presented in the theoretical part, the software used in the educational process was developed, which allows to conduct research in the acoustic paths of magnetostrictive displacement transducers. It consists of 5 modules, including the main one containing the menu and shown in Figure 6. When you click on the "About authors" button in it, the window shown in Figure 7 appears.

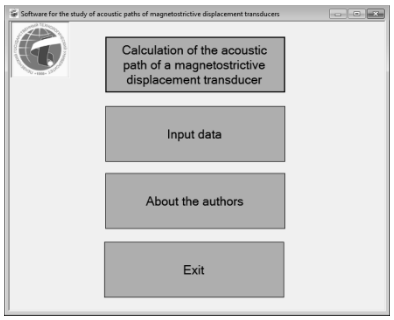


Fig. 6. The main form of the developed software.

Fig. 7. A form containing information about the authors.

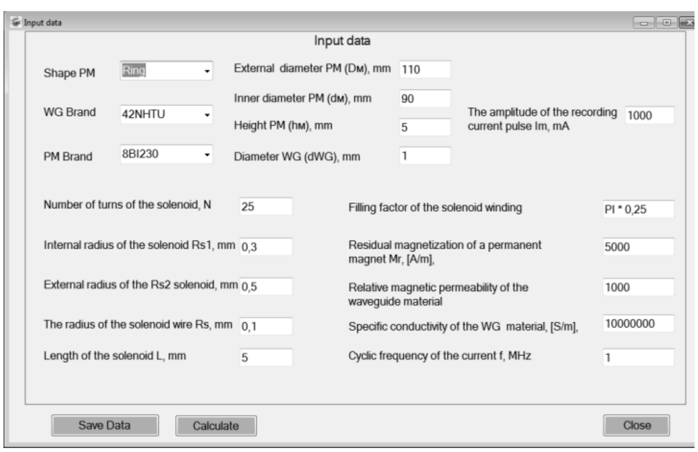


Fig. 8. Input Data Editing Form.

The "Input data" form (Figure 8) appears when the corresponding button is pressed in the main form and allows you to save to a text file, extract from it and work with information about the basic parameters and properties of the structural elements of the acoustic path of the magnetostrictive linear displacement converter. In this form, it is possible to select the shape, brand and properties of a permanent magnet and enter its parameters, enter the value of the diameter and properties of the waveguide material, the amplitude of current pulses and their cyclic oscillation frequency, the parameters and dimensions of the solenoid, the number of turns and the filling factor of its winding. After filling out this form, it becomes possible to calculate the output data either by using the "Calculate" button or by pressing the top button of the main form. The output data calculation form, the screen form of which is shown in Figure 9, allows you to obtain software-calculated data on the properties of a permanent magnet and a waveguide, as well as compare the resulting value of the resulting magnetic field strength with its minimum and maximum possible values (check whether this value is in the working area).

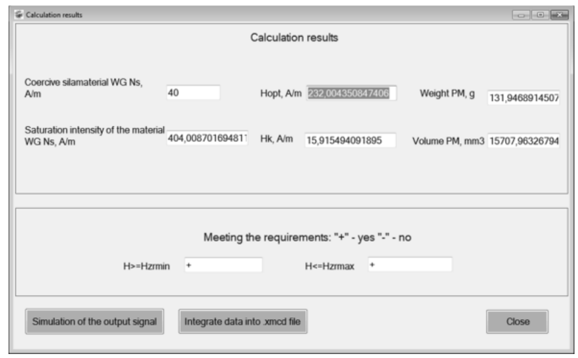


Fig. 9. Output data calculation form.

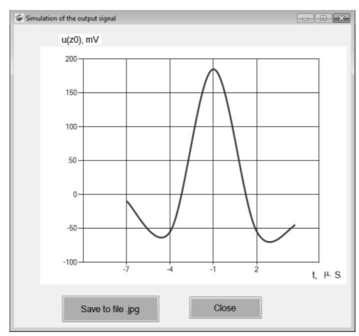


Fig. 10. The form of graphical construction of the output signal.

Also, the software can get a graphical representation of the output voltage generated by the solenoid or transmit the obtained values to MathCad to build data in this system. The results of one of the computational experiments to study the output signal generated by the solenoid from time using the developed software are shown in Figure 10. To check the adequacy of its display, it is possible to conduct an experimental test carried out in the experimental part.

IV. EXPERIMENTAL PART

To verify the adequacy of computational experiments, an experimental test was carried out using a laboratory stand assembled by the authors of the article, containing a triangular-shaped pulse generator, a reproduction solenoid that converts a moving torsional wave into an electrical signal, and a reproduction signal amplifier. The oscillogram of the excitation signal and the measuring signal is shown in Figure 12.

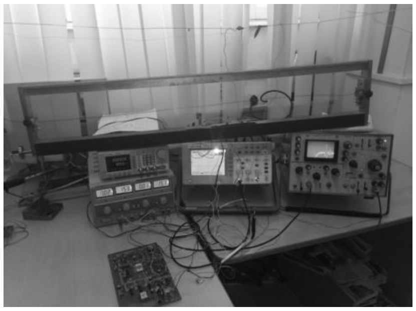
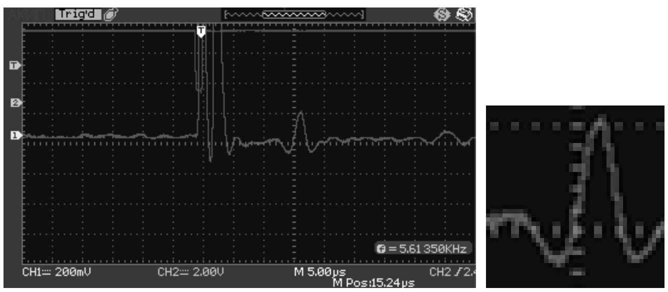


Fig. 11. Experimental installation.



(a) *b)*

Fig. 12. Experimental verification to determine the output signal. a) The received output signal and b) its scaled part containing the output signal generated by the recording current pulse.

The results of experimental verification for the values used in computational experiments showed a coincidence not only of the shape of the output signal, but also of its duration. The amplitude value of the output signal differed by no more than 10%, due to errors in the properties and parameters of the annular permanent magnet, waveguide and solenoid, as well as imperfection of the winding and switching of the solenoid.

V. Conclusions

Thus, mathematical models and a numerical method were refined and developed in the work, which makes it possible to conduct research in acoustic paths of magnetostrictive displacement transducers. The use of the developed software in the educational process will allow not only to study the main phenomena and processes occurring in the acoustic paths of magnetostrictive devices, but also to design new structures and select the necessary dimensions and properties of structural elements, which presents prospects for the development of new classes and designs of magnetostrictive devices. The results of computational experiments obtained by the developed software coincided with experimental verification using an experimental setup, which confirms the adequacy of the presented models and the developed numerical method.

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