Scholars Journal of Engineering and Technology (SJET)
Abbreviated Key Title: Sch. J. Eng. Tech.
ISSN 2347-9523 (Print)
ISSN 2321-435X (Online)

A Unit of Scholars Academic and Scientific Society, India
www.saspublishers.com

Calculation of the Complex Frequency Characteristic of Electromagnetic-Acoustic Transducers in the Excitation Mode

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Original Research Article

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Article History
Received: 12.04.2018
Accepted: 20.04.2018
Published: 30.04.2018

DOI:
10.36347/sjet.2018.v06i04.005

Abstract: In this paper the mathematical model of an electromagnetic type electroacoustic transducer in the excitation (radiation) mode of ultrasonic waves in metals is determined. To solve the dynamic magneto elastic problem, the method of successive approximations is proposed. This method is based on the assumption that the ΔE-effect is small (less than 20%). It is shown that zero approximation to the exact value of the displacement vector components of the ferrimagnet material particles, allows to preserve in solutions the information about design and geometric parameters of the alternating magnetic field source. The first approximation gives corrections that may decrease the amplitude values of the displacement vector components of the metal material particles. In addition, the error determining displacement vector components does not exceed the biquadratic of the magneto mechanical coupling coefficient, that is, one - a maximum two percent.
Keywords: electroacoustic transducer of electromagnetic type, complex frequency characteristic, excitation mode, method of successive approximations, ΔE effect.

INTRODUCTION

Electroacoustic transducers of electromagnetic type are used for non-contact excitation and registration of ultrasonic waves for purpose of non-destructive testing and technical diagnostics of metal products. The parameters and characteristics of electromagnetic-type transducers almost completely determine the technical and economic parameters of defect ology equipment.

The development of competitive devices for nondestructive testing and technical diagnostics of metal products is practically impossible without a clear understanding of the various parameters influence of the transducers components on its transfer characteristics - the complex frequency response and the impulse response, that is actually is a Fourier transform of the complex frequency response. Thus, the complex frequency response in the excitation or detection (registration) mode of ultrasonic waves is the primary (fundamental) mathematical description of the electromagnetic-type transducer in this or that mode of operation. With this definition, it becomes clear that the terms "mathematical model" and "complex frequency response" of the converter are equivalent concepts.

As far as judging by the available publications (4 – 9) in the world practice of theoretical studies of electromagnetic type transducers, the question of the complex frequency characteristic of the transducers is not something that has not been developed - it is not even put on the agenda.

In this paper the theoretical basis for calculating the complex frequency response of an electromagnetic-type transducer in the mode of ultrasonic wave's excitation in metals are described.

MAIN PART

The typical design of an electromagnetic type electroacoustic transducer that operates in the mode of ultrasonic wave excitation consists of three basic elements (see fig. 1). The first element is the source of a permanent magnet field (not shown in the fig.1). It creates in the metal sample volume a magnetic field that does not vary in time with the intensity $\vec{H}^0(x_k)$ (x_k - coordinates of the point in Cartesian coordinate system).

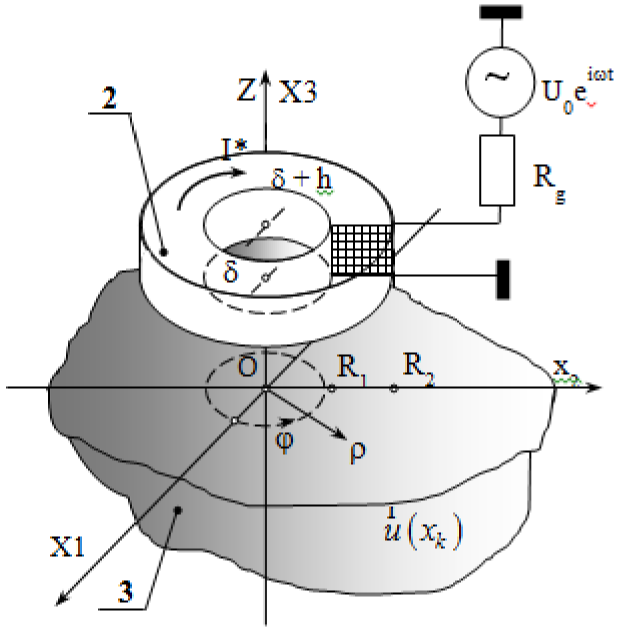

Fig-1:Typical construction of electromagnetic acoustic transducer working in ultrasonic wave mode

The second element is the source of the alternating magnetic field. This usually a system of conductors that can be located on a ferromagnetic core and through that an alternating current flows $I(t)=I^{*}e^{i\omega t}$ (t - time, I^{*} - amplitude of electric current, $i=\sqrt{-1}$ - imaginary unit, ω - circular frequency of sign change). This system of conductors creates in the metal volume a time-varying (alternating) magnetic field with intensity $\vec{H}(x_k,\omega)e^{i\omega t}$, where $\vec{H}(x_k,\omega)$ - the spatially developed amplitude of the vector of the alternating magnetic field intensity, that depends on the frequency ω and coordinates, points x_k of field characteristics observation.

The third required transducer element is a certain volume of metal that is located in the immediate vicinity of the alternating magnetic field source and in in this element the energy of the alternating magnetic field is converted into displacements of the material particles of metal. These displacements will be described by a vector $\vec{u}(x_k)e^{i\omega t}$ assuming in this case that in the presence of a strong magnetic bias field, when the strong inequality $\left|\vec{H}^{0}(x_k)\right| >> \left|\vec{H}^{*}(x_k,\omega)\right|$ is satisfied, the process of transformation $\vec{H}^{*}(x_k,\omega) \Rightarrow \vec{u}(x_k)$ is linear.

With all the above, allows write down the signal conversion algorithm that is realized during the electromagnetic excitation of electromagnetic waves in metals:

$$\begin{array}{c} U_g e^{i\omega t} \Rightarrow I^{*}e^{i\omega t} \Rightarrow \vec{H}^{*}(x_k,\omega)e^{i\omega t} \Rightarrow \\ \Rightarrow \begin{pmatrix} \rho_0, c^{H}_{ijkl}, r, \\ \mu^{\varepsilon}_{nm}, m_{pqij} \end{pmatrix} \Rightarrow \vec{u}(x_k)e^{i\omega t} \\ \Uparrow \\ \vec{H}^{0}(x_k) \end{array} \qquad (1)$$

Where U_g – the difference of electric potentials at the output of the generator of electrical signals. The symbols of physical parameters of metals are written in parentheses: ρ_0 – density; c^{H}_{ijkl} – moduli of elasticity in the demagnetized state; r – specific electric conductivity is a tensor of the second rank with a spherical index surface; μ^{ε}_{nm} – component of the permeability tensor, experimentally determined in the regime of constancy of elastic deformations (symbol ε); m_{pqij} – component of the magnetostriction constant tensor.

Since the point at that the result of the action of the transducer is determined, that is, the amplitude of the displacement $\vec{u}(x_k)$, can be chosen in the volume of the metal arbitrarily, so electromagnetic type transducer is a physical system with a fixed electrical input (these are the points of electrical connection of the generator of electrical signals with the conductors of the source of the alternating magnetic field) and with the mechanical output distributed in space (this is the set of points in that the displacement $\vec{u}(x_k)$ can be determined). Since the transformation $U_g \Rightarrow \vec{u}(x_k)$ is linear, is possible the following entry

$$\vec{u}(x_k) = U_g \vec{W}(x_k, \omega, \Pi), \quad (2)$$

Where $\vec{W}(x_k, \omega, \Pi)$ – vector transfer characteristic of a electromagnetic type excitation transducer (the symbol Π in the argument list means the set of physical parameters of the system). Components $W_j(x_k, \omega, \Pi)$ of the vector function $\vec{W}(x_k, \omega, \Pi)$ have the meaning of complex frequency characteristics of the transducer in the excitation mode of the j-th component of the displacement vector of the material particles of the metal.

Consider a method for determining of the function components $\vec{W}(x_k, \omega, \Pi)$. The components $\vec{u}(x_k)$ of the displacement vector of the material particles of the metal satisfy the second Newton's law in differential form that in terms of the amplitudes of the changing in time physical fields according to the law $e^{i\omega t}$ is written in the following form

$$\frac{\partial \sigma_{ij}}{\partial x_i} + \rho_0 \omega^2 u_j - L_j = 0 \ \forall x_k \in V \ \ (i, j = 1, 2, 3) \quad (3)$$

where σ_{ij} – amplitude value of the tensor component of mechanical stresses in the deformed by an alternating magnetic field metal volume; L_j – j-th vector component of the Lorentz forces volume density, and $L_j = \varepsilon_{jmn} J_m \left(\mu_{ns}^{\varepsilon} H_s^0 \right)$; ε_{jmn} – Levi-Civita tensor component that is equal to plus one when the indices j, m, n form a permutation of numbers 1, 2,3 with an even number of disturbances, equal to minus one, when in the permutation an odd number of disturbances, and is equal to zero when any two of the three indices are equal (coincide); J_m – m-th vector component of the density eddy current of conduction. The symbol V in relation (3) denotes the volume of the metal.

The electromagnetic state of the deformable metal is determined by Maxwell's equations, that neglecting the displacement currents, are written in terms of the physical fields amplitude values varying in time according to law $e^{i\omega t}$, are written as follows

$$\varepsilon_{msj} \frac{\partial H_j}{\partial x_s} = r E_m, \ \varepsilon_{prm} \frac{\partial E_m}{\partial x_r} = -i\omega B_p, \quad (4)$$
$$(j, m, p, r, s = 1, 2, 3)$$

where $\vec{H}$ and $\vec{E}$ – vectors of intensity of magnetic and electric fields; $\vec{B}$ – vector of magnetic induction.

Eliminating the component E_m from equations (4), we can write

$$\varepsilon_{prm} \varepsilon_{msj} \frac{\partial^2 H_j}{\partial x_s \partial x_r} + i\omega r B_p = 0 \ \forall x_k \in V, \quad (5)$$
$$(j, m, p, r, s = 1, 2, 3)$$

The connecting link between the fundamental equations of mechanic (3) and electrodynamic (5) are the equations of the deformable ferrimagnet physical state. The linearized version [1] of the general relations of the phenomenological theory of Vlahos's magnetostrictive phenomena [2] has the form

$$\sigma_{ij} = c_{ijkl}^{H} \frac{\partial u_k}{\partial x_l} - m_{pqij} H_p^0 H_q , \qquad (6)$$

$$(i, j, k, l, p, q = 1,2,3)$$

$$B_p = m_{pmns} H_p^0 \frac{\partial u_s}{\partial x_n} + \mu_{pr}^{\varepsilon} H_r . \qquad (7)$$

$$(p, m, n, r, s = 1,2,3)$$

Substituting relations (6) into equations (3) and expressions (7) into equations (5), obtain

$$c_{ijkl}^{H} \frac{\partial^2 u_k}{\partial x_i \partial x_l} + \rho_0 \omega^2 u_j - m_{pqij} \frac{\partial\left(H_p^0 H_q\right)}{\partial x_i} - \qquad (8)$$
$$- L_j = 0 \ \forall x_k \in V, \ (i, j, k, l, p, q = 1,2,3),$$

$$\varepsilon_{prm} \varepsilon_{msj} \frac{\partial^2 H_j}{\partial x_s \partial x_r} + i\omega r m_{pmns} H_p^0 \frac{\partial u_s}{\partial x_n} + i\omega r \mu_{pr}^{\varepsilon} H_r = \qquad (9)$$
$$= 0 \ \forall x_k \in V, \ (j, m, n, p, r, s = 1,2,3).$$

It should be emphasized that the vector $\vec{H} = \vec{H}^* + \vec{h}$, where the $\vec{H}^*$ – magnetic field intensity, that is created in the volume of the metal by an electromagnetic type transducer, $\vec{h}$ – is the intensity vector of the internal magnetic field that arises in a deformable ferromagnetic due to the rotation of magnetic domains (converse magnetostrictive effect). The vector $\vec{H}^*$ by its definition satisfies the Maxwell equations

$$\varepsilon_{prm} \varepsilon_{msj} \frac{\partial^2 H_j^*}{\partial x_s \partial x_r} + i\omega r \mu_{pr}^{\varepsilon} H_r^* = 0 \ \forall x_k \in V$$

Taking into account the latest comments, write the equations (8) and (9) as follows:

$$c_{ijkl}^{H} \frac{\partial^2 u_k}{\partial x_i \partial x_l} + \rho_0 \omega^2 u_j - m_{pqij} \frac{\partial\left(H_p^0 h_q\right)}{\partial x_i} - \qquad (10)$$
$$- f_j^* = 0 \ \forall x_k \in V, \ (i, j, k, l, p, q = 1,2,3),$$

$$\varepsilon_{prm} \varepsilon_{msj} \frac{\partial^2 h_j}{\partial x_s \partial x_r} + i\omega r m_{pmns} H_p^0 \frac{\partial u_s}{\partial x_n} +$$
$$+ i\omega r \mu_{pr}^{\varepsilon} h_r = 0 \ \forall x_k \in V, \qquad (11)$$
$$(j, m, n, p, r, s = 1,2,3),$$

where $f_j^* = L_j + m_{pqij} \partial\left(H_p^0 H_q^*\right) / \partial x_i$ – the volume density of external loads, that is, the Lorentz force and the Joule forces or magnetostrictive forces (the second term).

It is obvious that the change in the electromagnetic state of dynamically deformable metal volume elements is accompanied by the emission of the electromagnetic field energy into the surrounding space. In other words, in the space surrounding the metal object, there is an electromagnetic scattering field, the magnetic component of that has intensity $\tilde{H}(x_k) e^{i\omega t}$. Assuming that the magnetic and dielectric properties of the surrounding space are determined by the constants $\mu_0 = 4\pi \cdot 10^{-7} \ H/m$ and $\chi_0 = 8{,}85 \cdot 10^{-12} \ F/m$, i.e $\tilde{B} = \mu_0 \tilde{H}$ and $\tilde{D} = \chi_0 \tilde{E}$, where $\tilde{D}$ and $\tilde{E}$ – vectors of electrical induction and field intensity of the electromagnetic scattering field electric component, arrive at the following system of equations:

$$\varepsilon_{prm} \varepsilon_{msj} \frac{\partial^2 \tilde{H}_j}{\partial x_s \partial x_r} - k_0^2 \tilde{H}_p = 0 \ \forall x_k \notin V, \qquad (12)$$
$$(j, m, p, r, s = 1,2,3),$$

where $k_0^2 = \omega^2 \mu_0 \chi_0 = \omega^2 / c^2$; $c = 1/\sqrt{\mu_0 \chi_0}$ – propagation speed of electromagnetic excitation in vacuum. The solutions of the equations system (12) must satisfy the conditions of physical realizability of the field source, i.e, the limiting conditions

$$\lim_{R \to \infty} \left[\tilde{H}_j(x_k), \frac{\partial \tilde{H}_j(x_k)}{\partial x_p} \right] = 0, \ (j, p = 1,2,3), \quad (13)$$

Where R – distance from the surface of the metal ware S to the point with coordinates x_k in that the components $\tilde{H}_j(x_k)$ are determined

The uniqueness of the equations systems (10) - (12) solution is ensured by the unconditional fulfillment of the limiting relation (13) and the conditions on the deformable metal surface S, that are written in the following form

$$n_p \left(c^H_{pqkl} \frac{\partial u_k}{\partial x_l} - m_{ijpq} H_i^0 h_j - \sigma^*_{pq} \right) = 0 \ \forall x_k \in S, \quad (14)$$
$$(i, j, k, l, p, q = 1,2,3)$$

$$\varepsilon_{kpm} n_p \left(h_m - \tilde{H}_m \right) = 0 \ \forall x_k \in S, \ (k, p, m = 1,2,3) \quad (15)$$

$$n_p \left(m_{pmns} H_p^0 \frac{\partial u_s}{\partial x_n} + \mu^\varepsilon_{pr} h_r - \mu_0 \tilde{H}_p \right) = 0 \ \forall x_k \in S, \quad (16)$$
$$(p, m, n, s, r = 1,2,3)$$

where n_p – projection of the vector of the unit external normal at the point with coordinates x_k on the surface S on the coordinate axes of the right-handed Cartesian coordinate system; $\sigma^*_{pq} = M^*_{pq} + m_{ijpq} H_i^0 H_j^*$ – the surface density of external loads – the ponder motive action of the electromagnetic field (tensor component of the Maxwell's field tension M^*_{pq}) and the Joule forces (magnetostrictive forces) – the second term

THE RESULTS OF NUMERICAL RESEARCH

Naturally, the solution of the dynamic theory of magneto elasticity boundary problem, that in the general case consists of nine partial differential equations of the second order (10) - (12) and nine main boundary conditions (14) - (16), is associated with significant computational difficulties.

Having overcome these difficulties, it is possible to preserve specific connectivity effects in the obtained solutions, i. e., the consonant action of the elastic forces and the internal magnetic field in the volume of the deformable metal. The effects of connectivity are manifested, first of all, in increasing the elasticity modulus of the metal (the so-called ΔE -affect). In addition, quantitative changes undergo magnetic permeability, magnetostrictive constants and even electrical conductivity. This is a key question, that is due to the fact that the elastic properties of a polycrystalline (i.e., isotropic in a demagnetized state) metal acquire an insignificant anisotropy. And this entails far-reaching consequences.

At the same time, based on quantitative estimates that can be formulated on the basis of simplest model problems exact solutions, it can be argued that the maximum changes in the elasticity modulus of a metal never exceed 20% of their original value in a demagnetized state. The electrical conductivity of metals greatly reduces the levels of ΔE -effect manifestation.

It can be assumed that in the ferromagnetic group metals, when they are dynamically deformed by an alternating magnetic field, the elasticity modulus changes do not exceed 10% of their original value. This allows to avoid the joint solution of the equations system (10) - (12) and implement the method of successive approximations to the exact values of the vectors, $\vec{u}(x_k)$, $\vec{h}(x_k)$ and $\tilde{\vec{H}}(x_k)$.

Represent the exact solutions $\vec{u}(x_k)$ and $\vec{h}(x_k)$ of the boundary problem (10) - (16) in the form of the following series:

$$\vec{u}(x_k)=\vec{u}^{(0)}(x_k)+\sum_{m=1}^{\infty}\Delta\vec{u}^{(m)}(x_k),$$
$$\vec{h}(x_k)=\vec{h}^{(1)}(x_k)+\sum_{m=2}^{\infty}\Delta\vec{h}^{(m)}(x_k), \quad (17)$$

Where $\vec{u}^{(0)}(x_k)$ and $\vec{h}^{(1)}(x_k)$ – the zero and first ($\vec{h}^{(0)}(x_k)=0$) approximations to the exact values of the vectors $\vec{u}(x_k)$ and $\vec{h}(x_k)$; $\Delta\vec{u}^{(m)}(x_k)$ and $\Delta\vec{h}^{(m)}(x_k)$ – corrections to the initial approximations at subsequent iterative steps. The magnetic scattering field $\tilde{H}(x_k)$ is found in the same way as the internal magnetic field $\vec{h}(x_k)$.

In the zeroth approximation, the boundary-value problem of dynamic magnetoelasticity "contracts" to the boundary problem of the harmonic oscillations excitation in an isotropic solid by a system of volume and surface loads, that is written in the following form

$$c_{ijkl}^{H}\frac{\partial^2 u_k}{\partial x_i \partial x_l}+\rho_0\omega^2 u_j-f_j^*=0\ \forall x_k\in V, \quad (18)$$
$$(i,j,k,l=1,2,3),$$
$$n_p\left(c_{pqkl}^{H}\frac{\partial u_k}{\partial x_l}-\sigma_{pq}^*\right)=0\ \forall x_k\in S, \quad (19)$$
$$(k,l,p,q=1,2,3),$$

The solution of boundary value problem (18) - (19) for axisymmetric ally propagating Lamb waves is given in [3]. The external loads f_j^* and σ_{pq}^* given by the problem condition form the amplitude multipliers of the excited ultrasonic waves.

Since the distribution in space of the volume and surface densities of external forces is mainly determined by the alternating magnetic field distribution character in the space, that in turn is due to the design and dimensions of the source of the alternating magnetic field in the electromagnetic-type transducer, expect that in the calculation formulas for the amplitude factors of ultrasonic waves with-stored information about the transducer parameters and structure. Thus, the solution of the boundary value problem (18, 19) makes it possible to formulate estimates of the complex frequency characteristic of the electromagnetic type transducer with an error that does not exceed 10%, i.e., ΔE-effect manifestation levels that are directly proportional to the numerical values of the square of the magneto mechanical coupling coefficient $K_{(ijkl)}^2$, wherein $\Delta c_{ijkl}=c_{ijkl}^{H}K_{(ijkl)}^2$.

After determining the zero approximation $\vec{u}^{(0)}(x_k)$ to the exact value $\vec{u}(x_k)$, the first approximation for the internal magnetic field and the magnetic field vector of the scattering are determined. The boundary value problem is solved as follows:

$$\varepsilon_{prm}\varepsilon_{msj}\frac{\partial^2 h_j^{(1)}}{\partial x_s \partial x_r}+i\omega r\mu_{pr}^{\varepsilon}h_r^{(1)}+i\omega r m_{pmns}H_p^0\frac{\partial u_s^{(0)}}{\partial x_n}= \quad (20)$$
$$=0\ \forall x_k\in V,\quad (j,m,n,p,r,s=1,2,3)$$
$$\varepsilon_{prm}\varepsilon_{msj}\frac{\partial^2 \tilde{H}_j^{(1)}}{\partial x_s \partial x_r}-k_0^2\tilde{H}_p^{(1)}=0\ \forall x_k\notin V, \quad (21)$$
$$(j,m,p,r,s=1,2,3)$$
$$\lim_{R\to\infty}\left[\tilde{H}_j^{(1)}(x_k),\frac{\partial \tilde{H}_j^{(1)}(x_k)}{\partial x_p}\right]=0,\ (j,p=1,2,3) \quad (22)$$

$$\varepsilon_{kpm} n_p \left(h_m^{(1)} - \tilde{H}_m^{(1)} \right) = 0 \ \forall x_k \in S, \ \left(k, p, m = 1,2,3 \right) \quad (23)$$

$$n_p \left(m_{pmns} H_p^0 \frac{\partial u_s^{(0)}}{\partial x_n} + \mu_{pr}^{\varepsilon} h_r^{(1)} - \mu_0 \tilde{H}_p^{(1)} \right) = \quad (24)$$
$$= 0 \ \forall x_k \in S, \ \left(p, m, n, s, r = 1,2,3 \right)$$

Where the vector components $\vec{u}^{(0)}(x_k)$ are considered known quantities.

After determining the first approximations $\vec{h}^{(1)}(x_k)$ and $\tilde{\vec{H}}^{(1)}(x_k)$, it becomes possible to determine the correction $\Delta\vec{u}^{(1)}(x_k)$ of the first approximation. Substituting the value $\vec{u}^{(1)}(x_k) = \vec{u}^{(0)}(x_k) + \Delta\vec{u}^{(1)}(x_k)$ into equation (10), obtain the following result

$$c_{ijk\mathrm{l}}^{H} \frac{\partial^2 \Delta u_k^{(1)}}{\partial x_i \partial x_\mathrm{l}} + \rho_0 \omega^2 \Delta u_j^{(1)} - m_{pqij} \frac{\partial \left(H_p^0 h_q^{(1)} \right)}{\partial x_i} = \quad (25)$$
$$= 0 \ \forall x_k \in V, \ \left(i, j, k, \mathrm{l}, p, q = 1,2,3 \right)$$

The uniqueness of the equations system (25) solution, that are written in neglecting the perturbations of the eddy current of conduction, that are due to the internal magnetic field, is provided by the boundary conditions

$$n_p \left(c_{pqk\mathrm{l}}^{H} \frac{\partial \Delta u_k^{(1)}}{\partial x_\mathrm{l}} - m_{ijpq} H_i^0 h_j^{(1)} \right) = 0 \ \forall x_k \in S, \quad (26)$$
$$\left(i, j, k, \mathrm{l}, p, q = 1,2,3 \right)$$

The recording of that does not take into account the perturbations of the numerical values of the Maxwell tension tensor components due to the internal magnetic field.

After determining the correction $\Delta\vec{u}^{(1)}(x_k)$, the first approximation $\vec{u}^{(1)}(x_k) = \vec{u}^{(0)}(x_k) + \Delta\vec{u}^{(1)}(x_k)$ to the exact solution $\vec{u}(x_k)$ has an error that does not exceed $K_{(ijk\ell)}^4$, i.e., the order of one percent. The substitution of the first approximation $\vec{u}^{(1)}(x_k)$ in (11) and the boundary conditions (16) allows to determine the corrections $\Delta\vec{h}^{(2)}(x_k)$ and $\Delta\tilde{\vec{H}}^{(2)}(x_k)$ from the values of the correction $\Delta\vec{u}^{(1)}(x_k)$. The error of the second approximation to the exact values of the vectors $\vec{h}(x_k)$ and $\tilde{\vec{H}}(x_k)$ also should not exceed the value $K_{(ijk\mathrm{l})}^4$.

At this step, iterative process is can be interrupted. The components of the vector transfer characteristic are determined with an error that does not exceed the values $K_{(ijk\ell)}^4$.

CONCLUSION

In the paper present solution of the boundary problem calculation of the complex frequency characteristic of electromagnetic-acoustic transducers in the excitation mode

It is shown that this solution consisting, in the general case, of nine partial differential equations of the second order, and makes it possible to preserve the coupling effect of elastic and magnetic fields in the deformable ferromagnet volume, that manifests itself in an increase in the elastic moduli of the metal (ΔE -effect).

The phenomenon of the ΔE - effect arises from the simultaneous manifestation of direct and inverse magnetostrictive effects in a ferromagnet deformed by a magnetic field. To solve the dynamic magnetoelastic problem, a method of successive approximations was proposed.

The sequential implementation of proposed computational procedures, allows to construct a mathematical model of an electroacoustic transducer of the electromagnetic type in the ultrasonic wave excitation mode, that basically contains the fundamental positions of mechanics of the deformable solids and classical electrodynamics, and takes into account the main regularities of dynamic magnetoelasticity.

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