DETERMINATION OF MAGNETOSTRICTIVE CONSTANTS OF A POLYCRYSTALLINE FERROMAGNETIC BY RESONANCE FREQUENCIES OF RADIAL VIBRATIONS OF A RING

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We constructed a mathematical model of radial vibrations of a ring made of a polycrystalline ferromagnetic (magnetostrictive) material. We show the appearance of the resonance absorption of the energy of a magnetic field source at certain frequencies, which is accompanied by a resonant increase and decrease in the inductance of a toroidal coil, whose core is a ring of the material under study. We propose an algorithm for the determination of material constants of a polycrystalline ferromagnetic by measured frequencies of magnetomechanical resonances.

1. Introduction

At the magnetization, ferromagnetics (FMs) change their sizes and a shape due to the magnetostriction (MS). On the other hand, at a mechanical deformation of preliminarily magnetized FMs, their magnetization is also changed. It is the so-called Villari effect or the inverse MS effect [1,2]. Magnetostrictive constants are determined experimentally within the well-known methods of direct measurements of small displacements, namely: tensometric [3], interferometric [4], capacitance, and other methods. These methods are characterized by an insufficient accuracy, a low sensitivity in some cases, and a certain boundedness of the frequency range. The measurement of the magnetization of FMs at various types of their deformation is carried on, as a rule, by observing the hysteresis loops of FMs [5] or with the help of the Faraday effect [6]. These methods are labor-consuming and cannot give exact results. Among the fundamental works, in which a great attention was given to the measurement of magnetostrictive constants, it is worth to separate works [7] and [8]. However, these works are of applied character and are oriented to the engineering calculation of magnetostrictive transducers of specific types and to the construction of their equivalent electric circuits [8]. Thus, the problem of the determination of material constants of ferromagnetic materials remains unsolved from the view point of the statement of a physical experiment up to now. The studies of MS and the Villari effect can be joined in the frame of a single experiment, which is proposed in this work. If a FM is simultaneously placed in an external constant magnetic field and an external variable magnetic field of a certain frequency, it begins, as a mechanical system, to vibrate in a resonant manner due to MS. These vibrations cause the appearance of mechanical stresses, a further change in the magnetization, and, respectively, a change of the total magnetic field in a FM.

2. Mathematical Model of Inductance Coil with a Radially Vibrating Ferromagnetic Core

We consider a mathematical model of a physical state of the specimen made of a magnetostrictive material under study and, on its basis, propose a new method of measurement of material constants of a polycrystalline FM by resonance frequencies of radial vibrations of a ring positioned into a toroidal coil. As material constants, we mean the collection of the following quantities: components of the tensor of elasticity moduli of a demagnetized FM, components of the tensor of piezomagnetic constants, and components of the magnetic permittivity tensor of a FM.

The structure of the model of a coil with inductance L_k is shown in Fig. 1.

Coil 1 contains N windings of a wire on the core. Core *2* is produced of a polycrystalline ferromagnetic (magnetostrictive) material and is placed in the middle of a casing (the casing is not shown) touching it at several points. The core sizes are as follows: R_1 and R_2 are the inner and outer radii, respectively, and h is the core thickness. A specific feature of the coil structure consists in that that the core is not squeezed by windings, which would hamper the appearance of elastic mechanical vibrations in the core. The coil under study is fed by a direct current I^0 which creates a circular constant bias field with strength $H^0_\vartheta = NI^0/R_0$, where ϑ is the circular coordinate (polar angle) of a cylindrical coordinate system (ρ, θ, z), whose origin is placed at the coil core center, and $R_0 = (R_1 + R_2)/2$ is the mean radius of the core. Simultaneously, the coil is fed by an alternating current I^* so that $I^0 \gg I^*$, which is equivalent to the condition $\mathbf{H}^0 \gg \mathbf{H}^*$, where $\mathbf{H}^0$ and $\mathbf{H}^*$ are the strength vectors of the constant and variable magnetic fields.

If the strength of the constant bias field is chosen so that the ring core is not magnetized to the saturation, then the joint action of the constant and variable magnetic fields, whose strength vectors have only a single circular component, induces radial (along the radius ρ) vibrations of material particles in a ring ferromagnetic specimen. During a deformation of the core, an additional magnetic field supplementing the field of an external source arises. The appearance of the additional magnetic field in the coil core can be explained on the basis of the Villari effect, due to which changes in the specimen magnetization and in the magnetic field induction occur at a change in mechanical stresses in the core. The initial phase of oscillations of this field depends on the ratio of the frequency of the external source and the resonance frequency of the mechanical oscillatory system. In this case, the energy of a source of the external magnetic field is transferred almost completely into the deformable core bulk. A change in the energy capacity of the specimen causes a change in the inductance of coil. Indeed, the inductance of a coil can be determined in terms of the magnetic energy of the field localized in the coil core bulk [9], namely:

$$L_k = \frac{1}{(I^*)^2} \int_V \mathbf{B}^* \cdot \mathbf{H}^* dV, \qquad (1)$$

where I^*, $\mathbf{B}^*$, and $\mathbf{H}^*$ are the amplitudes of the electric current, magnetic induction, and strength of the magnetic field, respectively, which vary harmonically in time, and V and dV are the volume and an element of the core

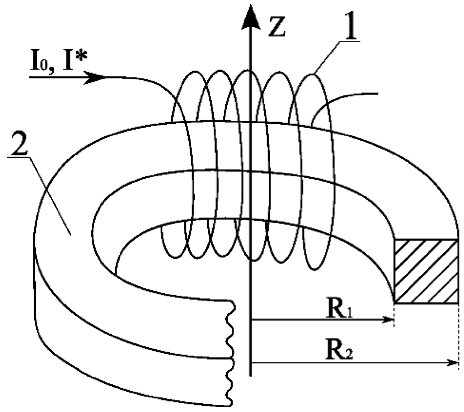

Fig. 1. Structure of a coil with inductance L_k

volume. Amplitude values of components of the vector of displacements of material particles at any point of the core coil at any time moment are determined by the ratios of three forces: elastic force, inertial force, and magnetoelastic force. These forces are proportional to the product of the strengths of constant and variable magnetic fields, i.e., they are proportional to a degree of orientation of magnetic domains and to the magnitude of the influence of the variable magnetic field on them. At some frequency f_p called the frequency of a magnetomechanical resonance, the elastic forces and inertial forces mutually compensate each other. In this case, large radial displacements of material particles arise in the specimen bulk. This is accompanied by an additional orientation of domains. As a result, the magnetic induction in the specimen bulk attains the saturation.

Thus, the magnetic energy of the coil and the core, i.e., the energy of the inductance L_k, will attain the maximum value at the frequency f_p. If the frequency of a variable magnetic field exceeds somewhat the resonance frequency f_p, and if the displacement of material particles of a ferromagnetic is else quite large, then the magnetic induction of the field caused by elastic displacements of material particles becomes counterphase with respect to the induction of the magnetic field of a current I^*. Therefore, the net magnetic induction L_k in the coil core bulk decreases. We call this frequency conditionally the frequency of a magnetomechanical antiresonance, f_a, which is somewhat higher than the frequency f_p.

It is worth noting that an increase in the coefficient of self-induction L_k at the frequency f_p and its decrease at the frequency f_a are damped by energy losses in the core material and at the points of mechanical contact of the core and a casing, on which the winding is positioned. For this reason, changes of the inductance at the frequencies f_p and f_a will have a bounded amplitude.

As the frequency ω increases further, the displacements of material particles decrease sharply, and the contribution of deformations to the dynamic magnetization of the core becomes insignificant. Numerical values of the resonance and antiresonance frequencies are determined by sizes and physico-mechanical parameters of the core material. This yields the possibility to solve the inverse problem: by values of the experimentally registered frequencies $f_{\rm p}$ and $f_{\rm a}$, it will be possible to calculate the material constants of a ferromagnetic material. To formulate an algorithm of the recalculation of numerical values of the resonance and antiresonance frequencies into numerical values of the material constants of a ferromagnetic, it is necessary to calculate the coefficient of self-induction $L_{\rm k}$ of a coil with vibrating ferromagnetic core. From the general definition (1) of the inductance $L_{\rm k}$ in the case of a uniform arrangement of windings on a ring core, we obtain the following formula for calculations:

$$L_{\rm k} = \frac{2\pi}{(I^*)^2} \int\limits_{R_1}^{R_2} \int\limits_{-h/2}^{h/2} \rho B_\vartheta^* \cdot H_\vartheta^* d\rho dz, \tag{2}$$

where ρ is a value of the radial coordinate in the cylindrical coordinate system. In a separate case where $I^0 \gg I^*$, which is equivalent to the condition $\left|\mathbf{H}^0\right| \gg |\mathbf{H}^*|$, where $\mathbf{H}^0$ and $\mathbf{H}^*$ are the strength vectors of the constant and variable magnetic fields, the equations of state of a ferromagnetic yield the relations

$$\sigma_{ij}^* = c_{ijkl}^H \varepsilon_{kl}^* - m_{pqij} H_p^0 H_q^*, \tag{3}$$

$$B_s^* = m_{rsnm} H_r^0 \varepsilon_{nm}^* + \mu_{sl}^\varepsilon H_l^*, \tag{4}$$

where σ_{ij}^* is the amplitude value of a component of the tensor of net mechanical stresses harmonically varying in the course of time, and c_{ijkl}^H is a component of the tensor of elasticity moduli of a demagnetized ferromagnetic, ε_{kl}^* is the amplitude value of a component of the tensor of deformations of the ferromagnetic core, m_{pqij} is a component of the tensor of magnetostrictive constants, B_s^* is a component of the vector of the net magnetic induction, and μ_{sl}^ε is a component of the tensor of magnetic permittivities which is measured in the mode of a steady deformation.

In the frame of the solved problem, components of the strength vectors of the constant and variable magnetic fields are determined by the law of total flow of these fields, and elastic deformations are determined by the Newton second law:

$$\sigma_{ij,j}^* + \rho_0 \omega^2 u_i^* = 0 \forall x_k \in V, \tag{5}$$

where ρ_0 is the density of a ferromagnetic, and u_i^* is the amplitude of the i-th component of the vector of displacements of material particles of a ferromagnetic. The comma between indices means the operation of differentiation of the expression written before the comma with respect to the coordinate, whose index stands after the comma. Since the vectors of the strength of magnetic fields and the magnetization in this problem have only a single circular component, the uniqueness of the solution of the system of differential equations (5) is ensured by the boundary conditions

$$n_j \sigma_{ij}^* = 0 \forall x_k \in S, \tag{6}$$

where n_j is a component of the outer normal to the surface S bounding the volume V of the ferromagnetic core. Since all physical fields in the ring core are characterized by the axial symmetry, the boundary-value problem (5), (6) in the cylindrical coordinate system takes the form [10]

$$\sigma_{\rho\rho,\rho}^* + \sigma_{\rho z,z}^* + \left(\sigma_{\rho\rho}^* - \sigma_{\vartheta\vartheta}^*\right)/\rho + \rho_0 \omega^2 u_\rho^* = 0 \forall (\rho, z) \in V, \tag{7}$$

$$\sigma_{z\rho,\rho}^* + \sigma_{zz,z}^* + \sigma_{z\rho}^*/\rho + \rho_0 \omega^2 u_z^* = 0 \forall (\rho, z) \in V, \tag{8}$$

$$\sigma_{\rho\rho}^*\big|_{\rho=R_1,R_2} = 0, \quad \sigma_{\rho z}^*\big|_{\rho=R_1,R_2} = 0, \tag{9}$$

$$\sigma_{z\rho}^*\big|_{z=\pm h/2} = 0, \quad \sigma_{zz}^*\big|_{z=\pm h/2} = 0. \tag{10}$$

The net mechanical stresses are determined from the equation of state (3) as follows:

$$\sigma_{\rho\rho}^* = c_{11}^H \varepsilon_{\rho\rho}^* + c_{12}^H \varepsilon_{\vartheta\vartheta}^* + c_{13}^H \varepsilon_{zz}^* - m_{211}^0 H_\vartheta^*,$$

$$\sigma_{\vartheta\vartheta}^* = c_{21}^H \varepsilon_{\rho\rho}^* + c_{22}^H \varepsilon_{\vartheta\vartheta}^* + c_{23}^H \varepsilon_{zz}^* - m_{222}^0 H_\vartheta^*,$$

$$\sigma_{zz}^* = c_{31}^H \varepsilon_{\rho\rho}^* + c_{32}^H \varepsilon_{\vartheta\vartheta}^* + c_{33}^H \varepsilon_{zz}^* - m_{233}^0 H_\vartheta^*, \quad \sigma_{\rho z}^* = c_{55}^H \varepsilon_{\rho z}^*, \tag{11}$$

where $m_{kij}^0 = m_{pkij} H_{\rm p}^0$ are the piezomagnetic constants.

The vector of displacements of material particles from the equilibrium position has a single nonzero radial component uρ. In this case, the components of the tensor of strains $\varepsilon_{\rho\rho} \equiv \varepsilon_\rho = u_{\rho,\rho}$, and $\varepsilon_{\vartheta\vartheta} \equiv \varepsilon_\vartheta = u_\rho/\rho$. We note that a polycrystalline FM in the demagnetized state is isotropic by elastic and magnetostrictive properties, i.e., the material constants c_{ijkl}^H and m_{pqij} are components of isotropic tensors of the fourth rank and are determined in terms of two constants,

$$c^H_{ijkl} = \lambda\delta_{ij}\delta_{kl} + G(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}),$$

$$m_{pqij} = m_2\delta_{pq}\delta_{ij} + \frac{m_1 - m_2}{2}(\delta_{pi}\delta_{qj} + \delta_{pj}\delta_{qi}), \qquad (12)$$

where λ and G are the Lamé constants or the moduli of elasticity (G is the shear modulus), δ_{ij} is the Kronecker delta, and m_1 and m_2 are constants which are determined experimentally. The definition of material constants (12) implies that $c^H_{11} = c^H_{22} = c^H_{33} = \lambda + 2G$, $c^H_{12} = c^H_{13} = c^H_{21} = c^H_{23} = \lambda$, $c^H_{55} = G$, and $m_{21} = m_{23} = m_2$ and $m_{22} = m_1$. Equation (4) takes the form

$$B^*_\vartheta = m^0_{211}\varepsilon_{\rho\rho} + m^0_{222}\varepsilon_{\vartheta\vartheta} + m^0_{233}\varepsilon_{zz} + \mu^\varepsilon_2 H^*_\vartheta, \qquad (13)$$

where $m^0_{211} = m^0_{233} = m_2 H^0_\vartheta$ $m^0_{222} = m_1 H^0_\vartheta$.

Let us assume that the coil core is a thin ring, i.e., $(R_2 - R_1)/R_0 \ll 1$, and $h/R_0 \ll 1$. In this case, $\sigma^*_{\rho\rho} = \sigma^*_{zz} = 0$, and the vector of displacements of material particles of the coil core is practically completely determined by the component u^*_ρ which does not change its value in the limits of the plane of a cross-section of the core, i.e., it does not depend on the coordinates ρ and z. In this case, $\sigma^*_{\rho z} = 0$ by definition, and Eq. (8) becomes the identity. The boundary conditions (9) and (10) are satisfied automatically. The condition for the normal stresses $\sigma^*_{\rho\rho}$ and σ^*_{zz} to be equal to zero allows us to determine the deformations $\varepsilon^*_{\rho\rho}$ and ε^*_{zz} in terms of the relative elongation of the middle line of the ring, i.e., in terms of the deformation $\varepsilon^*_{\vartheta\vartheta}$ as follows:

$$\varepsilon^*_{\rho\rho} = \varepsilon^*_{zz} = -\nu\varepsilon^*_{\vartheta\vartheta} + \frac{\nu m^0_{211}}{\lambda} H^*_\vartheta, \qquad (14)$$

where ν is the Poisson's ratio of a demagnetized (isotropic) material of the core, and $\varepsilon^*_{\vartheta\vartheta} = u^*_\rho / R_0$ is a relative change of the length of a circle with radius R_0. With regard for relation (14), the equation of state (12) and (13) for the core material can be presented in the form

$$\sigma^*_{\vartheta\vartheta} = Y\frac{u^*_\rho}{R_0} - m_\vartheta H^*_\vartheta, \quad B^*_\vartheta = m_\vartheta \frac{u^*_\rho}{R_0} + \mu^\sigma_2 H^*_\vartheta, \qquad (15)$$

where Y is the Young modulus of the demagnetized ferromagnetic, $m_\vartheta = m^0_{222} - 2\nu m^0_{211}$ is the piezomagnetic constant in the mode of uniaxial deformation (compression – tension) of a thin ring, and μ^σ_2 is the magnetic permittivity in the mode of steadiness (the equality to zero) of the stresses $\sigma^*_{\rho\rho}$ and σ^*_{zz}. The substitution of the above-defined stresses $\sigma^*_{\rho\rho}$, σ^*_{zz}, and $\sigma^*_{\vartheta\vartheta}$ to Eq. (5) transforms it into an equation for the required displacement $u^*_\rho : -Y\frac{u^*_\rho}{R_0^2} + \frac{m_\vartheta}{R_0} H^*_\vartheta + \rho_0\omega^2 u^*_\rho = 0$. This implies that $u^*_\rho = R\frac{m^2_\vartheta H^*_\vartheta}{Y[1-(\gamma R_0)s^2]}$, $B^*_\vartheta = \left\{\mu^\sigma_2 + \frac{m^2_\vartheta}{Y\left[1-(\gamma R s_0)^2\right]}\right\} H^*_\vartheta$, where $\gamma = \omega/\sqrt{Y/\rho_0}$ is the wave number of radial vibrations of a thin isotropic ring.

From definition (1) of the coefficient of self-induction L_k, we obtained the formula for calculations of the inductance of a coil, whose core performs mechanical vibrations,

$$L_\mathrm{k} = \left\{\mu^\sigma_2 + \frac{m^2_\vartheta}{Y\left[1-(\gamma R s_0)^2\right]}\right\} \frac{N^2 h\,(R_2 - R_1)\,\mu^\sigma_2}{\pi\,(R_1 + R_2)} =$$

$$= L_0[1 + k_0(\omega)], \qquad (16)$$

where

$$L_0 = \frac{N^2 h\,(R_2 - R_1)\,\mu^\sigma_2}{\pi\,(R_1 + R_2)},$$

Let us assume that no magnetostrictive effects are present in the core bulk, i.e., $m^0_{21} = m^0_{22} = 0$ and $m_\vartheta = 0$. Then formula (16) is transformed into the well-known relation for the calculation of the inductance L_0 of the coil on a ring core with the small (relative to the mid-line radius) size of a cross-section.

With regard for magnetostrictive effects, a frequency dependence of the coefficient of self-induction L_k is revealed. At the frequency f_p which corresponds to the dimensionless wave number $\gamma_\rho R_0 = 1$, the coil inductance L_k increases in the resonance manner, whereas, at the frequency $f_a > f_\mathrm{p}$, which corresponds to the dimensionless wave number $\gamma_a, R_0 = \sqrt{1 + \vartheta^2/Y\mu}$, $L_\mathrm{k} \to 0$.

In the real situation where the oscillatory system, i.e., the core in a casing, losses energy, changes of the coil inductance are bounded at the resonance frequency f_p and the antiresonance one f_a.

We note that the condition $\gamma_\rho R_0 = 1$ yields the well-known formula for the resonance frequency of free vibrations of a ring $\omega_0 = 1/R_0\sqrt{Y/\rho_0}$.

3. Results of Experimental Studies and Their Discussion

For the experimental studies, we fabricated a coil with inductance L_k on the basis of a ring core made of nickel-zinc ferrite of grade F-107 [8]. The coil contained $N = 100$ windings of a wire 0.2 mm in diameter, uniformly

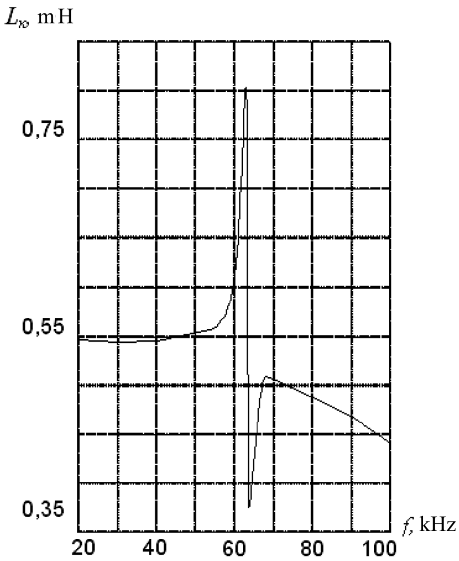

Fig. 2. Experimental data on the coil inductance $L_{\rm k}$ versus the frequency of a varying magnetic field

positioned on a casing. The core had the following sizes: $R_2 = 12.5 \times 10^{-3}$ m; $R_1 = 10.5 \times 10^{-3}$ m; $h = 1.5 \times 10^{-3}$ m.

From the dc source, the coil with inductance $L_{\rm k}$ under study was fed by a direct current I^0 which created a constant circular bias magnetic field with the strength $H_\vartheta^0 \approx 0.4$ kA/m. in the coil bulk. The amplitude of the alternating current I^* was selected under the condition for the amplitude of the varying coil inductance $L_{\rm k}$ to be maximum at the resonance. The measurement of the coil inductance $L_{\rm k}$ was carried out by means of the determination of its reactive resistance by the standard method.

In Fig. 2, we present the plot of experimental data on the inductance $L_{\rm k}$ versus the frequency of a varying magnetic field. There, two resonance frequencies $f_{\rm p}$ and $f_{\rm a}$ are clearly seen. We note that, as was expected, an increase in the coefficient of self-induction $L_{\rm k}$ at the frequency $f_{\rm p}$ and its decrease at the frequency $f_{\rm a}$ have bounded values due to the energy losses in a core material and at points of the mechanical contact of the core and a casing, on which the winding is placed.

The high quality of the oscillatory system ($Q > 100$) ensures the satisfactory coincidence of the resonance frequencies measured by the reactive resistance of the coil and the real values of magnetomechanical resonances of the coil core.

By the experimentally determined frequency $f_{\rm p}$ of the magnetomechanical resonance corresponding to the wave number γ_ρ such that $\gamma_\rho R_0 = 1$, we determine the Young modulus $Y = 4\pi^2 f_{\rm p}^2 R_0^2 \rho_0$. The magnetic permittivity μ_2^σ is determined from the results of measurements of the inductance $L_{\rm k}$ at frequencies $f \ll f_{\rm p}$. In this case, $L_{\rm k} = L_0$. At the frequency of the magnetomechanical antiresonance $f_{\rm a}$, the following condition is satisfied:

$$\frac{m_\vartheta^2}{\mu_2^\sigma Y} \frac{1}{[1 - 4\pi^2 f_{\rm a}^2 \rho_0 R_0^2 / Y]} = -1. \qquad (17)$$

From relation (17), we determine the constant m_ϑ, by using the earlier known values of Y and μ_2^σ.

Thus, by three measured quantities, namely $f_{\rm p}$, f_a, and L_0, we get three material constants Y, μ_2^σ, and m_ϑ. According to the experiment, their values are: Y=121 GPa; m_ϑ=316 T; $\mu_2^\sigma = 28\mu_0$, where $\mu_0 = 4\pi \times 10^{-7}$ H/m. For comparison, the constant m_ϑ is found in [8] to be 350 T at the magnetic field $H_\vartheta^0 = 0.8$ kA/m.

4. Conclusions

By the example of the inductance coil with a ring core made of a magnetostrictive material, we constructed and studied a mathematical model of the inductance coil with a vibrating ferromagnetic core. We have proved that the inductance of a coil varies in a resonance manner at certain frequencies. We present the results of experimental studies of the dependence of the inductance on the frequency for a coil, whose ferromagnetic (magnetostrictive) core can undergo mechanical vibrations. The obtained experimental results confirm the results of theoretical calculations by the proposed mathematical model. Thus, by measured values of the inductance at low frequencies and two measured frequencies of resonances of the inductance, it is possible to determine the magnetic permittivity of a nondeformed magnetostrictive ferromagnetic and the modulus of elasticity and the piezomagnetic constant of a material, of which the core of an inductance coil is fabricated. The proposed method of measurement of material constants in the frame of a physical experiment supplements the available procedures of registration of the magnetostriction.

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ВИЗНАЧЕННЯ МАГНІТОСТРИКЦІЙНИХ КОНСТАНТ ПОЛІКРИСТАЛІЧНОГО ФЕРОМАГНЕТИКА ЗА РЕЗОНАНСНИМИ ЧАСТОТАМИ РАДІАЛЬНИХ КОЛИВАНЬ КІЛЬЦЯ

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Р е з ю м е

У роботі побудовано математичну модель радіальних коливань кільця з полікристалічного феромагнітного (магнітострикційного) матеріалу. Показано, що на певних частотах виникає резонансне поглинання енергії від джерела магнітного поля, яке супроводжується резонансними збільшенням і зменшенням індуктивності тороїдальної котушки, осердям якої є кільце з досліджуваного матеріалу. Запропоновано алгоритм визначення матеріальних констант полікристалічного феромагнетика за виміряними значеннями частот магнітомеханічних резонансів.