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Study of transmission characteristics of disk transducer in the radially propagated Rayleigh wave excitation mode

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Abstract

A mathematical model of a capacitive ultrasonic transducer is designed allowing to emit ultrasonic vibrations into an electrically conductive product. The influence of a polarizing electrostatic field on the Coulomb forces formation in the surface layer of a metal sample is determined. A closed solution to the electrostatics problem is obtained for a piecewise homogeneous medium in which a half-space is filled with metal having finite values of electrical conductivity and magnetic permeability. An expression is obtained for calculating the surface density of a static electric charge on the metal sample surface. As part of the mathematical model of a capacitive sensor in the mode of converting electric energy to high-frequency mechanical (ultrasonic) energy in metals, closed solutions for electrostatics and electrodynamics problems are constructed in relation to a piecewise-homogeneous medium in which a half-space is filled with metal having finite values of electrical conductivity and magnetic permeability. It is determined that a capacitive disk transducer excites forces acting normally to the surface of electrically conductive products. A quantitative assessment of the surface density of the Coulomb forces is made. The main factors determining the sensitivity of a capacitive disk transducer are specified. As an example of using the simulation results, the amplitude factor of radially propagating Rayleigh waves is calculated. The concept of the wave characteristics of the transducer in the excitation mode of ultrasonic surface waves is introduced.

Keywords: capacitive transducer; surface density of the Coulomb forces; ultrasonic waves excitation by surface loads; amplitude factor of a radially propagating Rayleigh wave; wave characteristic of the transducer in the radiation mode.

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Introduction

In all areas of industry, ultrasonic methods of measurement, quality control of products and materials, and diagnostics are widely used [1]. In almost all cases of using traditional high-frequency methods of ultrasonic measurements, the contact method is used (applying contact liquid, which is placed between the electro-acoustic transducer and the research object) [1]. Contact method of testing requires covering the product surface with a viscous, well-wettable liquid (machine or transformer oil, glycerin, etc.). It means that preparing the surface of the research object (RO) and a significant consumption of contact fluid requires significant material and economic costs [2]. It should be noted that some materials do not allow the use of contact fluid [1].

It is possible to substantially reduce the disadvantages of traditional measurement methods by using non-contact methods of excitation and reception of high-frequency ultrasonic pulses [3–4] (without using contact liquid), the most known of which are electromagnetic-acoustic [3] and capacitive [4]. The electromagnetic-acoustic method is implemented by using magnetic and electromagnetic fields, and capacitive method uses electric fields. However, with its significant advantages [3], the electromagnetic-acoustic method has a significant drawback, which can be seen in measurements of ferromagnetic RO produced in the country in huge quantities: pipes, rails, sheets, intermediates, etc. The disadvantage is due to the strong attraction of the electromagnetic-acoustic transducer to RO, as well as the great difficulties of removing metal particles and scale adhering to the transducer.

The capacitive method does not have the above disadvantages of the EMA method; however, it is traditionally believed that the conversion of the electric field energy into the elastic displacements of the RO surface layer is insignificant [4–5]. Therefore, it is currently relevant to conduct comprehensive studies aimed at finding technical solutions for creating effective capacitive sensors [6] both in the mode of excitation of high-frequency ultrasonic vibrations and in the mode their reception. This article is a continuation of articles

[5, 7] aimed at increasing the excitation efficiency of high-frequency elastic vibrations in RO from electrically conductive materials by capacitive transducers.

The purpose of the work is mathematical and computer modeling and experimental confirmation of the efficiency of converting electric field energy into ultrasonic vibrations of various types of waves.

The results of previous studies

In [5], the authors showed that the construction of a basic mathematical model of a capacitive transducer (CT) in the excitation mode of ultrasonic waves is divided into two, successively solved main tasks. The first task is electrodynamics used to determine the Coulomb forces on the surface of a metal sample formed by CT. The second task is the boundary problem of the elasticity dynamic theory of the harmonic wave excitation by a surface loads system generated by CT. When solving the first problem [5], an expression is obtained for calculating the surface density of electric charges on the surface of an electrically conductive sample in the static approximation, which determines the Coulomb forces acting on the RO surface. It is shown that, in contrast to the traditional concept, charges are concentrated not only under the CT electrode. This is important for ultrasonic field parameters formation in the studied object and, accordingly, for the results of measurements and diagnostics.

In article [7], the second part of the problem stated in [5] is solved when limiting the excitation of only longitudinal waves and the presence of charge density is confirmed experimentally at a considerable distance from the CT electrode projection onto the RO surface.

At the same time, industry requires high-speed production tools and technologies for measuring, monitoring and diagnosing products with significant surface areas: capacities, large power transformers, sheets, large diameter pipes, intermediates, etc. It is possible to provide such technologies by using surface waves excited contactless, especially when diagnosing RO from ferromagnetic materials.

Content, analysis and research results

The generalized scheme for constructing CT in the excitation mode of ultrasonic waves is shown in Fig. 1. The transducer is a metal electrode 1 of arbitrary shape, which is located at a certain distance above the surface of the metal sample 2. A constant-time electric potential U_0 is applied to the metal electrode, which forms on the surface $x_3 = 0$ of the metal sample electric charge with a surface density of $\sigma^0(x^1, x^2)$, where x^1, x^2, x^3 are the coordinate lines of the right-handed Cartesian coordinate system, the origin of which is located on the metal sample surface.

Simultaneously with the constant potential U_0, an electric potential with an amplitude value U^* is supplied to the metal electrode, which varies in time according to the harmonic law $e^{i\omega t}$ ($i = \sqrt{-1}$; ω – cyclic frequency;

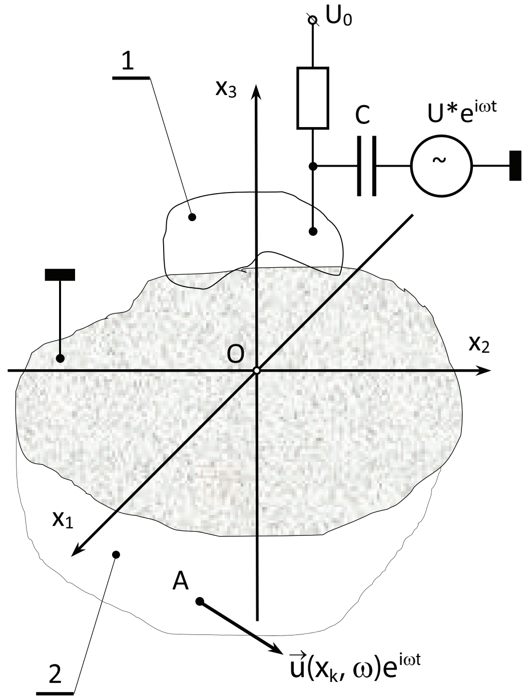

Fig. 1. Design scheme of a capacitive electroacoustic transducer in the mode of excitation of ultrasonic waves in a metal sample

t – time). This potential creates an alternating electric field with intensity $\vec{E}^* e^{i\omega t}$ ($\vec{E}^*$ – the amplitude of the intensity vector of alternating electric field).

Assume that the inequality $U^* << U_0$ is satisfied. Then the surface charges that are created by an alternating electric field cannot be taken into account. In this case, an alternating electric field linearly interacts with a static electric charge, as a result of which Coulomb forces with a surface density $\sigma^*_{3j}(x_1, x_2, t)$, ($j$ = 1, 2, 3) are applied on the surface $x^3 = 0$ of the metal sample, which are defined as follows

$$\sigma^*_{3j}(x_1, x_2, t) = \sigma^0(x_1, x_2) E^*_j(x_1, x_2, 0) e^{i\omega t}, \quad (j = 1, 2, 3), \tag{1}$$

where $E^*_j(x_1, x_2, 0)$ are the amplitude values of the alternating electric field intensity vector components on the surface $x^3 = 0$ of the metal sample.

The amplitude values of the surface density of Coulomb forces $\sigma^*_{3j}(x_1, x_2)$ or, using the terminology of a deformable solid mechanics, tangential and normal surface loads, create dynamic deformations of the metal object surface in the area of constant and variable electric fields. From the region of dynamic deformations, excess energy is carried away by elastic waves. Taking into account the linearity of the physical system and the processes existing in it, we define the displacement vector of the metal material particles as a value harmonically changing in time with an amplitude value $\vec{u}(x_k, \omega)$, where x_k are the coordinates of the observation point of the wave field (arbitrarily chosen point A in Fig. 1). The amplitude values of the wave field of displacements $\vec{u}(x_k, \omega) e^{i\omega t}$ at any point inside the metal sample satisfy the equation of steadystate harmonic vibrations. In the invariant form with respect to the choice of the coordinate system, this equation is written as follows [8]

$$(\lambda + 2G)\operatorname{grad}\operatorname{div}\vec{u}(x_k,\omega) - G\operatorname{rot}\operatorname{rot}\vec{u}(x_k,\omega) + \rho_0\omega^2\vec{u}(x_k,\omega) = 0, \quad (2)$$

where λ and G – Lame constants for isotropic metal with elastic properties; ρ_0 is the metal density.

The displacements $\vec{u}(x_k,\omega)e^{i\omega t}$ of the metal material particles, i.e., the solutions of equation (2), create strains in the metal volume, as a result of which elastic forces appear, which are determined through mechanical stresses $\sigma_{ij}(x_k,\omega)e^{i\omega t}$ $(i, j = 1, 2, 3)$. On the metal surface $x^3 = 0$, Newton's third law in differential form must be satisfied, according to which the following boundary conditions must be satisfied

$$\sigma_{3j}(x_1, x_2, 0) = \sigma^*_{3j}(x_1, x_2), \quad (j = 1, 2, 3), \quad (3)$$

where $\sigma^*_{3j}(x_1, x_2)$ are amplitude values of the surface density of the Coulomb forces (see 1). The fulfillment of boundary conditions (3) ensures the solution uniqueness of the equation (2).

In [9], using the Hankel integral transforms, the excitation problem of radially propagating axisymmetric Rayleigh waves by a system of volume and surface loads is solved. In this case, the boundary problem of the dynamic theory of elasticity is formulated in a more general formulation compared to the boundary problem (2), (3), namely

$$(\lambda + 2G)\operatorname{grad}\operatorname{div}\vec{u}(x_k,\omega) - G\operatorname{rot}\operatorname{rot}\vec{u}(x_k,\omega) + \rho_0\omega^2\vec{u}(x_k,\omega) - \vec{f}^*(x_k,\omega) = 0\,\forall \in V, \quad (4)$$

$$n_i\left[\sigma_{ij}(x_k,\omega) - \sigma^*_{ij}(x_k,\omega)\right] = 0\,\forall x_k \in S, \quad (5)$$

where $\vec{f}^*(x_k,\omega)$ is the amplitude of the volumetric density vector of external forces according to the law $e^{i\omega t}$; V is half-space volume $x^3 \leqslant 0$; n_i is the i-th component of the unit vector of the external normal to the surface $S(x_3 = 0)$ of the elastic half-space; the amplitude value of the surface density of external forces.

The result of solving this problem in a cylindrical coordinate system (ρ, φ, z), the origin of which is aligned with the beginning of the Cartesian coordinate system, and the z axis of which coincides with the Ox_3 axis, obtained under the assumption that the fields of external forces are independent of the polar angle φ, is written as follows

$$\vec{u}(\rho,z,\omega) = \vec{e}_\rho u_\rho(\rho,z,\omega) + \vec{e}_z u_z(\rho,z,\omega), \quad (6)$$

where $\vec{e}_\rho$ and $\vec{e}_z$ are unit vectors of a cylindrical coordinate system; $u_\rho(\rho,\varphi,\omega)$ and $u_z(\rho,z,\omega)$ are the components of the amplitude value of the displacement vector $\vec{u}(\rho,z,\omega)$ of material particles of the metal half-space, which varies with time according to the law $e^{i\omega t}$. The components of the displacement vector are defined by the following expressions:

$$u_\rho(\rho,z,\omega) = A_R(\omega)u_\rho(z,\gamma_R)H_1^{(2)}(\gamma_R\rho), \quad (7)$$

$$u_z(\rho,z,\omega) = A_R(\omega)u_z(z,\gamma_R)H_0^{(2)}(\gamma_R\rho), \quad (8)$$

where $A_R(\omega)$ is an amplitude factor of the Rayleigh wave; $u_\rho(z, \gamma_R)$ and $u_z(z, \gamma_R)$ are eigenfunctions of a homogeneous boundary-value problem, which is written by relations (4) and (5) having $\vec{f}^*(x_k,\omega) = 0$ and $\sigma^*_{ij}(x_k,\omega) = 0$; $\gamma_R = \omega / v_R$ Rayleigh wave number (v_R Rayleigh wave propagation velocity); $H_\upsilon^{(2)}(\gamma_R\rho)$ ($\upsilon = 0;1$) is the Hankel function of the second kind of order υ.

The amplitude multiplier $A_R(\omega)$ [5, 10] is written as follows

$$A_R(\omega) = -\frac{i\pi\gamma_R\left(\gamma_R^2 + \beta^2\right)^2}{2G\Delta_R'(\chi_R)\alpha k_s^2}\int_{-\infty}^{0}\left[\begin{matrix} f_\rho^*(\gamma_R,z)u_\rho(z,\gamma_R) + \\ + f_z^*(\gamma_R,z)u_z(z,\gamma_R)\end{matrix}\right]dz - \frac{i\pi\gamma_R}{2G\Delta_R'(\chi_R)}\left[\left(\gamma_R^2 + \beta^2\right)\sigma^*_{zz}(\gamma_R) + 2\gamma_R\beta\sigma^*_{z\rho}(\gamma_R)\right], \quad (9)$$

where $f_\rho^*(\gamma_R,z)$, $f_z^*(\gamma_R,z)$, $\sigma^*_{z\rho}(\gamma_R)$ and $\sigma^*_{zz}(\gamma_R)$ are Hankel integral images of volume and surface load components, which are written as direct Hankel integral transforms of the following form

$$\begin{Bmatrix} f_\rho^*(\gamma_R,z) \\ \sigma^*_{z\rho}(\gamma_R)\end{Bmatrix} = \int_0^\infty \rho\begin{Bmatrix} f_\rho^*(\rho,z) \\ \sigma^*_{z\rho}(\rho)\end{Bmatrix} J_1(\gamma_R\rho)d\rho;$$

$$\begin{Bmatrix} f_z^*(\gamma_R,z) \\ \sigma^*_{zz}(\gamma_R)\end{Bmatrix} = \int_0^\infty \rho\begin{Bmatrix} f_z^*(\rho,z) \\ \sigma^*_{zz}(\rho)\end{Bmatrix} J_0(\gamma_R\rho)d\rho,$$

where $J_\upsilon(\gamma_R\rho)$ ($\upsilon = 0;1$) are Bessel functions of order υ. The wave numbers α, β, and γ_R are interconnected by the condition of presence of a propagating Rayleigh wave at a given frequency ω, which is written as follows

$$\Delta_R(\chi_R) = \left(\gamma_R^2 + \beta^2\right)^2 - 4\gamma_R^2\alpha\beta = 0, \quad (10)$$

where $\chi_R \equiv \gamma_R^2$; wherein $\gamma_R^2 - \alpha^2 = k_\ell^2$ and $\gamma_R^2 - \beta^2 = k_s^2$; k_s and k_ℓ are wave numbers of non-interacting shear and longitudinal waves, respectively, which propagate with velocities $v_s = \sqrt{G/\rho_0}$ and $v_\ell = \sqrt{(\lambda + 2G)/\rho_0}$ (ρ_0 is material density). The symbol $\Delta_R'(\chi_R)$ in formula (9) denotes the first derivative of the function $\Delta_R(\chi_R)$ with respect to the variable χ_R. The eigenfunctions $u_\rho(z, \gamma_R)$ and $u_z(z, \gamma_R)$ of the homogeneous boundary-value problem (components of the displacement vector of material particles in a normal wave) are determined by the following relations:

$$u_\rho(z,\gamma_R) = e^{\alpha z} - \frac{2\alpha\beta}{\gamma_R^2 + \beta^2}e^{\beta z},$$
$$u_z(z,\gamma_R) = -\frac{\alpha}{\gamma_R}\left(e^{\alpha z} - \frac{2\gamma_R^2}{\gamma_R^2 + \beta^2}e^{\beta z}\right). \quad (11)$$

Table 1

Dimensionless wave numbers and the velocity of Rayleigh surface waves for various Poisson's ratio

ν	$\zeta = \gamma_R/k_s$	v_R/v_s	$f(\nu)$
0.00	1.144123	0.874032	-1.170822
0.02	1.139051	0.877924	-1.114026
0.04	1.134069	0.881781	-1.059085
0.06	1.129180	0.885599	-1.005999
0.08	1.124385	0.889375	-0.954756
0.10	1.119688	0.893106	-0.905359
0.12	1.115089	0.896790	-0.857783
0.14	1.110589	0.900423	-0.812010
0.16	1.106191	0.904003	-0.768031
0.18	1.101894	0.907528	-0.725811
0.20	1.097700	0.910996	-0.685329
0.22	1.093608	0.914404	-0.646549
0.24	1.089620	0.917752	-0.609446
0.26	1.085734	0.921036	-0.573974
0.28	1.081950	0.924257	-0.540094
0.30	1.078269	0.927413	-0.507774
0.32	1.074688	0.930503	-0.476957
0.34	1.071207	0.933526	-0.447603
0.36	1.067825	0.936483	-0.419666
0.38	1.064540	0.939373	-0.393092
0.40	1.061351	0.942195	-0.367835
0.42	1.058256	0.944951	-0.343844
0.44	1.055253	0.947640	-0.321066
0.46	1.052340	0.950263	-0.299450
0.48	1.049516	0.952820	-0.278952
0.50	1.046778	0.955313	-0.259516

The condition of existence (10) or, as it is not quite correctly called, the Rayleigh dispersion equation, is easily reduced to a bicubic equation with respect to a dimensionless quantity $\zeta = \gamma_R/k_s$. The composition of this equation includes the Poisson coefficient v as a parameter. Over the entire range of changes in the numerical values of the Poisson's ratio ($0 \leqslant v \leqslant 0.5$), the equation $\Delta_R(\chi_R) = 0$ has one real root $\zeta = \gamma_R/k_s$, the numerical values of which are shown in the second column of Table 1. In the third column, the relative velocities v_R/v_s of the surface Rayleigh wave are written.

For a capacitive disk transducer, power factors are $\vec{f}^*(\rho, z) = 0$ and $\sigma^*_{z\rho}(\rho) = 0$. Moreover, expression (9) for calculating the amplitude factor of the Rayleigh wave is the following

$$A_R(\omega) = -\frac{i\gamma_R \pi(\gamma_R^2 + \beta^2)}{2G\Delta'_R(\chi_R)} \int_0^\infty \rho\sigma^*_{zz}(\rho) J_0(\gamma_R\rho) d\rho. \quad (12)$$

It is not difficult to show that the ratio $(\gamma_R^2 + \beta^2)/\Delta'_R(\chi_R)$ is a constant independent from frequency ω, which will be denoted by a symbol $f(v)$. The numerical values of this constant are determined by the Poisson's ratio value and are shown in the fourth column of Table 1. Substituting into the calculation formula (12) the expression for the surface density of Coulomb forces (13), deduced by the authors in [7]

$$\sigma^*_{zz}(\rho) = \sigma_0(\rho) E^*_z(\rho, 0) = = \sigma_0 \left[\int_0^{x_{max}} x W(x) J_0\left(x\frac{\rho}{R}\right) dx \right]^2, \quad (13)$$

where

$$\sigma_0 = C_0^2 U_0 U^* / (\pi^2 R^4 \chi_0) \approx \chi_0 U_0 U^* / \delta^2.$$

We obtain an expression for calculating the amplitude factor of the Rayleigh wave, which is excited by a capacitive disk transducer

$$A_R(\omega) = -i A_0 W(\Omega), \quad (14)$$

where $A_0 = \pi\sigma_0 R f(v)/(2G)$ is an absolute sensitivity of a capacitive disk transducer of radius R in the excitation mode of radially propagating Rayleigh waves. With an average value of the shear modulus of steels $G = \sqrt{79 \cdot 89} = 83.85$ hPa at a load of $\sigma_0 = 88.5$ Pa and $R = 5 \times 10^{-3}$ m, the dimension value $A_0 = 4.75 \times 10^{-12}$ m. By the symbol $W(\Omega)$ ($\Omega = \gamma_R R$ is the dimensionless wave number or, which is the same, dimensionless frequency, since $\gamma_R R = \omega(R/v_R) = \omega\tau_0$) in formula (14) the frequency-dependent function of the following content is indicated

$$W(\Omega) = \Omega \int_0^\infty \xi \tilde{\sigma}^*_{zz}(\xi) J_0(\Omega\xi) d\xi, \quad (15)$$

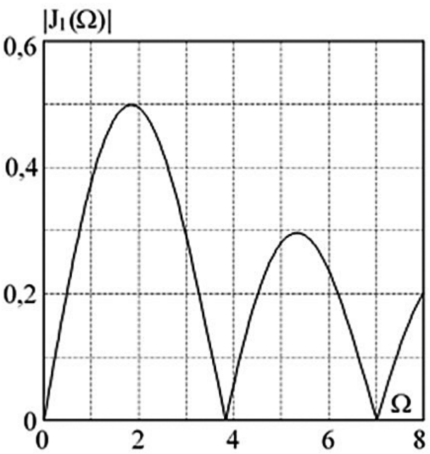

Fig. 2. The graph of the function $J_1(\Omega)$

where $\xi = \rho / R$ is a dimensionless radial coordinate; $\tilde{\sigma}^*_{zz}(\xi)$ is a dimensionless function, which depends on the dimensionless radial coordinate and is the second factor on the right-hand side of expression (13). As follows from the ones presented in Fig. 2 in the graphs article [7], the main contribution to the numerical values of the integral (15) is given by the function values $\tilde{\sigma}^*_{zz}(\xi)$ in the interval $0 \leqslant \xi \leqslant 1$. Therefore, to perform practical calculations, expression (15) must be written in the following form

$$W(\Omega) \cong \Omega \int_0^1 \xi \tilde{\sigma}^*_{zz}(\xi) J_0(\Omega \xi)\, d\xi. \qquad (16)$$

Before discussing the calculations results made via formula (16), we consider simple (model) situations.

Consider the approximation at which the surface density of Coulomb forces does not change within the area $0 \leqslant \rho \leqslant 1,\ R$, i.e.

$$\tilde{\sigma}^*_{zz}(\xi) = \begin{cases} 1 \forall \xi \le 1.5; \\ 0 \forall \xi > 1.5. \end{cases}$$

With such a specification of the surface density of Coulomb forces, integral (16) is elementarily calculated analytically and the function $W(\Omega) = J_1(\Omega)$. The graph of this function is shown in Fig. 2.

Analysis of the data in Fig. 2 shows that the function $W(\Omega)$ has local maxima which levels monotonically decrease with increasing dimensionless wave number Ω or dimensionless frequency $\omega\tau_0$, where $\tau_0 = R / v_R$ is the time scale. It is especially necessary to emphasize that at certain frequencies the function $W(\Omega)$ vanishes, i.e., external forces act on the loading area, and elastic disturbances are not observed outside this area.

The indicated features of the frequency-dependent change in the function $W(\Omega)$ are explained by the interference of wave fields that are radiated into the elastic medium by various parts of the deformable solid, which are in the region of external forces.

Conclusions

1. An expression is obtained for calculating the amplitude factor of a radially propagating Rayleigh wave, which is excited by a capacitive transducer with a disk electrode.

2. The concept of the wave characteristic of a capacitive transducer with a disk electrode is introduced.

3. The sufficient efficiency for the excitation of radially propagating Rayleigh waves is shown, which allows diagnosing products with a large area.

Дослідження передатних характеристик дискового перетворювача ємнісного типу в режимі збудження радіально поширюваних хвиль Релея

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Анотація

Розроблено математичну модель ємнісного ультразвукового перетворювача, що дозволяє випромінювати ультразвукові коливання в електропровідний виріб. Розглянуто вплив поляризуючого електростатичного поля на формування сил Кулона у поверхневому шарі металевого зразка. Отримано вираз для розрахунку поверхневої щільності статичного електричного заряду на поверхні зразка металу. У рамках математичної моделі ємнісного давача в режимі перетворення електричної енергії у високочастотну механічну (ультразвукову) в металах будуються замкнуті рішення задач для електростатики та електродинаміки щодо кусково-однорідного середовища, в якому напівпростір заповнено металом, що має кінцеві значення електропровідності та магнітної проникності. Визначено, що ємнісний дисковий перетворювач збуджує сили, що діють нормально на поверхні електропровідних виробів. Проведено кількісну оцінку поверхневої щільності сил Кулона. Вказано основні фактори, що визначають чутливість ємнісного дискового перетворювача. Як приклад використання результатів моделювання виконано розрахунок коефіцієнта амплітуди радіально поширюваних хвиль Релея. Введено поняття хвильових характеристик перетворювача в режимі збудження ультразвукових поверхневих хвиль. Показано, що діапазон частот, в якому реалізується ефективне збудження поверхневих хвиль Релея, повністю визначається радіусом дискового електрода, а також відстанню між електродом і поверхнею металевого листа.

Ключові слова: ємнісний перетворювач; поверхнева щільність сил Кулона; збудження ультразвукових хвиль поверхневими навантаженнями; амплітудний множник радіально поширюваної хвилі Релея; хвильова характеристика перетворювача в режимі випромінювання.

Исследование передаточных характеристик дискового преобразователя емкостного типа в режиме возбуждения радиально распространяющихся волн Рэлея

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Аннотация

Разработана обобщающая математическая модель электромеханического сенсора, преобразующего электрическую энергию в высокочастотные механические колебания, предназначенного для измерений, контроля и диагностики электропроводных изделий и материалов. В рамках математической модели сенсора емкостного типа в режиме преобразования электрической энергии в высокочастотную механическую (ультразвуковую) в металлах построены замкнутые решения задач электростатики и электродинамики для кусочно-однородной среды, в которой полупространство заполнено металлом с конечными значениями электрической проводимости и магнитной проницаемости. Показано, что дисковым преобразователем емкостного типа возбуждаются силы, действующие нормально на поверхности электропроводного изделия. Выполнена количественная оценка поверхностной плотности сил Кулона. В качестве примера использования результатов моделирования осуществлен расчет амплитудного множителя радиально распространяющихся волн Рэлея. Введено понятие волновой характеристики преобразователя в режиме возбуждения ультразвуковых поверхностных волн.

Ключевые слова: емкостной преобразователь; поверхностная плотность сил Кулона; возбуждение ультразвуковых волн поверхностными нагрузками; амплитудный множитель радиально распространяющейся волны Рэлея; волновая характеристика преобразователя в режиме излучения.

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