DOI: https://doi.org/10.15407/techned2019.06.018

IMPROVING PRINCIPLES OF ELECTRIC ENERGY PULSE TRANSFORMATION INTO HIGH-FREQUENCY MECHANICAL ENERGY USING CAPACITIVE METHOD

O.N. Petrishchev[2*], K.L. Nozdrachova[1], G.M. Suchkov[1***], R.P. Mygushchenko[1****], O.Yu. Kropachek[1*****], S.Yu. Plesnetsov[1******]**
[1] National Technical University Kharkiv Polytechnic Institute,
2, Kirpichova str., Kharkiv, 61002, Ukraine. E-mail: hpi.suchkov@gmail.com
[2] National Technical University of Ukraine Igor Sikorsky Kyiv Polytechnic Institute,
pr. Peremohy, 37, Kyiv, 03056, Ukraine. E-mail: petrischev@ukr.net

Closed solutions of electrostatic and electrodynamics problems are formed in metals for a piecewise-homogeneous medium, where half-space is filled with metal of finite values having electrical conductivity and magnetic permeability being implemented within the framework of a mathematical model for capacitive type sensor when converting electrical energy into high-frequency mechanical (ultrasonic). It is shown that a disk transducer of a capacitive type excites forces acting normally on the surface of an electrically conductive product. A quantitative assessment of Coulomb forces for the surface density is carried out. The main factors determining a disk converter sensitivity of capacitive type are stated. Capacitive transducers should be used for measuring, control and diagnostic equipment.
References 10, figures 3.
Key words: mathematical modeling, ultrasonic sensor model, capacitive transducers, electric field, charge density, electrode, impulses, measurements, diagnostics.

Introduction. Electrically conductive products and materials are widely used in industry. As a rule, their quality is checked using non-destructive diagnostic testing methods, the most common of which is ultrasonic testing (UT). However, the traditional UT method requires surface conditioning of a product and contact liquid [1]. The cost of UT testing is significant. Using non-contact UT methods can greatly reduce such costs [2]. Electromagnetic acoustic (EMA) method is the most famous among all [1-3]. But this method has a significant drawback, due to the requirement of using a powerful magnetic field. Therefore, the EMA method is mainly used in automatic diagnostic systems [4]. The method of converting electrical energy into mechanical and vice versa (excitation and reception of ultrasonic pulses) by capacitive transducers (CTs) using constant and pulsed electric fields is also used [1, 2, 5, 6]. The principle of this method is illustrated in Fig. 1. CT is made in the form of a metallic circular disk *1*, which is located at a distance δ above the surface of the electrically conductive sample *2*. A time-constant electric potential U_0 is applied to the metal disk *1*, forming an electric charge on the metal sample surface with surface density $\sigma^0(\rho)$, where ρ, φ, z are the coordinate lines of the cylindrical coordinate system, which origin is located on the metal sample surface (at the point O), and the *z* axis is aligned with the symmetry axis of the disk *1*. Obviously, the electric fields and surface density $\sigma^0(\rho)$ of the induced electrical charge does not depend on the circular coordinate φ. Simultaneously with a constant potential U_0, a time-varying according to the law $e^{i\omega t}$ ($i=\sqrt{-1}$; ω – cyclic frequency; t – time) electric potential is applied to a metal disk with an amplitude value U^*. This potential creates an alternating electric field with intensity $\vec{E}^* e^{i\omega t}$ ($\vec{E}^*$ – amplitude of the intensity vector of the alternating electric field). The interaction of constant and alternating electric fields in the surface layer of the metal leads to the appearance of elastic mechanical vibrations that propagate into the product 2.

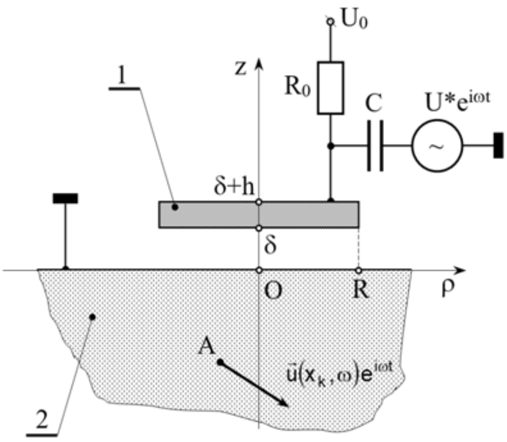

Fig. 1

CTs do not generate an attractive force with ferromagnetic products, which makes their use in portable measuring de-

ORCID ID: * https://orcid.org/0000-0003-2984-1340; ** https://orcid.org/0000-0002-1996-2301 ;
*** https://orcid.org/0000-0002-1805-0466 ; **** https://orcid.org/0000-0002-3287-9772 ;
***** https://orcid.org/0000-0001-5899-0252 ; ****** https://orcid.org/0000-0001-8428-5426

vices a significant advantage. Traditionally, the capacitive method of converting electrical energy into mechanical and vice versa has low sensitivity [1]. Therefore, theoretical, model and experimental studies aimed at increasing the sensitivity of the capacitive diagnostic method are promising for practice. It is necessary to study and define the influence of factors determining CT operation and to show possible ways to increase their sensitivity.

Therefore, the studies aimed at creating CT for diagnostics of ferromagnetic, electrically conductive and electrically conductive non-ferromagnetic materials are relevant.

The aim of the work is mathematical and computer modeling focused on creating the principles for converting electrical energy into mechanical (ultrasonic) using capacitive method.

Results of the previous studies. The authors [7] studied distribution of electric charges on the metal surface (see Fig. 1) created by the potential U_0. A number of assumptions were made. The charges on the disk 1 surface are evenly distributed. The following inequality $U^* << U_0$ is performed.

The authors [7] showed that constructing a mathematical model for CT in the radiation mode of ultrasonic waves naturally falls into two, consistently solved problems. The first is the problem of electrodynamics determining the Coulomb forces on the surface of a metal sample. The second is the boundary problem of dynamic elasticity on the harmonic wave excitation by a system of surface loads. Solution of this problem allows writing explicit expression for calculating the components of a vector function $\vec{W}^u(x_k, \omega, \Pi)$, that is, completing mathematical model for CT in the excitation mode. Here, the vector function $\vec{W}^u(x_k, \omega, \Pi)$ depends on the point A coordinates of the observation over excited wave field, that is, from the set of numbers $x_k \equiv \rho, \varphi, z$, the circular frequency ω of the influence sign change and the set of physical and mechanical parameters (the symbol Π in the vector function argument list) of the described physical system, that is CT. The vector function $\vec{W}^u(x_k, \omega, \Pi)$ was called the transfer characteristic for CT when converting electrical energy into mechanical (ultrasonic wave radiation).

The authors [7] solved the first problem of electrodynamics determining the Coulomb forces on the surface of a metal sample. It was shown that the main influencing factors determining charges density in the surface layer of a metal (and, consequently, the power and directional pattern of the excited ultrasonic field) are: polarizing voltage; transducer capacity (dielectric constant); transducer size; the gap size between transducer and product; transducer form.

A very important conclusion of the conducted study is the presence of a significant size of charge density areas on the metal surface beyond the CT disk electrode projection onto the metal surface. This effect should be taken into account when determining the directivity pattern of the CT ultrasonic field, since it is determined by the size of the “charge spot” on the metal.

The content and results of the study. The solution of the second problem concerning harmonic wave excitation by a system of surface loads generated when converting electrical energy into mechanical using CT is given below.

An alternating electric voltage $U^* e^{i\omega t}$ creates an alternating electric field in the vacuum surrounding the disk, which is described by a scalar potential $\Phi^*(\rho, z)e^{i\omega t}$. The amplitude value $\Phi^*(\rho, z)$ of the scalar potential satisfies equation (1),

$$\frac{1}{\rho}\frac{\partial}{\partial\rho}\left[\rho\frac{\partial\Phi^*(\rho,z)}{\partial\rho}\right]+\frac{\partial^2\Phi^*(\rho,z)}{\partial z^2}=-\frac{\rho_e}{\chi_0}. \qquad (1)$$

where $\rho_e = C_0 U^* f(\rho) f(z) / (\pi R^2 h)$. The “*” sign is used to mark the values of system parameters (usually of currents or voltages) formed within the system by external sources (i.e., generators), and which are independent from other parameters of the system; all the parameters of physical fields are considered to be complex functions by default.

This equation is solved by the method used in [7]. Having done all the necessary computational procedures, the following expression can be written for the domain $0 \le z \le \delta$ to calculate the integral image of the scalar potential of an alternating electric field

$$\Phi^*(\gamma, z) = \frac{C_0 U^*}{2\pi\gamma\chi_0} W(\gamma) e^{\gamma z} + B e^{-\gamma z}, \qquad 0 \le z \le \delta. \qquad (2)$$

An alternating electric field is fundamentally different from a constant one in that the radially oriented variable currents flow through the surface of metal. Amplitude of the radial vector component $j_\rho(\rho)$ of the current conduction density on the surface of a product

$$j_\rho(\rho) = r\,E_\rho(\rho,0), \tag{3}$$

where r – electrical conductivity of metal; $E_\rho(\rho,z)$ – phasor of the radial component of the electric-field vector in the metal volume changing harmonically in time; $E_\rho(\rho,0) = E_\rho(\rho,z)\big|_{z=0}$.

The surface $z = 0$ of media section must satisfy the condition [8]

$$E^*_\rho(\rho,0) = E_\rho(\rho,0), \tag{4}$$

where $E^*_\rho(\rho,0) = -\partial\Phi^*(\rho,z)/\partial\rho\big|_{z=0}$ – phasor of the radial component of the electric-field vector in the air.

Since $j_\rho(\rho)\,\mathrm{e}^{\mathrm{i}\omega t} = \partial\left[\sigma^*(\rho)\mathrm{e}^{\mathrm{i}\omega t}\right]/\partial t$, then the amplitude of the radial component of the surface current density $j_\rho(\rho) = i\omega\sigma^*(\rho)$, where $\sigma^*(\rho)$ is the surface density of the variable electric charge. Since $\sigma^*(\rho) = \chi_0 E^*_z(\rho,0)$, where $E^*_z(\rho,0)$ is the amplitude value of the axial component of the alternating electric field vector on the metal surface, the expression for calculating the amplitude of the surface current density is written as $j_\rho(\rho) = i\omega\chi_0 E^*_z(\rho,0)$. Taking into account the definition (3), we conclude that the following condition should be satisfied on the surface z = 0 of the metal

$$i\omega\chi_0 E^*_z(\rho,0) = r\,E_\rho(\rho,0). \tag{5}$$

The phasor values of the components $E_\rho(\rho,z)$ and $\mathrm{E}_z(\rho,z)$ of the alternating electric field vectors in the metal volume must satisfy the Maxwell equations, which are neglected by the displacement currents written in the following form

$$\mathrm{rot}\,\vec{H}(\rho,z) = r\,\vec{E}(\rho,z), \qquad \mathrm{rot}\,\vec{E}(\rho,z) = -\,i\,\omega\,\mu\,\vec{H}(\rho,z), \tag{6, 7}$$

where $\vec{H}(\rho,z)$ is the amplitude value of the electric field vectors of a vortex magnetic field changing harmonically in time; μ is the magnetic permeability of the metal (for metals of the non-ferromagnetic group $\mu = 4\pi\cdot10^{-7}$ H/m).

Calculating the rotor from both sides of equation (34), we get

$$\mathrm{rot\,rot}\,\vec{E}(\rho,z) = -\,i\,\omega\,\mu\,\mathrm{rot}\,\vec{H}(\rho,z).$$

Substituting in the right side of the last relation the right side of equation (6), we obtain a vector equation, which solutions determine the desired components of the alternating electric field vectors in the metal volume. This equation is written as follows

$$\mathrm{rot\,rot}\,\vec{E}(\rho,z) + i\omega\mu r\,\vec{E}(\rho,z) = 0\,. \tag{8}$$

In the case of axial symmetry, when the vector does not depend on the values of the circular coordinate φ, two scalar equations follow from the vector equation (8)

$$-\frac{\partial^2 E_\rho(\rho,z)}{\partial z^2} + \frac{\partial^2 E_z(\rho,z)}{\partial\rho\,\partial z} + i\omega\mu r\,E_\rho(\rho,z) = 0\,, \tag{9}$$

$$\frac{1}{\rho}\frac{\partial}{\partial\rho}\left\{\rho\left[\frac{\partial E_\rho(\rho,z)}{\partial z} - \frac{\partial E_z(\rho,z)}{\partial\rho}\right]\right\} + i\omega\mu r\,E_z(\rho,z) = 0\,. \tag{10}$$

Since the components $E_\rho(\rho,z)$ and $E_z(\rho,z)$ of the alternating electric field vectors must satisfy the principle of physical realizability of the field source, the solution of the equations system (9) and (10) can be carried out using Hankel integral transforms [9]. Let us define the integral images of the radial and axial components of the electric field vectors in the metal by the following relations:

$$E_\rho(\gamma,z) = \int_0^\infty \rho\,E_\rho(\rho,z)J_1(\gamma\rho)\,d\rho\,, \qquad E_z(\gamma,z) = \int_0^\infty \rho\,E_z(\rho,z)J_0(\gamma\rho)\,d\rho\,. \tag{11, 12}$$

Hankel direct transform (11) and (12) correspond to inverse transformations, which are written as follows

$$E_\rho(\rho,z)=\int_0^\infty \gamma E_\rho(\gamma,z)J_1(\gamma\rho)d\gamma, \qquad E_z(\rho,z)=\int_0^\infty \gamma E_z(\gamma,z)J_0(\gamma\rho)d\gamma. \qquad (13, 14)$$

Acting on equation (9) by transformation (11), and on equation (10) by transformation (12), we obtain the following system of differential equations

$$-\frac{\partial^2 E_\rho(\gamma,z)}{\partial z^2}-\gamma\frac{\partial E_z(\gamma,z)}{\partial z}+i\omega\mu r E_\rho(\gamma,z)=0, \qquad (15)$$

$$\gamma\frac{\partial E_\rho(\gamma,z)}{\partial z}+\left(\gamma^2+i\omega\mu r\right)E_z(\gamma,z)=0. \qquad (16)$$

From equation (16) it follows that

$$E_z(\gamma,z)=-\frac{\gamma}{\zeta^2}\frac{\partial E_\rho(\gamma,z)}{\partial z}, \qquad (17)$$

where $\zeta^2=\gamma^2+i\omega\mu r$.

Substituting the definition (17) of the component $E_z(\gamma,z)$ into equation (15), we obtain the equation which solution determines the radial component

$$\frac{\partial^2 E_\rho(\gamma,z)}{\partial z^2}-\zeta^2 E_\rho(\gamma,z)=0. \qquad (18)$$

The solution of equation (18) satisfying the principle of physical realizability of the field source is written as follows

$$E_\rho(\gamma,z)=\mathrm{C}e^{\zeta z}, \qquad (19)$$

where C – constant.

Given the fact that

$$E_\rho^*(\gamma,z)=-\int_0^\infty \rho\frac{\partial\Phi^*(\rho,z)}{\partial\rho}J_1(\gamma\rho)d\rho=\gamma\Phi^*(\gamma,z), \quad E_z^*(\gamma,z)=-\frac{\partial\Phi^*(\gamma,z)}{\partial z},$$

then the boundary conditions (4) and (5) form the following system of algebraic equations

$$-i\omega\frac{C_0U^*}{2\pi}W(\gamma)+i\omega\chi_0\gamma\mathrm{B}=r\mathrm{C}, \qquad \frac{C_0U^*}{2\pi\chi_0}W(\gamma)+\gamma\mathrm{B}=\mathrm{C}.$$

This system of equations is solved with respect to the desired constants B and C as follows

$$\mathrm{B}=-\frac{(r+i\omega\chi_0)}{(r-i\omega\chi_0)}\frac{C_0U^*}{2\pi\chi_0\gamma}W(\gamma), \qquad \mathrm{C}=-\frac{i\omega C_0U^*}{\pi(r-i\omega\chi_0)}W(\gamma).$$

Since the specific electrical conductivity of metals is of the order 10^7 S/m, a strong inequality $r>>\left|i\omega\chi_0\right|$ is always fulfilled in the technically feasible frequency range. From this fact it follows that

$$\mathrm{B}=-\frac{C_0U^*}{2\pi\chi_0\gamma}W(\gamma), \qquad \mathrm{C}=-\frac{i\omega C_0U^*}{\pi r}W(\gamma). \qquad (20)$$

Substituting the found constant B in the expressions for the components $E_\rho^*(\gamma,z)$ and $E_z^*(\gamma,z)$, we get

$$E_\rho^*(\gamma,z)=\frac{C_0U^*}{\pi\chi_0}W(\gamma)\,\mathrm{sh}(\gamma z), \qquad E_z^*(\gamma,z)=\frac{C_0U^*}{\pi\chi_0}W(\gamma)\,\mathrm{ch}(\gamma z). \qquad (21)$$

On the metal surface z = 0 the radial component is $E_\rho^*(\gamma,0)=0$, and the axial component is $E_z^*(\gamma,0)\neq 0$. Substituting the expression $E_z^*(\gamma,0)$ for the inverse Hankel transform (14), we obtain the expression for calculating the original $E_z^*(\rho,0)$ axial component of the electric field vector

$$E_z^*(\rho,0) = -\frac{C_0 U^*}{\pi \chi_0} \int_0^\infty \gamma W(\gamma) J_0(\gamma\rho) d\gamma = -\frac{C_0 U^*}{\pi R^2 \chi_0} \int_0^\infty x W(x) J_0(x) dx\,, \qquad (22)$$

where $x = \gamma R$ – dimensionless parameter of Hankel integral transform.

From the expression (22) it follows that in the domain with constant and variable electric fields, only normal surfaces z = 0 of the Coulomb force are present, which surface density is calculated using the following formula

$$\sigma_{zz}^*(\rho) = \sigma_0\ (\rho) E_z^*(\rho,0) = \sigma_0 \left[\int_0^\infty x\, W(x)\, J_0(x)\, dx \right]^2, \qquad (23)$$

where $\sigma_0 = C_0^2 U_0 U^* / (\pi^2 R^4 \chi_0) \approx \chi_0 U_0 U^* / \delta^2$. When δ = 0,1 mm, the potentials $U_0 = 1000$ V and $U^* = 100$ V the constant factor $\sigma_0 \approx 88{,}5$ Pa. It is necessary to emphasize that this is rather underestimate. Fig. 2 shows calculation results by the formula (23) the surface density of the Coulomb forces $\sigma_{zz}^*(\rho)$, where the constant factor was determined by the approximate formula $\sigma_0 \approx \chi_0 U_0 U^* / \delta^2$. The fixed values for performing this series of calculations were: the gap δ = 0,1 mm, the disk density $h = 1$ mm and the potentials $U_0 = 1000$ V, $U^* = 100$ V. The variable value was the radius of the metal disk, which numerical values are written down in Figure 2 near the corresponding dependencies. Values $\sigma_{zz}^*(\rho)$ in Pascals are plotted along the ordinate axis, and the dimensionless distance from the center of the metal disk is plotted along the abscissa axis. Increasing maximum values of the normal voltage $\sigma_{zz}^*(\rho)$ at $\rho = 0$, which is caused by the radius increase of the metal disk, undergoes a particular saturation at $R > 20$ mm. If we take into account that increasing the size of the loading site is accompanied by moving the working frequency band of the radiator to the low frequency range, then it can be argued that the radius of the metal disk of a capacitive type transducer is impractical to manufacture larger than 20 ... 25 mm.

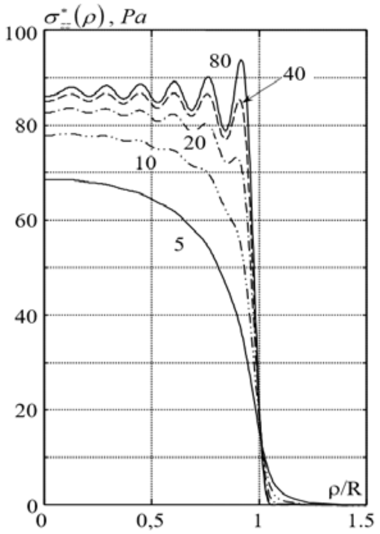

Fig. 2

Analysis of the data presented in Fig. 2 shows that the charge distribution over the object of verification surface is uneven. This fact shall be taken into account when designing CTs that excite ultrasonic pulses. This result is qualitatively confirmed by the data in [10].

Thus, knowing the density distribution of the Coulomb force on the metal surface, it is possible to determine the main characteristics of the wave field displacements of material particles in the volume of the metal object of verification, which is excited by CT.

When designing CTs that excite ultrasonic pulses, it is necessary to take into account not only radiating electrode diameter of the capacitive sensor, but also the charge distribution on the metal surface, since this effect will influence the radiation pattern of the acoustic field being formed.

The obtained theoretical and model studies are verified experimentally. For this, a special stand was made. Plane-parallel steel and brass samples were used as a study subject. CT electrode with a density of 0.03 mm and a diameter of 5 mm was placed on the metal through a dielectric strip with a density of 0.4 mm. The constant polarizing field was +850 V. The excitation was carried out by a pulse of 0.1 μs with an amplitude of 650 V. Receiving the excited ultrasonic signals that passed the metal twice, U1 and U2, was carried out using a miniature piezoelectric transducer (PZT) of 2x2 mm^2 with the opposite side of the sample. A typical study result is shown in Fig. 3.

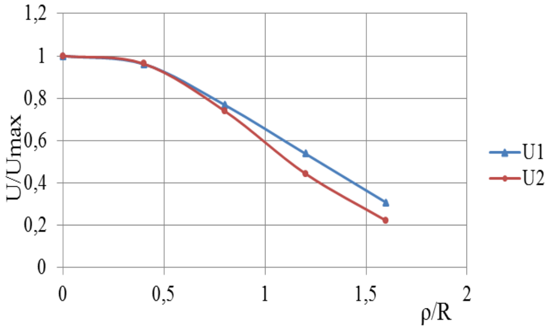

Fig. 3

Analysis of the results shown in Fig. 3 confirms the results of theoretical and model studies. It should be noted that similar experimental studies of the CT electrode dimensions up to 31 mm also confirm the results of theoretical and model studies on the electric charges distribution on the metal surface when converting electrical energy into high-frequency mechanical.

Conclusions.

1. Closed solutions of electrostatic and electrodynamics problems are formed for a piecewise-homogeneous medium, where half-space is filled with metal of finite values having electrical conductivity and magnetic permeability being implemented within the framework of a mathematical model for capacitive type sensor in the excitation mode of ultrasonic waves in metals (conversion of electrical energy into mechanical).

2. It is shown that a disk transducer of a capacitive type excites forces acting normally on the surface of an electrically conductive product. A quantitative assessment of Coulomb forces for the surface density is carried out.

3. The main factors determining a disk converter sensitivity of capacitive type are stated. They are: polarizing voltage; amplitude and frequency of high frequency voltage; transducer capacity (dielectric constant); transducer size; the gap size between transducer and product.

4. Capacitive transducers can be effectively used for measuring, control and diagnostic equipment.

1. Ermolov I.N., Lange Yu.V. Nondestructive testing: handbook. Vol. 3: Ultrasonic testing. Moskva: Mashinostroenie, 2004. 864 p. (Rus)

2. Palmer S.B. S. Dixon. Industrially viable non-contact ultrasound. *Insight*. 2003. Vol. 45. No 3. Pp. 211–217.

3. Migushchenko R.P., Suchkov G.M., Radev H.K., Petrishchev O.N., Desyatnichenko A.V. Electromagnetic-acoustic transducer for ultrasonic thickness gauging of ferromagnetic metal products without removing the dielectric coating. *Tekhnichna Elektrodynamika.* 2016. No 2. Pp.78-82. (Rus)

4. Suchkov G.M., Alekseev E.A., Zaharenko V.V. Energy and resource-saving devices and technologies of non-destructive testing. *Tekhnicheskaia diagnostika i nerazrushaiushchii kontrol*. 2006. No 4. Pp. 29–34. (Rus)

5. Zaytseva L.V. Film heterosystems of capacitors based on polyamide, indium oxides, tin and aluminum. PhD thesis: 01.04.07, Institute of electric physics and radiation technologies NAN of Ukraine. Kharkiv. 2015. 190 p. (Ukr)

6. Wright W.M.D., Hutchins D.A. Air-coupled testing of metals using broadband pulses in through-transmission. *Ultrasonics 37*. 1999. No 37. Pp. 19-22.

7. Suchkov G.M., Petrishchev O.N., Nozdracheva E.L., Romanyuk M.I. Excitation of ultrasonic waves in metals by a capacitive transducer. Part 1. *Tekhnicheskaia diagnostika i nerazrushaiushchii kontrol*. 2015. No 1. Pp. 45-50. (Rus)

8. Tamm I.E. Foundations of electricity theory. Moskva: Nauka, 1976. 616 p. (Rus)

9. Koshlyakov N.S., Gliner E.B., Smirnov M.M. Mathematical physics equations in partial derivatives. Moskva: Vysshaia shkola, 1970. 710 p. (Rus)

10. Feynman R., Leyton R., Sends M. Feynman's lectures on physics. Vol. 5. Elektrichestvo i magnetizm. Moskva: Mir, 1966. 296 p. (Rus)

Работа финансируется за счет авторов / The work is funded by the authors/

УДК 621.311.25:621.039. 621.311.22; 620.179.16

СОВЕРШЕНСТВОВАНИЕ ОСНОВ ИМПУЛЬСНОГО ПРЕОБРАЗОВАНИЯ ЕМКОСТНЫМ МЕТОДОМ ЭЛЕКТРИЧЕСКОЙ ЭНЕРГИИ В ВЫСОКОЧАСТОТНУЮ МЕХАНИЧЕСКУЮ

О.Н. Петрищев[2], К.Л. Ноздрачева[1], Г.М. Сучков[1], Р.П. Мигущенко[1], О.Ю. Кропачек[1], С.Ю. Плеснецов[1]
[1] Национальный технический университет «Харьковский политехнический институт», ул. Кирпичева, 2, Харьков, 61002, Украина. E-mail: hpi.suchkov@gmail.com
[2] Национальный технический университет Украины «Киевский политехнический институт им. И. Сикорского», пр. Победы, 37, Киев, 03056, Украина. E-mail: petrischev@ukr.net

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 поверхности электропроводного изделия. Выполнена количественная оценка поверхностной плотности сил Кулона. Установлены основные факторы, определяющие чувствительность дискового преобразователя емкостного типа. Емкостные преобразователи целесообразно использовать в измерительной, контрольной и диагностической технике.* Библ. 10, рис. 3.

Ключевые слова: математическое моделирование, модель ультразвукового сенсора, емкостной преобразователь, электрическое поле, плотность зарядов, электрод, импульсы, измерения, диагностика.

УДК 621.311.25:621.039. 621.311.22; 620.179.16

ВДОСКОНАЛЕННЯ ОСНОВ ІМПУЛЬСНОГО ПЕРЕТВОРЕННЯ ЄМНІСНИМ МЕТОДОМ ЕЛЕКТРИЧНОЇ ЕНЕРГІЇ У ВИСОКОЧАСТОТНУ МЕХАНІЧНУ

О.М. Петрищев[2], К.Л. Ноздрачова[1], Г.М. Сучков[1], Р.П. Мигущенко[1], О.Ю. Кропачек[1], С.Ю. Плєснецов[1]
[1] Національний технічний університет «Харківський політехнічний інститут»,
вул. Кирпичова, 2, Харків, 61002, Україна. E-mail: hpi.suchkov@gmail.com
[2] – Національний технічний університет України «Київський політехнічний інститут ім. І. Сікорського»,
пр. Перемоги, 37, Київ, 03056, Україна. E-mail: petrischev@ukr.net

У рамках математичної моделі сенсора ємнісного типу в режимі перетворення електричної енергії у високочастотну механічну (ультразвукову) в металах побудовані замкнені рішення задач електростатики та електродинаміки для кусково-однорідного середовища, де напівпростір заповнений металом із кінцевими значеннями електричної провідності та магнітної проникності. Показано, що дисковим перетворювачем ємнісного типу збуджуються сили, що діють нормально поверхні електропровідного виробу. Виконано кількісну оцінку поверхневої густини сил Кулона. Встановлено основні чинники, що визначають чутливість дискового перетворювача ємнісного типу. Ємнісні перетворювачі доцільно використовувати у вимірювальній, контрольній та діагностичній техніці. Бібл. 10, рис. 3.

Ключові слова: математичне моделювання, модель ультразвукового сенсора, ємнісний перетворювач, електричне поле, щільність зарядів, електрод, імпульси, вимірювання, діагностика.

1. Ермолов И.Н., Ланге Ю.В. Неразрушающий контроль: Справочник: В 7 т. Т. 3: Ультразвуковой контроль. М.: Машиностроение, 2004. 864 с.

2. Palmer S.B. S. Dixon. Industrially viable non-contact ultrasound. *Insight*. 2003. Vol. 45. No 3. Pp. 211–217.

3. Мигущенко Р.П., Сучков Г.М., Радев Х.К., Петрищев О.Н., Десятниченко А.В. Электромагнитно-акустический преобразователь для ультразвуковой толщинометрии ферромагнитных металлоизделий без удаления диэлектрического покрытия. *Технічна електродинаміка.* 2016. № 2. С. 78-82.

4. Сучков Г.М., Алексеев Е.А., Захаренко В.В. Энерго- и ресурсосберегающие приборы и технологии неразрушающего контроля. *Техническая диагностика и неразрушающий контроль*. 2006. № 4. С. 29–34.

5. Зайцева Л.В. Плівкові гетеросистеми ємнісних перетворювачів на основі поліаміду, оксидів індію, олова та алюмінію. Дисертація канд.техн.наук: 01.04.07, НАН України, Ін-т електрофізики і радіаційних технологій. Харків. 2015. 190 с.

6. Wright W.M.D., Hutchins D.A. Air-coupled testing of metals using broadband pulses in through-transmission. *Ultrasonics 37*. 1999. No 37. Pp. 19-22.

7. Сучков Г.М., Петрищев О.Н., Ноздрачева Е.Л., Романюк М.И. О возбуждении ультразвуковых волн в металлах емкостным преобразователем. Часть 1. *Техническая диагностика и неразрушающий контроль*. 2015. № 1. С. 45-50.

8. Тамм И.Е. Основы теории электричества. М.: Наука, 1976. 616 с.

9. Кошляков Н.С., Глинер Э.Б., Смирнов М.М. Уравнения в частных производных математической физики. М.: Высшая школа, 1970. 710 с.

10. Фейнман Р., Лейтон Р., Сэндс М. Фейнмановские лекции по физике. Т.5 Электричество и магнетизм. М.: Мир, 1966. 296 с.

Надійшла 19.04.2019
Остаточний варіант 06.06.2019