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FERROMAGNETIC DISC AS A SOURCE OF INTERFERENCE AUDIO FREQUENCY RANGE

Показано, що в результаті механічних коливань феромагнітного диску в постійному магнітному полі через зворотній магнітострикційний ефект, виникає намагніченість, що змінюється в часі. Це означає, що металеві елементи електронного обладнання, які вібрують в магнітному полі можуть бути джерелами низькочастотних електромагнітних завад. Такі джерела механічних вібрацій мають місце в апаратній кіноконцертного комплексу. Отримані математичні співвідношення для знаходження вектору напруженості змінного магнітного поля в об'ємі вібруючого феромагнітного диску. Представлені графіки нормованих прогинів на резонансних частотах для феромагнітного диску заданих розмірів. Отримані результати дозволили встановити важливий фактор формування ненавмисних електромагнітних завад і становлять практичний інтерес під час проектування чутливої апаратури.

Ключові слова: електромагнітна сумісність, магнітне поле, механічні вібрації, кіноконцертний зал, феромагнітний диск, низькочастотна завада.

Показано, что в результате механических колебаний ферромагнитного диска в постоянном магнитном поле из-за обратного магнитострикционного эффекта, возникает изменяющаяся во времени намагниченность. Это означает, что металлические элементы электронного оборудования вибрирующие в магнитном поле могут быть источниками низкочастотных электромагнитных помех. Такие источники механических вибраций имеют место в аппаратной киноконцертного комплекса. Получены математические соотношения вектора напряженности переменного магнитного поля в объеме колеблющегося ферромагнитного диска. Представлены графики нормированных прогибов на резонансных частотах для ферромагнитного диска заданных размеров. Полученные результаты позволили выявить важный фактор формирования непреднамеренных электромагнитных помех и представляют практический интерес при проектировании чувствительной аппаратуры.

Ключевые слова: электромагнитная совместимость, магнитное поле, механические вибрации, киноконцертный зал, ферромагнитный диск, низкочастотная помеха.

It is shown that, as a result of mechanical oscillations the ferromagnetic disk in a constant magnetic field due to the inverse magnetostriction effect, leads to the magnetization varies with time. This means that metallic parts of electronic equipment, with vibration under magnetic field conditions may be the sources of low-frequency electromagnetic interference. Such sources of mechanical vibrations can take place in the cinema and concert complex hardware room. Mathematical expressions vector of intensity alternating magnetic field in the volume of the oscillating disc of ferromagnetic are derived. The normalized graphics of deflection at the resonant frequencies of the ferromagnetic disc set sizes are presented. The results revealed an important factor in the formation of unintentional electromagnetic interference and are of practical interest in the design of sensitive equipment.

Keywords: electromagnetic compatibility, magnetic field, mechanical vibrations, cinema and concert hall, ferromagnetic disc, low-frequency interference.

Introduction. The topicality of the problem of electromagnetic compatibility (EMC) in modern conditions is constantly growing because of the increasing of sensitivity devices, increasing of external interference levels and expansion of frequency bands and emergence of new functions of electronic equipment. A reasonable example is contemporary multiplex (digital cinema & concert hall) [1-4], equipped with a variety of energy saturated apparatus, high-sensitivity equipment operating in the frequency range of sound to gigahertz.

About creation of the electromagnetic environment (EME) by variety of devices in multiplex are described in [5-9].

However, in the hardware room of a cinema and concert complex specific "non-ordinary" sources of unintentional EMI sonic and ultrasonic ranges through electromechanical units [10] are identified. As a result of experimental studies, low-frequency electromagnetic fields of audible frequency range were identified in the indoor cinema and concert hall hardware with a variety of functional equipment. Note that in mobile laboratories, hardware compartment of air and space technology, etc. take place different electromagnetic interference on kilohertz frequency range that does not come from outside, but unintentionally form units as a part of electronic equipment.

The sources of mechanical vibrations in the cinema and concert complex hardware are: supply and exhaust ventilation system connected to the projector and the passing on hardware; operating of moving equipment units (rotation: shutter, color wheel, the work of the film path, the electric motor (the platter, table rewinder, film projector, active cooling systems)); resulting vibration of acoustic systems operation and so on.

Suppose that the plate, which is used, for instance, as electromagnetic screen, vibrates at a constant or low frequency alternating magnetic field. Mechanical vibration pre-magnetized by ferromagnetic is accompanied by deformations of small capacity of plates, which causes the turns of magnetic domains (reverse magnetostrictive effect).

Objective paper: to derive formulas determining the intensity of the alternating magnetic field as the electromagnetic interference, caused by the vibration of the metal units component into electromagnetic environment formed by a constant magnetic field.

The bending ferromagnetic disc oscillations in a constant magnetic field. Consider a disk (position 1 on Fig. 1.), the diameter $2R_0$ and thickness $2h$, and $h/R_0 << 1$.

The disc is rigidly fixed in a holder (position 2 in Fig. 1), which makes axial harmonic vibrations $U_0 e^{i\omega t}$, where U_0 – the displacement amplitude of the reliance displacement from the equilibrium position, other characters - generally accepted.

The whole of construction is in a constant magnetic field, the magnetic induction vector is completely determined by the axial component B_z^ρ (ρ, z - the coordinate axis of the cylindrical coordinate system whose start is located in the middle plane of the disc.

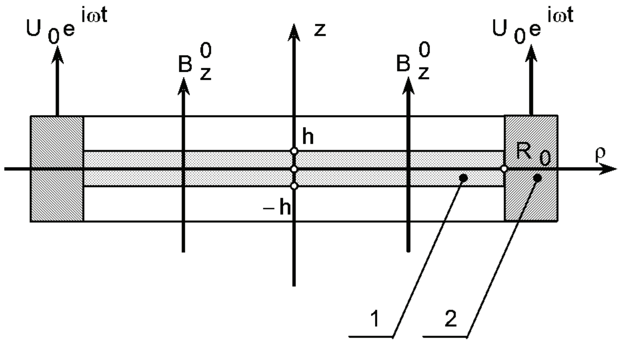

Figure 1 – Scheme to solve the ferromagnetic disc vibrations problem

Support axial vibrations form in the disk axially symmetric harmonic vibrations of lateral bending, as a result deflections appear $w(\rho)e^{i\omega t}$. The amplitude values of deflections $w(\rho)$, i.e. displacement in the axial direction of a mid-plane from of the vibrating disk of the equilibrium position, determined by the equation [11]

$$\nabla^4 w(\rho) - \lambda^4 w(\rho) = 0\,, \qquad (1)$$

where the differential operator $\nabla^4 = \frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial}{\partial\rho}\left(\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial}{\partial\rho}\right)\right)\right)$; λ – the wave index of lateral bending of axially symmetric vibrations - $\lambda = \sqrt[4]{3\omega^2\rho_0 R_0\left(1-\nu^2\right)/\left(Eh^2\right)}$; ρ_0, ν and E - density, Poisson's factor and Young's modulus of the material disc.

The general solution of equation (1):

$$w(\rho) = AJ_0(\lambda\rho) + BI_0(\lambda\rho)\,, \qquad (2)$$

where A and B are the constants that will be determined; $J_0(\lambda\rho)$ and $I_0(\lambda\rho)$ - Bessel function and the modified zero-order Bessel function.

For structure (Fig. 1) the general solution of (2) must satisfy the boundary conditions

$$w(R_0) = U_0\,; \quad \left.\frac{\partial w(\rho)}{\partial\rho}\right|_{\rho=R_0} = 0\,. \qquad (3)$$

By substituting (3) into expression (2), the constants A and B are determined and represented in the form:

$$w(\rho) = U_0\frac{I_1(\lambda R_0)}{D(\lambda R_0)}\left[J_0(\lambda\rho) + I_0(\lambda\rho)\frac{J_1(\lambda R_0)}{I_1(\lambda R_0)}\right], \qquad (4)$$

where $D(\lambda R_0) = J_0(\lambda R_0)I_1(\lambda R_0) + J_1(\lambda R_0)I_0(\lambda R_0)$ – determinant of the system of algebraic equations formed by substituting the expression (2) into the expression (3).

For some values of the argument λR_0 function is equal $D(\lambda R_0) = 0$. At frequencies which correspond to the roots x_m (m = 1,2,…) of the equation $D(x_m) = 0$ ($x = \lambda R_0$) deflections and deformations in the central part of the vibrating disk significantly increase. Obviously, these frequencies mean the resonant frequencies. For the disc size $h = 10^{-3}$ m and $R_0 = 10^{-1}$ m of the nickel brand НП2Т (Ni 98 %, Ti 2 %) [12] (E = 215 GPa; ν = 0,35 and $\rho_0 = 8{,}9\cdot 10^3$ kg/m^3) the first four roots of the equation $D(x_m) = 0$, i.e. $x_1 = 3{,}196221$, $x_2 = 6{,}306437$, $x_3 = 9{,}439499$ and $x_4 = 12{,}577131$ correspond to cyclic frequency, f_1 = 492,5 Hz, f_2 = 1917,5 Hz, f_3 = 4295,9 Hz and f_4 = 7626,5 Hz. Fig. 2 shows graphs of normalized by the value U_0 deflections on the referred above four resonant frequencies. The number of the resonant frequency is shown in the figure next to the corresponding curve in the figure. The calculations were carried out under the assumption that the quality factor is 500.

Axial displacement of the disc material particles, i.e. values $u_z(\rho) = w(\rho)$ correspond to the radial shift $u_\rho(\rho) = -z\partial w(\rho)/\partial\rho$, where z – the distance from the mid-plane of the disk. Radial movement generate radial and circumferential strain of compression-expansion $\varepsilon_{\rho\rho} = \partial u_\rho(\rho)/\partial\rho$ and $\varepsilon_{\phi\phi} = u_\rho(\rho)/\rho$. These deformations cause twists of the magnetic domains pre-magnetized by ferromagnetic disc. Thereby, the mechanical deformations in constant magnetic field form an alternating magnetization in the capacity of ferromagnetic vibrating disc.

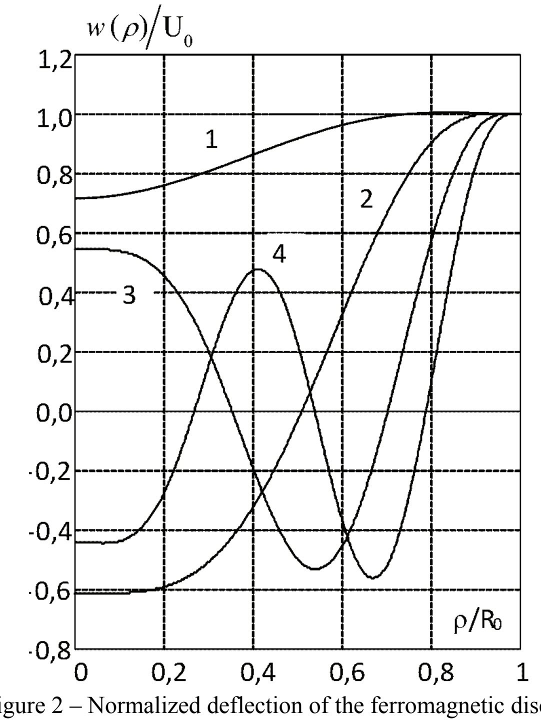

Figure 2 – Normalized deflection of the ferromagnetic disc on the first four resonance frequencies

In accordance of the linear approximation [13] general phenomenological theory of magnetostrictive effects [14] conditioned by mechanical deformations of the variable magnetization is determined by the magnetic induction vector $\vec{B}^V$

$$B_m^V = m_{pmnk}H_p^0\varepsilon_{nk}\,;\; p,m,n,k = 1,2,3\,, \qquad (5)$$

where m_{pmnk} – isotropic tensor component of the fourth rank of magnetostrictive constants which is determined:

$$m_{pmnk} = m_2\delta_{pm}\delta_{nk} + \frac{(m_1 - m_2)}{2}\left(\delta_{pn}\delta_{mk} + \delta_{pk}\delta_{mn}\right), \quad (6)$$

where m_1 and m_2 – magnetostrictive experimentally determined constant, and $m_2 \approx -m_1/2$; magnetostrictive constants depend on the composition of the ferromagnetic material and the magnitude of the magnetizing field [15]. Constant m_1 likely not exceed the value 1 H/m; δ_{pm}, …, δ_{mn} - Kronecker's symbols. In the formulas (5) and (6) summation over twice repeated indices is assumed. The symbols H_p^0 and ε_{nk} identify p-th components of the vector intensity of constant magnetic field and a component tensor of the deformation.

Since between symbols of the coordinate axis of a right-handed Cartesian rectangular coordinate system (x_1,x_2,x_3) and symbols of cylindrical coordinate system (ρ, ϕ, z) exist one to one correspondence $x_1 \Leftrightarrow \rho$, $x_2 \Leftrightarrow \phi$ and $x_3 \Leftrightarrow z$, then for the problem of the ferromagnetic disc vibrations Villari induction vector $\vec{B}^V$ is completely determined by the axial component

$$B_z^V = -m_2 H_z^0 z F(\rho), \quad (7)$$

where $H_z^0 = B_z^0 / \mu_{33}^\varepsilon$ – the axial component of the vector of the constant magnetic field in the ferromagnetic disk capacity; μ_{33}^ε – magnetic permeability (a component of the tensor of the second rank) in the direction of the bias-field; $z F(\rho) = z\left\{\partial^2 w(\rho)/\partial\rho^2 + \left[\partial w(\rho)/\partial\rho\right]/\rho\right\}$ – distribution function of volumetric deformation on the radius ρ and the thickness z of the vibratory disc.

The variable magnetic Villari induction generate within the capacity of the conductive disk low-frequency electromagnetic field, the characteristics of which must obey to the Maxwell equations. Neglecting the displacement currents, these equations are:

$$rot\,\vec{H} = \sigma\vec{E}; \quad (8)$$

$$rot\,\vec{E} = -i\omega\vec{B}, \quad (9)$$

where $\vec{H}$ and $\vec{E}$ - time-dependent amplitude values according to the law $e^{i\omega t}$ of the vectors of the magnetic and electric field; σ – specific electric conductivity of ferromagnetic (second rank tensor components with the spherical directional surface); $\vec{B}$ – magnetic induction vector in the capacity of deformed, pre-magnetized ferromagnetic. At linear approximation [13] m-th component of vector $\vec{B}$ is determined as: $B_m = B_m^V + \mu_{mk}^\varepsilon H_k$, where μ_{mk}^ε – component of the permeability tensor, experimentally determined in persistence mode (equal to zero) of mechanical deformation in a capacity of a ferromagnetic; H_k – amplitude value of the time-varying k-th component, according to the law $e^{i\omega t}$, of the internal magnetic field vector, which is stipulated to the rotation of the magnetic domains in the capacity of a deformable ferromagnetic materials.

In view of the latter definition, the system of Maxwell's equations (8) and (9) can be rolled into a single equation:

$$\left[rot\,rot\,\vec{H}\right]_m + i\omega\mu_{mk}^\varepsilon H_k = -i\omega\sigma B_m^V, \quad (10)$$

where $\left[rot\,rot\,\vec{H}\right]_m$ mean m-th component of the vector. Since the bending vibrations of the disc have axial symmetry, the peripheral component of the vector of the alternating magnetic field $H_\phi = 0$, and derivatives $\partial/\partial\phi$ of any characteristics of this field are also zero. Considering these circumstances, we obtain from (10) the system of partial differential equations:

$$-\frac{\partial^2 H_\rho}{\partial z^2} + \frac{\partial^2 H_z}{\partial\rho\partial z} + i\omega\mu_{11}^\varepsilon H_\rho = 0, \quad (11)$$

$$\frac{\partial^2 H_\rho}{\partial\rho\partial z} - \frac{\partial^2 H_z}{\partial\rho^2} + \frac{1}{\rho}\left(\frac{\partial H_\rho}{\partial z} - \frac{\partial H_z}{\partial\rho}\right) + i\omega\mu_{33}^\varepsilon H_z = -i\omega\sigma B_z^V, \quad (12)$$

where μ_{11}^ε - magnetic permeability in a perpendicular orientation of the constant bias- field.

The construction of the right-hand side of the equation (12), defined by (7), suggests that the solution of equations (11) and (12) can be found in the form:

$$H_\rho(\rho,z) = \sum_{k=0}^{\infty} H_\rho^{(k)}(\rho)\cos(\alpha_k z);$$

$$H_z(\rho,z) = \sum_{k=0}^{\infty} H_z^{(k)}(\rho)\sin(\alpha_k z), \quad (13)$$

where $\alpha_k = \pi(1+2k)/(2h)$.

Substituting the assumed solution (13) into equation (11), we obtain

$$\sum_{k=0}^{\infty}\left[H_\rho^{(k)}(\rho)\left(\alpha_k^2 + i\omega\sigma\mu_{11}^\varepsilon\right) + \alpha_k\frac{\partial H_z^{(k)}(\rho)}{\partial\rho}\right]\cos(\alpha_k z) = 0,$$

which implies that

$$H_\rho^{(k)}(\rho) = -\frac{\alpha_k}{\xi_k^2}\frac{\partial H_z^{(k)}(\rho)}{\partial\rho}, \quad (14)$$

where $\xi_k^2 = \alpha_k^2 + i\omega\sigma\mu_{11}^\varepsilon$.

Excepting with the ratio (14) the radial component $H_\rho^{(k)}(\rho)$ of the equation (12), we reduce it to form

$$\sum_{k=0}^{\infty}\frac{1}{\xi_k^2}\left[\frac{\partial^2 H_z^{(k)}(\rho)}{\partial\rho^2} + \frac{1}{\rho}\frac{\partial H_z^{(k)}(\rho)}{\partial\rho} - \zeta_k^2 H_z^{(k)}(\rho)\right]\sin(\alpha_k z) = \frac{1}{\mu_{11}^\varepsilon}B_z^V, \quad (15)$$

where $\zeta_k^2 = \mu_{33}^\varepsilon\xi_k^2/\mu_{11}^\varepsilon$.

Since the functions $\sin(\alpha_k z)$ on the interval $-h \le z \le h$ generate a system of orthogonal functions, i.e. the conditions are performed

$$\int_{-h}^{h}\sin(\alpha_k z)\sin(\alpha_m z)\,dz = \begin{cases} 0\;\forall\, k \ne m, \\ h\;at\;k = m, \end{cases}$$

it allows us to rewrite equation (15) in a more convenient form for further calculations

$$\frac{\partial^2 H_z^{(k)}(\rho)}{\partial\rho^2} + \frac{1}{\rho}\frac{\partial H_z^{(k)}(\rho)}{\partial\rho} - \zeta_k^2 H_z^{(k)}(\rho) = -J_k(\rho), \quad (16)$$

where $J_k = \dfrac{8(-1)^k h\xi_k^2 m_2 H_z^0}{\left[\pi(1+2k)\right]^2 \mu_{11}^{\varepsilon}} F(\rho)$.

The equation (16) is reduced to a dimensionless, relative to argument of the desired function $H_z^{(k)}$, form by multiplying by the ρ^2

$$x_k^2 \frac{\partial^2 H_z^{(k)}}{\partial x_k^2} + x_k \frac{\partial H_z^{(k)}}{\partial x_k} - x_k^2 H_z^{(k)} = -\frac{x_k^2}{\zeta_k^2} J_k(\rho), \quad (17)$$

where $x_k = \zeta_k \rho$ - dimensionless wave index.

The solution of the inhomogeneous ordinary differential equation (17) is found in the standard way of variation of constants [16], and is written

$$H_z^{(k)}(x_k) = \left[A_k + A_k(x_k)\right] I_0(x_k) + B_k(x_k) K_0(x_k), \quad (18)$$

where A_k – coefficient that have been determined, which ensures the uniqueness of the solution to the general equation (17) with zero right-hand side; $A_k(x_k)$ and $B_k(x_k)$ – varying coefficients (functions) that determine a particular solution of equation (17); $I_0(x_k)$ and $K_0(x_k)$ – modified zero-order Bessel function, and Macdonald function [17].

Variable factors $A_k(x_k)$ and $B_k(x_k)$ must satisfy condition

$$A_k'(x_k) I_0(x_k) + B_k'(x_k) K_0(x_k) = 0, \quad (19)$$

that provides a minimum of computations by solving the inhomogeneous equation (17). The dotted line in (19) denotes the first derivatives of the variable x_k.

In view of condition (19), first and second derivatives of the desired function $H_z^{(k)}(x_k)$ are calculated. Substituting these derivatives and supposed view of the solution (18) into equation (17), we obtain

$$A_k'(x_k) I_1(x_k) - B_k'(x_k) K_1(x_k) = -\frac{1}{\zeta_k^2} J_k(\rho). \quad (20)$$

Condition (19) and equation (20) form a system of algebraic equations, which are solved in a unique way relative to the quantity $A'_k(x_k)$ and $B'_k(x_k)$. Integrating the obtained results, we come to the expression for calculation of varying coefficients $A'_k(x_k)$ and $B'_k(x_k)$:

$$A_k(x_k) = -\frac{1}{\zeta_k^2} \int_0^{x_k} x J_k(\rho) K_0(x) dx;$$

$$B_k(x_k) = \frac{1}{\zeta_k^2} \int_0^{x_k} x J_k(\rho) I_0(x) dx, \quad (21)$$

where $x \equiv x_k$. After variable constants determining it can be written that

$$H_z^{(k)}(\zeta_k \rho) = A_k I_0(\zeta_k \rho) + Z_k(\zeta_k \rho); \quad (22)$$

$$H_\rho^{(k)}(\zeta_k \rho) = -\frac{\alpha_k \zeta_k}{\xi_k^2}\left[A_k I_1(\zeta_k \rho) + R_k(\zeta_k \rho)\right], \quad (23)$$

where A_k - constants that have to be determined; functions $Z_k(\zeta_k\rho)$ and $R_k(\zeta_k\rho)$ are defined by the following relations:

$$Z_k(\zeta_k \rho) = A_k(\zeta_k \rho) I_0(\zeta_k \rho) + B_k(\zeta_k \rho) K_0(\zeta_k \rho) = = H_0 p_k F_z^{(k)}(\lambda, \zeta_k, \rho),$$

$$R_k(\zeta_k \rho) = A_k(\zeta_k \rho) I_1(\zeta_k \rho) - B_k(\zeta_k \rho) K_1(\zeta_k \rho) = = H_0 p_k F_\rho^{(k)}(\lambda, \zeta_k, \rho);$$

$$H_0 = U_0 H_z^0 \frac{h m_2}{\mu_{33}^{\varepsilon} R_0^2}; \qquad p_k = \frac{8(-1)^k}{\left[\pi(1+2k)\right]^2};$$

$$F_z^{(k)}(\lambda, \zeta_k, \rho) = \frac{(\lambda\zeta_k)^2 R_0^2}{(\lambda^4 - \zeta_k^4) D(\lambda R_0)} \Big\{ (\lambda^2 - \zeta_k^2) I_1(\lambda R_0) \; ; \left[I_0(\zeta_k \rho) - J_0(\lambda \rho)\right] + +(\lambda^2 + \zeta_k^2) J_1(\lambda R_0)\left[I_0(\zeta_k \rho) - I_0(\lambda \rho)\right];$$

$$F_\rho^{(k)}(\lambda, \zeta_k, \rho) = \frac{(\lambda\zeta_k)^2 R_0^2}{(\lambda^4 - \zeta_k^4) D(\lambda R_0)};$$

$$\left\{(\lambda^2 - \zeta_k^2) I_1(\lambda R_0)\left[\frac{\lambda}{\zeta_k} J_1(\lambda\rho) + I_1(\zeta_k \rho)\right] - \right.$$

$$\left. -(\lambda^2 + \zeta_k^2) J_1(\lambda R_0)\left[\frac{\lambda}{\zeta_k} I_1(\lambda\rho) - I_1(\zeta_k \rho)\right]\right\}.$$

Constants A_k provide the absolute convergence of series (13). An essential feature of the convergence of these series is to satisfy the limiting conditions $\lim\limits_{k\to\infty} H_\beta^{(k)}(\zeta_k \rho) = 0$, where $\beta = \rho; z$. Sufficient sign is the final value of the sums of functions $H_\beta^{(k)}(\zeta_k \rho)$ at $k \to \infty$. Both features will be in ratios to calculate vector components of the alternating magnetic field strength in the vibrating drive only in the case where

$$A_k = -\frac{(\lambda\zeta_k)^2 (\zeta_k R_0)^2}{(\lambda^4 - \zeta_k^4) D(\lambda R_0)}\left[J_1(\lambda R_0) - I_1(\lambda R_0)\right]. \quad (24)$$

In this case, expressions (22) and (23) take the following form

$$H_z^{(k)}(\zeta_k \rho) = H_0 p_k W_z^{(k)}(\lambda, \zeta_k, \rho);$$

$$H_\rho^{(k)}(\zeta_k \rho) = -H_0 p_k \frac{\alpha_k \zeta_k}{\xi_k^2} W_\rho^{(k)}(\lambda, \zeta_k, \rho), \quad (25)$$

where

$$W_z^{(k)}(\lambda, \zeta_k, \rho) = \frac{(\lambda\zeta_k)^2 (\lambda R_0)^2}{(\lambda^4 - \zeta_k^4) D(\lambda R_0)}\left[J_0(\lambda\rho) I_1(\lambda R_0) - - J_1(\lambda R_0) I_0(\lambda \rho)\right];$$

$$W_\rho^{(k)}(\lambda, \zeta_k, \rho) = \frac{(\lambda\zeta_k)^2 (\lambda R_0)^2}{(\lambda^4 - \zeta_k^4) D(\lambda R_0)} \frac{\lambda}{\zeta_k}\left[J_1(\lambda\rho) I_1(\lambda R_0) - - J_1(\lambda R_0) I_1(\lambda \rho)\right].$$

Thus, the required components of the intensity vector of alternating magnetic field in the capacity of the vibrating ferromagnetic disc are defined by the following, absolutely convergent series

$$H_z(\rho, z) = H_0 W_z(\lambda, \rho, R_0) \sum_{k=0}^{\infty} p_k \frac{(\lambda\zeta_k)^2}{(\lambda^4 - \zeta_k^4)} \sin(\alpha_k z);$$

$$H_\rho(\rho, z) = -H_0 W_\rho(\lambda, \rho, R_0) \times \times \sum_{k=0}^{\infty} p_k \frac{\alpha_k \lambda (\lambda\zeta_k)^2}{\xi_k^2 (\lambda^4 - \zeta_k^4)} \cos(\alpha_k z), \quad (26)$$

where

$$W_z(\lambda,\rho,R_0)= =\frac{(\lambda R_0)^2}{D(\lambda R_0)}\left[J_0(\lambda\rho)I_1(\lambda R_0)-J_1(\lambda R_0)I_0(\lambda\rho)\right],$$

$$W_\rho(\lambda,\rho,R_0)= =\frac{(\lambda R_0)^2}{D(\lambda R_0)}\left[J_1(\lambda\rho)I_1(\lambda R_0)-J_1(\lambda R_0)I_1(\lambda\rho)\right].$$

There are obtained formula's components of alternating magnetic intensity to give information about the electromagnetic environment formed by fluctuating ferromagnetic disc.

Conclusion. It is proved that the mechanical vibrations the ferromagnetic details with magnetic field environmental conditions are the source of unintentional low-frequency electromagnetic interference.

Substantiated and shown complex mathematical formulas for calculating the magnetic field intensity for describe the electromagnetic environment in order to use, if necessary, effective means of ensuring electromagnetic compatibility.

References:

1. *Пилинский В. В.* Анализ допустимых регламентированных уровней эмиссии и чувствительности оборудования киноконцертного комплекса / *В.В. Пилинский, А.С. Чупахин, В.Б. Швайченко, А.А. Довженко* // Технологии ЭМС. − 2015. − № 3 (54). − С. 18-25.

2. *Пилинский В.В.* Особенности обеспечения электромагнитной совместимости современного киноконцертного комплекса. Часть 3. Расчет электромагнитных полей в функционально насыщенном помещении / *В.В. Пилинский, В.Б. Швайченко, А.С. Чупахин* // Техническая электродинамика. – Тематический выпуск «Силовая электроника и энергоэффективность», Тематический выпуск № 1. – 2012. – С. 135-140.

3. *Петрищев О.Н.* О природе источников электромагнитных помех звукового частотного диапазона / *О.Н. Петрищев, В.В. Пилинский, А.С. Чупахин* // Известия вузов. Радиоэлектроника (in press).

4. *Пилинский В.В.* Особенности обеспечения электромагнитной совместимости современного киноконцертного комплекса. Часть 2 – Формирование электромагнитной обстановки силовыми цепями киноконцертного оборудования / *В.В. Пилинский, М.В. Родионова, А.С. Чупахин* // Техническая электродинамика. – Тематический выпуск «Силовая электроника и энергоэффективность», Тематический выпуск № 4. – 2009. – С. 3-9.

5. *Walravens C.* Efficient Reduction of Electro- magnetic Interference Effects in Operational Amplifiers / *C. Walravens, S. Van Winckel, J.-M. Redout'e, M. Steyaert* // IET Electronics Letters. – Jan. 2007. – Vol. 43, №. 2. – PP. 84 – 85.

6. *Richelli A.* Design of a folded cascode opamp with increased immunity to conducted electromagnetic interference in 0.18um CMOS / *A. Richelli, G. Matig-A, J.-M. Redout'e* // Elsevier Microelectronics Reliability. – Mar. 2015. – Vol. 55, № 3−4. – PP. 654-661.

7. *Elliott Cole* Reducing electromagnetic interference (EMI) with low voltage differential signaling (LVDS) / *Elliott Cole* // Available at: http://www.ti.com/lit/an/slla030c/slla030c.pdf (accessed 5 March 2016).

8. *Armstrong K.* AES-X13 and Interference-free Pro-audio Systems / *K. Armstrong, T. Waldron* // IEEE International Symposium «EMC 2002», Sorrento, Italy, 2002. – Vol. 1. – Pp. 434-439.

9. *Ott H.W.* Electromagnetic Compatibility Engineering / *H.W. Ott*. – New York: Wiley Publ. 2009. – 843 p.

10. *Petrischev O.* Electroacoustic effects as motive of power electronics units EMI generation / *O. Petrischev, V. Pilinsky, M. Rodionova, V. Shvaichenko* // 19th International Wroclaw Symposium & Exhibition on Electromagnetic Compatibility (EMC-2008): Wroclaw, June 11-13 Proceeding, 2008. – PP. 405 – 410.

11. *Доннел Л.Г.* Балки, пластины и оболочки / *Л.Г. Доннел*. – М.: Наука, 1982. – 567 с.

12. Физические величины: Справочник / *А.П. Бабичев, Н.А. Бабушкина, А.М. Братковский* и др.; Под ред. *И.С. Григорьева, Е.З. Мейлихова*. – М.: Энергоатомиздат, 1991. – 1232 с.

13. *Петрищев О.Н.* Гармонические колебания пьезокерамических элементов. Часть 1. Гармонические колебания пьезокерамических элементов в вакууме и метод резонанса – антирезонанса / *О.Н. Петрищев*. – К.: Аверс, 2012. – 300 с.

14. *Власов К.Б.* Некоторые вопросы теории упругих ферромагнитных (магнитострикционных) сред / *К.Б. Власов* // Изв. АН СССР. Сер. физическая. – 1957. – Т. 21, № 8. – С. 1140–1148.

15. *Сыркин Л.Н.* Пьезомагнитная керамика / *Л.Н. Сыркин*. – Л.: Энергия, 1980. – 208 с.

16. Курс обыкновенных дифференциальных уравнений / *Еругин Н.П., Штокало И.З.* и др. – К.: Вища школа, 1974. – 472 с.

17. Справочник по специальным функциям с формулами, графиками и математическими таблицами / Под ред. *М. Абрамовица, И. Стиган*. – М.: Наука, 1979. – 832 с.

Bibliography (transliterated):

1.Pilinskij V.V., Chupahin A.S., Shvajchenko V.B., Dovzhenko A.A. Analiz dopustimyh reglamentirovannyh urovnej jemissii i chuvstvitel'nosti oborudovanija kinokoncertnogo kompleksa. Tehnologii JeMS. 2015. No 3 (54). pp.18−25.

2. Pilinskij V.V., Shvajchenko V.B., Chupahin A.S. Osobennosti obespechenija jelektromagnitnoj sovmestimosti sovremennogo kinokoncertnogo kompleksa. Chast' 3. Raschet jelektromagnitnyh polej v funkcional'no nasyshhennom pomeshhenii. Tehnicheskaja jelektrodinamika. Tematicheskij vypusk "Silovaja jelektronika i jenergojeffektivnost' ". Tematicheskij vypusk No 1. 2012. pp. 135-140.

3. Petrishhev O.N., Pilinskij V.V., Chupahin A.S. O prirode istochnikov jelektromagnitnyh pomeh zvukovogo chastotnogo diapazona. Izvestija vuzov. Radiojelektronika (in press).

4. Pilinskij V.V., Rodionova M.V., Chupahin A.S. Osobennosti obespechenija jelektromagnitnoj sovmestimosti sovremennogo kinokoncertnogo kompleksa. Chast' 2 – Formirovanie elektromagnitnoj obstanovki silovimi cepjami kinokoncertnogo oborudovanija. Tehnicheskaja jelektrodinamika. Tematicheskij vypusk "Silovaja jelektronika i jenergojeffektivnost' ", Tematicheskij vypusk No 4. 2009. pp. 3-9.

5. Walravens C., Van Winckel S., Redout'e J.-M., Steyaert M. Efficient Reduction of Electro- magnetic Interference Effects in Operational Amplifiers. IET Electronics Letters, Jan. 2007, Vol. 43, No 2, pp. 84-85.

6. Richelli A., Matig-A G., Redout'e J.-M. Design of a folded cascode opamp with increased immunity to conducted electromagnetic interference in 0.18um CMOS. Elsevier Microelectronics Reliability, Mar. 2015, Vol. 55, No 3-4, pp. 654-661.

7. Elliott Cole. Reducing electromagnetic interference (EMI) with low voltage differential signaling (LVDS). Available at: http://www.ti.com/lit/an/slla030c/slla030c.pdf (accessed 5 March 2016).

8. Armstrong K., Waldron T. AES-X13 and Interference-free Pro-audio Systems. IEEE International Symposium "EMC

2002", Sorrento, Italy, 2002, Vol. 1, pp. 434-439.

9. Ott H.W. Electromagnetic Compatibility Engineering. New York: Wiley Publ. 2009. 843 p.

10. Petrischev O., Pilinsky V., Rodionova M., Shvaichenko V. Electroacoustic Effects as Motive of Power Electronics Units EMI Generation. 19th International Wroclaw Symposium & Exhibition on Electromagnetic Compatibility (EMC-2008), Wroclaw, June 11-13 Proceeding, 2008, pp. 405-410.

11. Donnel L. G. Balki, plastiny i obolochki. Moscow: Nauka, 1982. 567 p.

12. Fizicheskie velichiny: Spravochnik. Babichev A.P., Babushkina N.A., Bratkovskij A.M. i dr.; Pod red. Grigor'eva I.S., Mejlihova E.Z. Moscow: Jenergoatomizdat, 1991. 1232 p.

13. Petrishhev O.N. Garmonicheskie kolebanija p'ezokeramicheskih jelementov. Chast' 1. Garmonicheskie kolebanija p'ezokeramicheskih jelementov v vakuume i metod rezonansa – antirezonansa. Kyyiv: Avers, 2012. 300 p.

14. Vlasov K. B. Nekotorye voprosy teorii uprugih ferromagnitnyh (magnitostrikcionnyh) sred. Izv. AN SSSR. Ser. fizicheskaja. 1957. Vol. 21. No 8. pp. 1140-1148.

15. Syrkin L. N. P'ezomagnitnaja keramika. Leningrad: Jenergija, 1980. 208 p.

16. Kurs obyknovennyh differencial'nyh uravnenij. Erugin N.P., Shtokalo I.Z. i dr. Kyyiv: Vishha shkola, 1974. 472 p.

17. Spravochnik po spetsialnyim funktsiyam s formulami, grafikami i matematicheskimi tablitsami. Pod red. Abramovitsa M., Stigan I. Moscow: Nauka, 1979. 832 p.

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Ферромагнитный диск – источник помех звукового диапазона частот / О.Н. Петрищев, В.В. Пилинский, А.С. Чупахин // Вісник НТУ «ХПІ». Серія: Техніка та електрофізика високих напруг. – Х.: НТУ «ХПІ», 2017. − № 15 (1237). − С. 111-116. − Бібліогр.: 17 назв. – ISSN 2079-0740.

Ferromagnetic disc as a source of interference audio frequency range / O.N. Petrischev, V.V. Pilinsky, A.S. Chupakhin // Bulletin of NTU "KhPI". Series: Technique and electrophysics of high voltage. – Kharkiv: NTU "KhPI", 2017. – № 15 (1237). − С. 111-116. – Bibliogr.: 17. – ISSN 2079-0740.

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