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Investigation of an internal friction in piezoceramic elements of electro-acoustic transducers

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Abstract

The results of investigation of an internal friction in the piezoelectric elements used in electro-acoustic transducers are presented in this paper.

Keywords: internal friction, piezoelectric element, resonance frequency, electro- acoustic transducers

Introduction

Internal friction in solid bodies is property to transform irreversibly the mechanical energy into heat during the process of its deformation [1]. The internal friction is among non- elastic or relaxation properties which are not described by the elasticity theory. This theory is based on an assumption about a quasi-static character of elastic deformation when in a deformable body thermodynamic balance is not violated.

In this case the pressure $\sigma(t)$ at any time instant is defined by the strain $\varepsilon(t)$ at the same instant. In a linear case $\sigma(t) = M_0\varepsilon(t)$, where M_0 is the static module of elasticity of an ideally elastic body, corresponding to the considered type of deformation (stretching, torsion, etc.). The body which is described by this law is called as ideally elastic. At periodic deformation of ideally elastic body σ and ε are in phase [2].

At deformation with a finite speed the thermodynamic balance in a body is violated causing corresponding relaxation process (returning to an equilibrium condition), accompanied by dissipation (dispersion) of elastic energy, i.e. its irreversible transition into heat.

For example, during bending of the uniformly heated plate, made of material which expands when heated, stretched fibers are cooled, compressed fibers are heated, and owing to that the transverse gradient of temperature originates, i.e. elastic deformation will cause violation of the thermal balance.

Equalization of temperature due to heat conductivity represents the relaxation process accompanied by irreversible transition of a part of an elastic energy into a thermal energy, by what the observed experimentally decay of free flexural vibrations may be explained [3].

During elastic deformation of an alloy with the uniform distribution of atoms of different components, redistribution of the components may take place related to differences of their dimensions.

Restoration of equilibrium distribution due to diffusion also represents a relaxation process. Exhibition of non-elastic, or relaxation properties, except the mentioned above, are elastic after- effects in pure metals and alloys [2].

Investigation of an internal friction in piezoelectric ceramics is of interest, as the internal friction in piezoelectric elements is a resistance of a piezoelement at the resonant frequency when inductive and capacitance impedances compensate each other. This impedance at the given voltage of the generator defines an electric current through a piezoelement, and therefore, the power of acoustic radiation of a piezoelement [3].

Therefore, the objective of this paper is presentation of investigation of an internal friction in piezoceramic elements used in electro-acoustic transducers.

Separate sections in monographs [2, 3] are devoted to research of an internal friction. Besides, investigation of a static pressure on an internal friction in piezoelectric elements is given in [4]. Publications [3, 5 - 10] are also devoted to investigation of researches of an internal friction in piezoceramic materials.

The analysis of energy dissipation in piezoelectric materials, having electromechanical coupling, represents a challenging task, solution of which is complicated by the fact that coefficients defining dissipation are amplitude dependent. Any piezoelectric material possesses mechanical and dielectric losses, macroscopic description of which is given, for example, in monographs [3, 5, 6]. These kinds of losses can be considered, for example, by complex representation of elastic and dielectric constants:

$$tg\delta_{м} = \frac{s''}{s'} \quad (\text{or } \frac{c''}{c'}); \qquad (1)$$

$$tg\delta_{э} = \frac{\varepsilon''}{\varepsilon'} \quad (\text{or } \frac{\beta''}{\beta'}). \qquad (2)$$

In a number of works, for example [7, 8], it is proposed to consider piezoelectric losses in a piezoelectric materials as

$$tg\delta_{эм} = \frac{d''}{d'}(\frac{e''}{e'}, \frac{g''}{g'}, \frac{h''}{h'}). \qquad (3)$$

It has been confirmed experimentally [9, 10].

According to [6], there are three types of a friction:
- constant or Coulomb;+
- liquid;
- solid body.

The coulomb friction is proportional to the mass of a moving element and does not depend on a movement speed. This type of a friction practically is absent in simple oscillatory systems and does not represent interest in a considered case.

Liquid friction is a classical kind of an internal friction when resistance is constant, and the resistance force of is proportional to the speed. This kind of losses in the given work is not considered.

The friction of a solid body is characteristic for elastic deformations of solid bodies and represents the greatest interest in our case.

Experience shows that a mechanical energy in heat is transformed due to compliance. A quality factor of a compliance element depends only on properties of a material. It is given by [3, 12, 13]:

$$Q_T = \frac{1}{\omega KR}, \tag{4}$$

where ω is the angular frequency, R is the resistance describing losses.

Though in general the quality factor Q_T depends on the frequency ω, it is experimentally established, that for the majority of solid bodies Q_T in an audible range of frequencies it is approximately constant. Therefore in the case of the solid body friction the quality factor Q_T may be assumed as a material constant Then resistance of losses in inverse proportion to the frequency:

$$R = 1/(\omega K Q_T).$$

At the constant Q_T the mechanical impedance may presented as

$$Z = R + j\omega M + \frac{1}{j\omega K} = R(1 + jQ_T\nu'), \tag{5}$$

where $\nu' = (\omega/\omega_0)\nu$.

During modeling piezoceramic resonators are usually represented by an equivalent electromechanical lumped circuit in which it is assumed R=const, what corresponds to the case of a liquid friction, or in a general case of a mechanical system - to the external friction proportional to the movement speed.

In case of free vibrations of a piezoelectric resonator the mechanical losses represented by such circuit correspond to the friction of a solid body. Therefore resistance of mechanical losses R is frequency-is dependent.

As the internal friction is defined by deformation of elements of a compliance, in the equation $M\frac{d\upsilon}{dt} + R\upsilon + \frac{1}{K}\xi = F$ it is expedient to unite resistance of losses and a compliance, considering, that for a harmonic excitation $d\xi/dt = j\omega\xi$

$$M\frac{d^{2\xi}}{dt^2} + \Lambda\xi = F, \tag{6}$$

where $\Lambda = (1/K)(1 + j\omega KR) = \Lambda_0(1 + j\eta)$ is the complex stiffness. From Eq. 6 follows, that a real part Λ defines rigidity of system, and imaginary part is proportional to the factor of losses.

Elastic properties of piezoceramic material are described by five independent elastic constants. According to it is possible to distinguish five independent kinds of the internal friction, described by five complex elastic constants.

In a solid body the internal friction can be of hysteresis or relaxation type. The type of the an internal friction may be determined from the frequency response of η.

Dielectric losses. The basic contribution into dissipation of an electric energy in the case of alternating current in piezoceramic material is brought by polarization processes. As these processes are defined by dielectric properties of a material the most convenient is representation of losses at polarization processes by introduction of a complex dielectric permeability

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{7}$$

and of dielectric losses

$$tg\delta = \frac{\varepsilon''}{\varepsilon'}. \tag{8}$$

In most cases $\varepsilon = \varepsilon' - j\varepsilon'' = const$, hence, $tg\delta = const$. The last condition corresponds to the processes of polarization which are not dependent on a speed of change of the electric field. However, as it is known, dielectric materials, and in particular ferroelectric materials, are characterized by the whole spectrum of relaxation mechanisms of polarization, when depending on the speed of change of the oscillation frequency, the polarization processes do not reach the steady state. In similar cases the complex dielectric permeability depends on a frequency

$$\varepsilon(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega). \tag{9}$$

Thus, the piezoceramic material is characterized by five different types of an internal mechanical friction, for example $tg\varphi^E_{s11}$, $tg\varphi^E_{s12}$, $tg\varphi^E_{s13}$, $tg\varphi^E_{s33}$, $tg\varphi^E_{s44}$; two kinds of dielectric losses: $tg\varphi^T_{\varepsilon 11}$, $tg\varphi^T_{\varepsilon 33}$, and also three kinds of piezoelectric losses: $tg\varphi_{d31}$; $tg\varphi_{d33}$; $tg\varphi_{d15}$.

In the results published up to now there are no discussions to which complex elastic coefficients correspond the determined quality factors. Meanwhile in a dynamic longitudinal mode of vibrations of a bar in the electric field, perpendicular to its length is defined $tg\varphi^E_{s11}$, in the field, parallel to its length, - the value $tg\varphi^D_{s33}$, in the thickness vibration mode of plates - $tg\varphi^D_{c33}$, etc.

Most often the mechanical quality factor of piezoceramic materials is defined in a radial mode of vibrations of a disk or in a longitudinal mode of a bar vibrating in the electric field, perpendicular to the length of the bar [3]. In the specified cases identical values of the quality factor $(Q^E_{s11} = 1/tg\varphi^E_{s11})$ are reached under condition $tg\varphi^E_{s11} = tg\varphi^E_{s12}$. If this condition is not kept the value of the quality factor determined in the radial mode of a disk may differ from Q^E_{s11} depending on a sign of the difference $\varphi^E_{s11} - \varphi^E_{s12}$.

In the given work the results of measurements of an internal friction in piezoceramic elements used in electro-acoustic transducers are presented.

The internal friction was measured under the scheme shown in Fig. 1 at the resonant frequency. In this case ωL and $\frac{1}{\omega C}$ of the piezoelectric element are equal and compensate each other, and the resistance of the piezoelectric element is equal to the internal friction r_0.

The resistance R is selected according to a condition $R << r_0$.

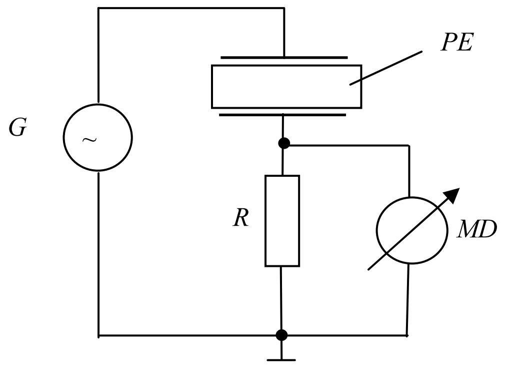

Fig. 1. **The scheme of measurement of an internal friction of a piezoelectric element: PE- piezoelectric element, *G* – generator Г3-106, MD –voltmeter В3-38**

In the given work the dependencies r_0 on the following parameters of a piezoelectric element were defined:

- the areas of electrodes;
- the locations of electrodes;
- vibration mode.

Measurements were performed for the piezoelectric elements manufactured of the piezoceramics ЦТС-19 (Ø50 × 1mm) and ЦТБС-3 (Ø50 × 1,2 mm), and also for a bimorph piezoelectric element (BPE), made of the piezoelectric element Ø50 × 1,2 mm (ЦТБС-3) and metal plate Ø200×1mm from brass Л63.

One of the electrodes of each piezoelement was split into three parts of the equal area (~ 650 mm^2) in the shape of a disk with the diameter Ø28 mm and two semi- disks Ø50 × Ø29 mm (Fig. 2).

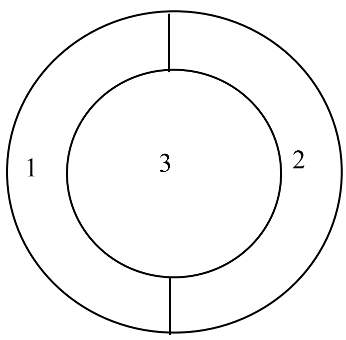

Fig. 2. **The scheme of division of electrodes of a piezoelement: 1,2 - electrodes in the shape of half rings, 3 - disk electrode**

The internal friction r_0 was measured at connection of the electrodes 1, 2, 3 separately and in various combinations.

The measurements were carried out at the resonant frequency of radial vibrations f = 55 kHz for the disk Ø50×1,2 mm made of piezoceramics ЦТБС-3.

The results of measurements r_0 are presented in Table 1.

Table 1.

Electrodes	1	2	3	1+2	1+3	1+2+3
r_0 , *Ω*	115,5	115,3	44,7	46,7	70	33

From the results presented in Table 1 follows, that at increase in the area of electrodes the resistance r_0 decreases, what is quite obvious. Less obvious is the fact which requires explanation, that the resistance r_0 at connection of the central electrode (disk 3, Fig. 2) is less than the resistance of the peripheral electrodes possessing the equal area.

Determination of the internal friction r_0 depending on a frequency, material of the piezoelectric element and vibration mode was carried out for monomorph piezoelectric elements Ø50 × of 1,2 mm (ЦТБС-3), Ø50 × 3 mm (ЦТС-19) and the bimorph piezoelectric element (BPE).

Measurements were performed at the resonant frequency of radial vibrations for monomorph piezoelements Ø50 × 1,2; ЦТБС-3 - 55 kHz and Ø50×1, ЦТС-19 - 39 kHz and for BPE (Ø50 × 1,2 mm, ЦТБС-3 and plate Ø200×1 mm made of Л63) - 2,9 kHz. During measurements the electrodes 1, 2, 3 were connected between themselves.

The frequencies below the basic resonant frequency were created by connection to the piezoelectric element of the inductance L_{ad} which together with the inter-electrode capacity of the piezoelectric element C_{el} created the series-resonant circuit the resonant frequency of which is given by [11]:

$$f_p = \frac{1}{2\pi\sqrt{L_{ad} \cdot C_{el}}} \qquad (10)$$

Table 2

Piezoelement Ø50×1,2mm, ЦТБС-3	f_p, kHz	55,3	1,0	0,655
Piezoelement Ø50×1,2mm, ЦТБС-3	r_0 , kΩ	0,033	5,2	8,4
Piezoelement Ø50×3mm, ЦТС-19	f_p, kHz	39,2	1,6	1,05
	r_0 , kΩ	0,035	9,2	16,9
BPE Ø50×1,2mm, ЦТБС-3, Ø200×1mm, Л63	f_{p1}, kHz	2,9	1,02	0,65
	r_{01} , kΩ	1,8	5,4	10,3

From Table 2 follows, that when the frequency is reduced, the resistance r_0 increases, what is confirmed by data published elsewhere [3, 6 and 7].

Besides, for the bimorph piezoelectric element (flexural vibrations, piezoelectric element Ø50×1,2 mm, ЦТБС-3) the value of the resistance r_0 is a little higher at identical frequencies (1,0 and 0,65 kHz), than for the monomorph transducer (Ø50×1,2 mm, ЦТБС-3).

It is necessary to point out that the value r_0 is lower for the monomorph transducer made of the piezoelectric element Ø50×1,2 mm, piezoceramics ЦТБС-3, than for the monomorph piezoelement Ø50×3 mm made of the piezoceramics ЦТС-19.

Conclusions

1. Piezoceramic material is characterized by five kinds of an internal mechanical friction, for example $tg\varphi_{s11}^{E}$, $tg\varphi_{s12}^{E}$, $tg\varphi_{s13}^{E}$, $tg\varphi_{s33}^{E}$, $tg\varphi_{s44}^{E}$; two kinds of dielectric losses: $tg\varphi_{\varepsilon 11}^{T}$, $tg\varphi_{\varepsilon 33}^{T}$, and also three kinds of piezoelectric losses: $tg\varphi_{d31}$; $tg\varphi_{d33}$; $tg\varphi_{d15}$.
2. In the case of radial vibrations of a piezoelectric disk, in the centre of the piezoelectric element the resistance r_0 has a smaller value, than on a periphery.
3. The resistance r_0 increases when the frequency decreases.
4. With the increase of the area of electrodes the resistance r_0 decreases.
5. The value of the resistance r_0 for the piezoelectric element Ø50×1mm made of piezoceramics ЦТБС-3 is less than for the piezoelectric element Ø50×3mm made of the piezoceramics ЦТС-19.
6. For the bimorph piezoelectric element the resistance r_0 is higher than for the monomorph transducer.
7. The obtained information may be useful at designing of electro-acoustic transducers. The further research can be directed on development of methods, circuits and devices for decrease of the internal friction in piezoelectric elements of electro- acoustic transducers.

References

1. The physical encyclopaedia. http://www.femto.com.ua/
2. **Postnikov V. S.** Internal friction in metals. M.: Mashinostroenie. 1975. (in Russian).
3. Piezoceramic transducers: The directory. Ed. S. I. Pugachev. L.: Sudostroenie. 1984. P. 256. (in Russian).
4. **Minaev I. G., Sharapov V. M.** About influence of pressure on an internal friction piezoceramic ЦТС. Izvestiya vuzov SSSR. Physics. 1976. № 9. (in Russian).
5. **Poplavko Yu. M.** Physics dielectric. Kiev: Vyscha shkola. 1980. (in Russian).
6. **Skuchik E.** Simple and complex oscillatory systems. M.: Mir. 1971. (in Russian).
7. **Holland R.** Representation of dielectric, elastic and piezoelectric losses by complex coefficients. IEEE transaction on sonics and ultrasonics. 1967. Vol. SU – 14. No.1. P.18-20.
8. **Land C. E., Smith G. W., Westagate C. R**. The dependence of Small – Signal parameters of ferroelectric ceramic resonators upon state of polarization. IEEE transaction on sonics and ultrasonics. June 1964. Vol. .SU – 11. P..8-19.
9. **Prudko N. I., Bobyl V. G.** Method for definition of complex constants of piezoceramic, used in hydroacoustic transducers. Materials of III Far East acoustic conference Part.2. Acoustic aerials and transducers. Vladivostok. 1975. P. 272-276. (in Russian).
10. **Holland R.** Measurement of piezoelectric phase angles in a ferroelectric ceramic. IEEE transaction on sonics and ultrasonics. 1970. Vol. .SU– 17. No.2. P.123-124.
11. Patent of Ukraine No.56930. A method of creation of acoustic vibrations by means of a piezoelectric element. Sharapov V. M. and others. 25.01.2011 (in Ukrainian).
12. **Sharapov V. M., Musienko M. P., Sharapova E. V.** Piezoelectric sensors. Ed. by V.M. Sharapov. Moscow: Technosphera. 2006. P. 632. (in Russian).
13. **Sharapov V.** Piezoceramic sensors. Springer, 2011. P. 498. http://dx.doi.org/10.1007/978-3-642-15311-2

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Elektroakustinių keitiklių vidinės trinties pjezokeraminiuose elementuose tyrimai

Reziumė

Tirti vidinę trintį pjezokeramikoje ypač aktualu, kai pjezoelementų darbiniai dažniai artimi rezonansiniams dažniams. Straipsnyje nagrinėjama pjezoelementų vidinės trinties priklausomybė nuo tamprumo deformacijų kietuosiuose kūnuose. Vidinės trinties matavimai atliekami rezonansiniam dažniui, kai pjezoelemento induktyvioji ir talpinė varžos kompensuoja viena kitą. Pjezoelemento vienas elektrodas buvo padalytas į 3 lygias dalis ir išmatuota kiekvienos dalies vidinė varža esant 55 kHz rezonansiniam dažniui. Didėjant elektrodų plotui vidinė varža mažėja. Be to, centrinio elektrodo varža mažesnė negu šoninių elektrodų esant spinduliniams virpesiams. Mažinant žadinimo dažnį pjezoelemento vidinė varža didėja.

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