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RELATIONS BETWEEN LOSSES IN PIEZOELECTRIC CERAMIC AND THE MAGNITUDE OF ITS VIBRATION LEVEL

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In the paper the method of the mechanical and electrical loss measurements using a piezoelectric transformer has been applied to determine the relations between the losses and the magnitude of the vibration velocity, strain and stress. The measurements and calculations have been realized for the soft and hard PZT-type ceramics. Good accordance of the obtained results with the results obtained by the other authors, applying different measurement methods, proves the usability of the method of loss measurements proposed by the author.

1. Introduction

Modified with various additives piezoelectric ceramic with the basic composition $\mathrm{Pb(Zr_xTi_{1-x})O_3}$ is widely used in the piezoelectronics [5]. Recently the quantity of its applications in high power devices (ultrasonic transducers, piezoelectric transformers, piezoelectric motors, translators, actuators) has increased considerably. The ceramic in these devices is excited by high electric fields to mechanical vibrations with high amplitude. As yet there is no complete and exact description of the domain phenomena that cause the large increase of losses and changes of material constants of ceramics in high fields. The kinetics and the physical mechanism of processes that occur in polycrystalline ferroelectrics in high external fields are very complicated and they have not been completely investigated [9, 13, 16, 23]. Recently good results have been obtained by the authors applying the Rayleigh law (originally discovered for ferromagnetic materials) to the description of the domain phenomena in a piezoelectric ceramic [4, 6, 17, 29]. In the high fields range the nonlinear effects [8, 26, 28] make impossible to apply standard methods of loss measurements. The threshold electric field for the occurence of nonlinearity depends on the conditions of the operation of the piezoelectric ceramic. Stresses induced in the piezoceramic resonator under resonant mode conditions cause that the threshold electric field is much lower than under off resonant conditions [26].

In the previous paper [24] we have proposed the method of the determination of electrical and mechanical losses applying the measurements of voltage ratios in a piezoelectric transformer instead of the measurements of resonator quality factors. The results of the measurements of losses as a function of input electric field have been presented. The magnitude of the output mechanical signal is very important for designers and users of piezoelectric elements. Therefore results of investigations of ceramic properties and measurements of losses are presented most often as a function of vibration velocity [22, 25, 30, 31] or induced stresses [26]. The method of loss measurements applied by the author is shortly recalled in Sec. 2. In Sec. 3 the results of the measurements of the changes of ceramic material constants with the increasing electric field are presented. They are necessary for subsequent calculations. Ceramic material constants were measured using standard methods [1, 3, 7]. The results of the calculations of the magnitude of the vibration velocity, mechanical stress and strain induced in the transformer are presented in Sec. 4 as a function of driving electric field. The relations between the magnitude of electrical and mechanical losses in the piezoelectric ceramic and above mentioned mechanical quantities are presented in Sec. 5. The losses have been measured and calculated using the method described in [24] and recalled in Sec. 2.

2. Application of a piezoelectric transformer to loss measurements

Various designs of piezoelectric transformers are known, with various polarizations of individual parts and with various shapes, e.g. [12, 21, 32]. For the loss measurements we applied a ring-shaped piezoceramic transformer with the electrodes divided with the ratio 1:1 [24]. The thickness and width of a ring were small in comparison with its radius. Such a shape has an important advantage — the stress and strain distribution is uniform in the whole ring. The piezoelectric ceramic was poled along the thickness direction. One pair of vacuum evaporated silver electrodes constituted the input of the transformer, the second pair — its output. Piezoelectric transformers have been already applied for the measurements of various properties of piezoelectrics, e.g. [11, 19, 20].

Analytical description of the physical processes (direct and converse piezoelectric effect, secondary effects, higher order effects) and their interactions in piezoelectric transformers is very difficult. Therefore equivalent circuits are applied to analyse transformer operation. However a large number of simplificating assumptions is necessary [12, 24].

We have used KLM equivalent circuit to obtain the following equations describing mechanical and electrical losses [24]:

$$\tan\delta_m = \frac{\phi^2 R_L (1 - A_0)}{\pi Z_0 A_0}, \tag{2.1}$$

$$\tan\delta_e = (1 - k_{31}^2)\frac{\phi^2 X_e (\tan\delta_m)^{-1} - \pi A_\infty Z_0}{\phi^2 X_e A_\infty (\tan\delta_m)^{-1}}, \tag{2.2}$$

$$\phi = \frac{\pi w d_{31}}{s_{11}^E}, \tag{2.3}$$

$$Z_0 = \pi w t \sqrt{\frac{\rho}{s_{11}^E}}\,, \tag{2.4}$$

$$X_e = \frac{1}{\omega C_0}\,, \tag{2.5}$$

$$C_0 = \frac{\pi a w \varepsilon_{33}^T}{t}\left(1 - k_{31}^2\right), \tag{2.6}$$

where R_L — transformer load resistance, $A_0 = U_{\mathrm{OUT}}/U_{\mathrm{IN}}$ for $R_L \to 0$ (in this case $U_{\mathrm{OUT}} < U_{\mathrm{IN}}$), $A_\infty = U_{\mathrm{OUT}}/U_{\mathrm{IN}}$ for $R_L \to \infty$, U_{IN} — input voltage, U_{OUT} — output voltage, k_{31} — electromechanical coupling coefficient, $w = (D_{\mathrm{EXT}} - D_{\mathrm{INT}})/2$, $a = (D_{\mathrm{EXT}} + D_{\mathrm{INT}})/4$, D_{INT} — internal diameter of the ceramic ring, D_{EXT} — external diameter of the ceramic ring, t — thickness of the ceramic ring, d_{31} — piezoelectric constant, s_{11}^E — elastic compliance, ρ — density, ε_{33}^T — permittivity.

For the determination of loss it is not sufficient to measure only the voltage ratios for two limits of the loading of the piezoelectric transformer. In the high fields range the material constants of the piezoelectric ceramic change with the increase of the driving electric field [2, 27]. This is due to the domain structure of the ceramics [4, 6, 17, 33]. Very high electric fields and mechanical stresses can cause durable changes in the domain structure and ceramic parameters [10, 13]. In most cases the degradation of the polarization state occurs in high electric fields especially when the frequencies are near the resonance frequency of the piezoelectric element [23]. The changes of the resonance frequency of the piezoceramic element due to the changes of its material constants should be considered in the design of piezoelectric devices, e.g. piezoelectric motors [14].

3. Changes of the material coefficients of the piezoelectric ceramic due to the increase of the driving electric field

As we have mentioned in Sec. 2, the knowledge of the magnitude of ceramic material constants for the definite magnitude of the driving electric field is necessary to the calculations of losses using Eqs. (2.1) – (2.6). It is also necessary to the calculations of the magnitude of the mechanical signal (Sec. 4). In [26] the authors have published the following empirical formula describing the changes of the material coefficients of the piezoelectric ceramic as a function of the driving electric field:

$$\frac{\Delta x}{x_0} = \frac{x - x_0}{x_0} = \alpha E_{\mathrm{IN}}, \tag{3.1}$$

where $x = d_{31}$, Y^E, ..., x_0 — x measured at the low field level, α — proportionality coefficient.

In Figs. 1 – 4 the results of the measurements of $\dfrac{\Delta\varepsilon_{33}^T}{(\varepsilon_{33}^T)_0}$, $\dfrac{\Delta s_{11}^E}{(s_{11}^E)_0}$, $\dfrac{\Delta k_{31}}{(k_{31})_0}$, $\dfrac{\Delta d_{31}}{(d_{31})_0}$ are presented for two kinds of ceramic used to make the piezoelectric ring transformers [24]: a — soft PZT-type ceramic, b — hard PZT-type ceramic. The continuous lines correspond to the formula (3.1). The experimentally obtained values of α for the material constants of the used ceramics are tabulated in Table 1. The values of α for the soft ceramic

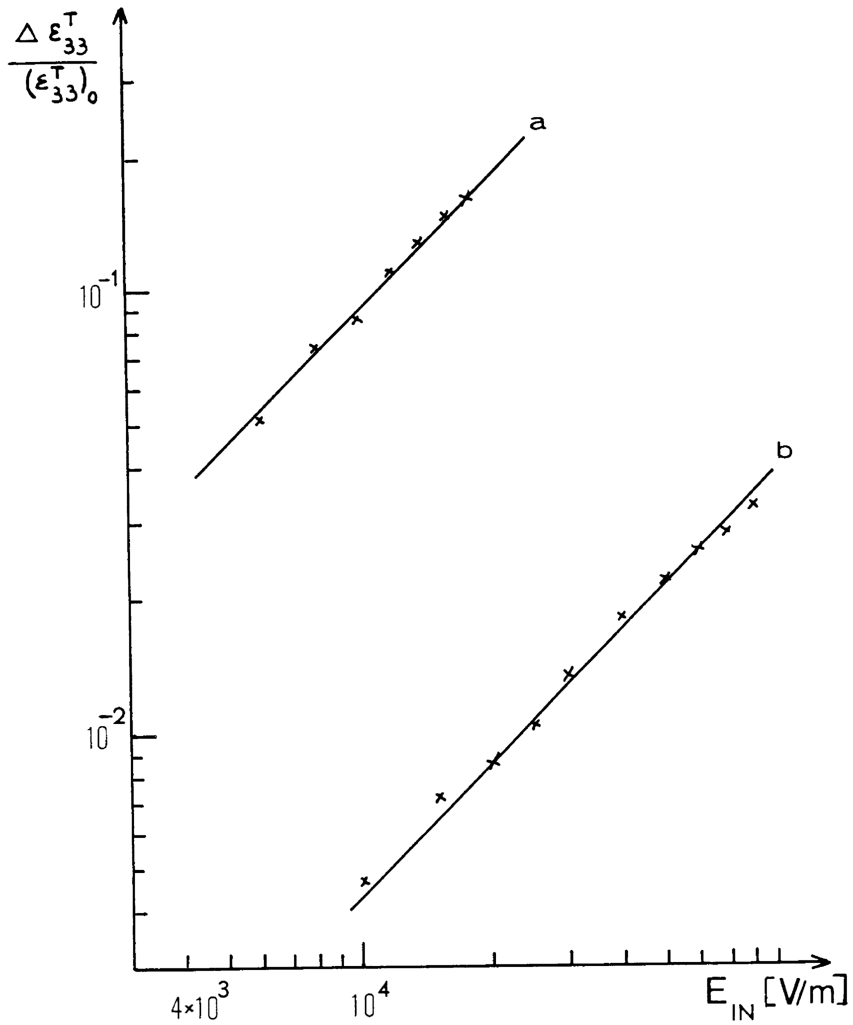

Fig. 1. Dependence of the changes of the permittivity on the input electric field, a — soft PZT-type ceramic, b — hard PZT-type ceramic, × — measured values, continuous line — calculated using (3.1).

Table 1. Values of α coefficient.

Material constant	Soft PZT-type ceramic	Hard PZT-type ceramic
d_{31}	$4 \cdot 10^{-5}$	$1.9 \cdot 10^{-5}$
s_{11}^E	$9 \cdot 10^{-6}$	$2.1 \cdot 10^{-6}$
k_{31}	$2.8 \cdot 10^{-5}$	$1.6 \cdot 10^{-5}$
ε_{33}^T	$9 \cdot 10^{-6}$	$4.3 \cdot 10^{-7}$

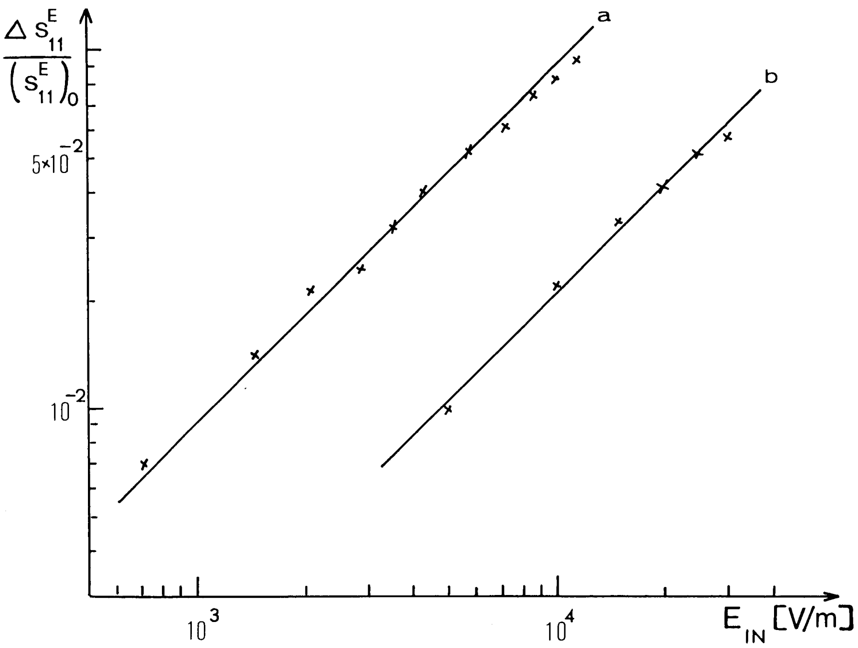

Fig. 2. Dependence of the changes of the elastic compliance on the input electric field, a — soft ceramic, b — hard ceramic, × — measured values, continuous line — calculated using (3.1).

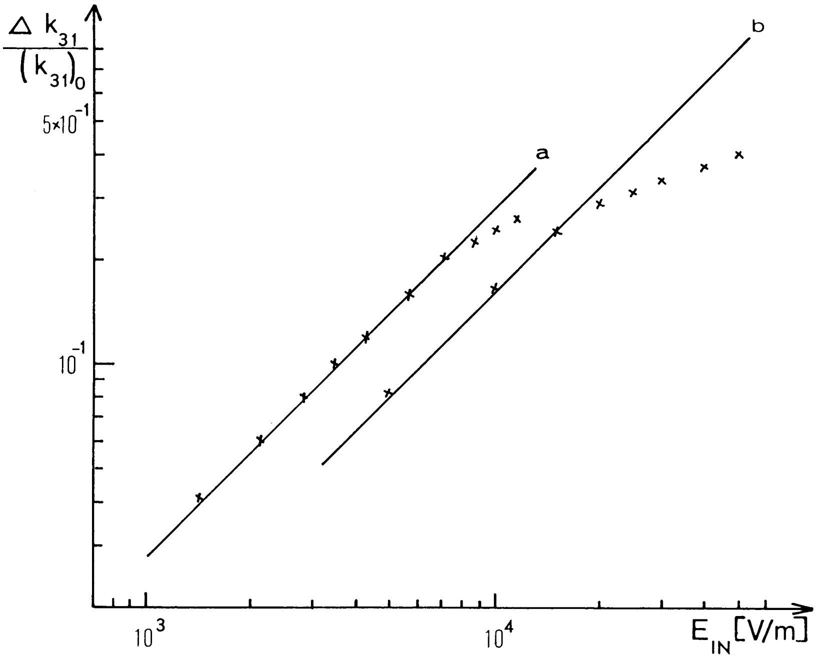

Fig. 3. Dependence of the changes of the electromechanical coupling coefficient on the input electric field, a — soft ceramic, b — hard ceramic, × — measured values, continuous line — calculated using (3.1).

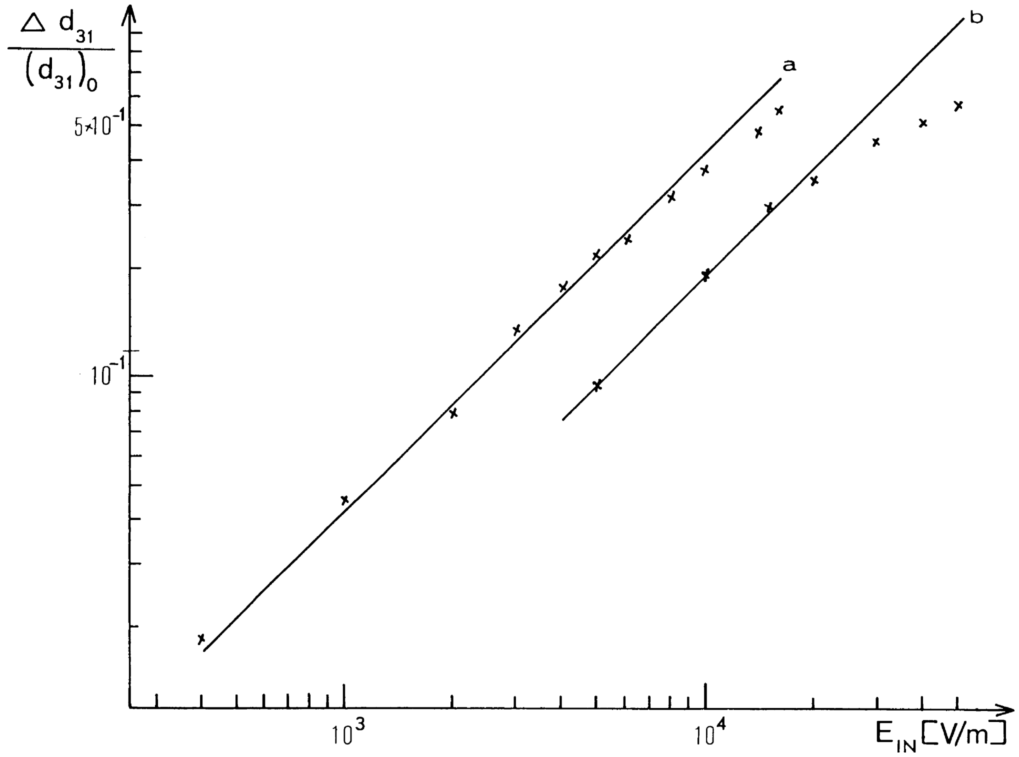

Fig. 4. Dependence of the changes of the piezoelectric constant on the input electric field, a — soft ceramic, b — hard ceramic, × — measured values, continuous line — calculated using (3.1).

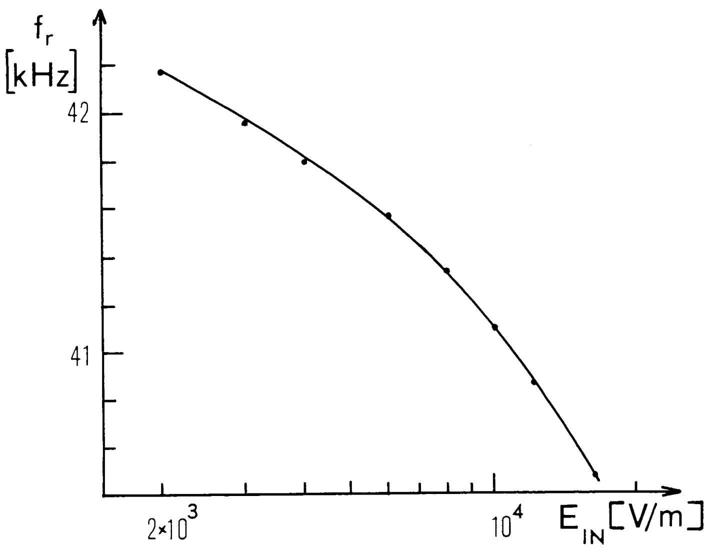

Fig. 5. Dependence of the resonance frequency on the input electric field for the ring made of the soft PZT-type ceramic.

are higher than for the hard one because the mobility of 90° domain walls is higher in the soft ceramic [33]. The manner of changes of the material constants and the range of electric fields are in accordance with earlier published results, e.g. [10, 17, 26]. For the electromechanical coupling coefficient k_{31} (Fig. 3) and the piezoelectric constant d_{31} (Fig. 4) one can see the distinct deflection of the measured values from the relation (3.1) in the range $E_{\mathrm{IN}} \geq 10^4$ V/m.

The changes of the material constants of the ceramic as a function of E_{IN} cause that the resonance frequency f_r of the piezoelectric element changes also. Figure 5 presents an example of the dependence of f_r on the magnitude of the driving electric field for a ring with full electrodes, the soft PZT-type ceramic.

4. Vibration velocity, strain and stress in a ring transformer

One can measure the displacement amplitude or vibration velocity of piezoelectric elements using a laser interferometer or a fibre optic vibrometer. In the case of a piezoceramic element the measurement circuit must have high sensitivity because ceramic surfaces have poor reflecting properties, especially for the ceramics with coarse grains and high porosity. The measurement circuit with very high sensitivity and very narrow light beam would be necessary for the measurement of the radial displacement of thin ceramic ring. Strains can be measured using a tensometer bridge. Unfortunately the ceramic driven by the high electric field warms up. This effect causes important measurements errors and impedes to apply tensometers.

One can calculate the strain amplitude $S_{1\ \max}$ applying the theory of ring vibrations [1, 18] and taking into the consideration the used configuration of electrodes [3]:

$$S_{1\ \max} = 1/2\, d_{31} E_{\mathrm{IN}} Q_m\,, \tag{4.1}$$

similarly for the amplitude of radial displacement $u_{\max}$:

$$u_{\max} = S_{1\ \max} a, \tag{4.2}$$

the amplitude of vibration velocity $v_{\max}$:

$$v_{\max} = \frac{1}{2} d_{31} E_{\mathrm{IN}} Q_m \frac{1}{\sqrt{\rho s_{11}^E}}\,. \tag{4.3}$$

the root-mean-square value of vibration velocity v:

$$v = \frac{1}{\sqrt{2}} v_{\max} = \sqrt{2}\,\pi f_r u_{\max} = \frac{1}{2\sqrt{2}} d_{31} E_{\mathrm{IN}} Q_m \frac{1}{\sqrt{\rho s_{11}^E}}\,, \tag{4.4}$$

and the amplitude of induced stress $T_{1\ \max}$:

$$T_{1\ \max} = \frac{S_{1\ \max}}{s_{11}^E} = \omega^2 a^2 \rho S_{1\ \max} = \sqrt{\frac{\rho}{s_{11}^E}} v_{\max} = \sqrt{\frac{2\rho}{s_{11}^E}} v = \frac{1}{2}\, \frac{d_{31}}{s_{11}^E} E_{\mathrm{IN}} Q_m\,. \tag{4.5}$$

In the calculations one should use the measured values of the ceramic material constants as a function of input electric field, presented in Sec. 3.

The quality factor measured using standard methods should be inserted as Q_m into equations (4.1)–(4.5) when the ceramic is driven by low electric field and the electric losses can be neglected. In the range of high electric fields the electric losses cannot be neglected and one should insert into the above equations [25]:

$$Q_m = \frac{1 - k_{31}^2}{\tan\delta_m + k_{31}^2 \tan\delta_e}\,. \tag{4.6}$$

The magnitude of Q_m (E_{IN}) can be calculated using the results of the measurements of $\tan\delta_e(E_{\mathrm{IN}})$ and $\tan\delta_m(E_{\mathrm{IN}})$ obtained by means of the method described in Sec. 2 and the results of the measurements of k_{31} (E_{IN}) (Sec. 3).

Figures 6–8 present the strain $S_{1\,\max}$, the vibration velocity v and the stress $T_{1\,\max}$ as a function of the input electric field for the ring piezoelectric transformers for a soft PZT-type piezoelectric ceramic with low quality factor and for a hard PZT-type piezoelectric ceramic with high quality factor. One can see that the vibration velocity, strain and stress do not increase proportionally to the increase of E_{IN}, even in the range of relatively low electric fields. The dependence of the output voltage of the piezoelectric transformer on the magnitude of its input voltage is similar [24]. Similar results have been also obtained in [27]. The authors of that paper measured the vibration velocity of rectangular plates (L–E mode) made of various ceramics. They used an optical sensor. The curves v (E_{IN})

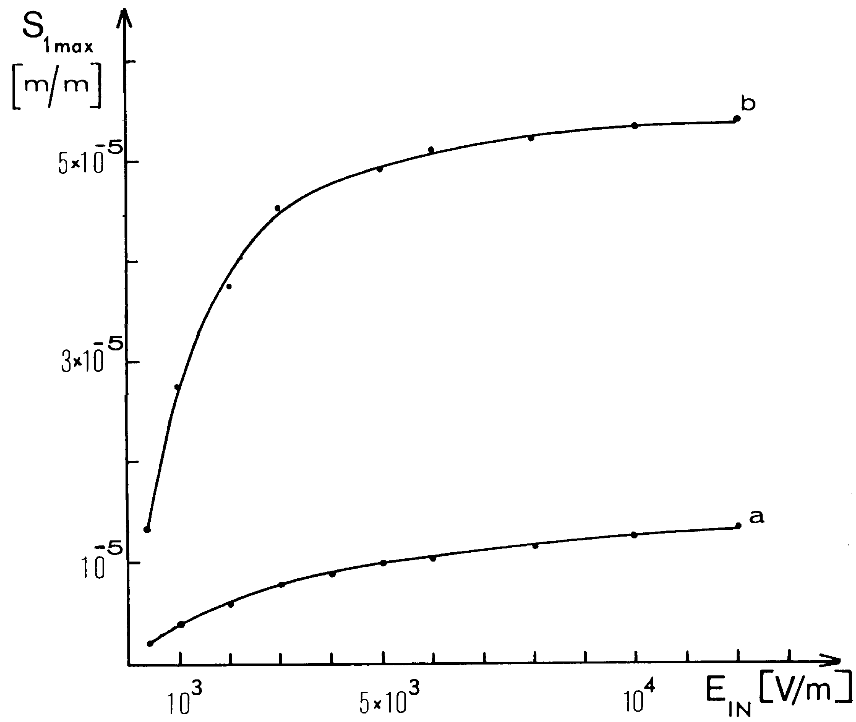

Fig. 6. Maximal strain as a function of the input electric field for the ring piezoelectric transformer, a) soft ceramic, $D_{\mathrm{EXT}} = 30$ mm, $D_{\mathrm{INT}} = 16$ mm, $t = 5$ mm; b) hard ceramic, $D_{\mathrm{EXT}} = 38$ mm, $D_{\mathrm{INT}} = 28$ mm, $t = 5$ mm.

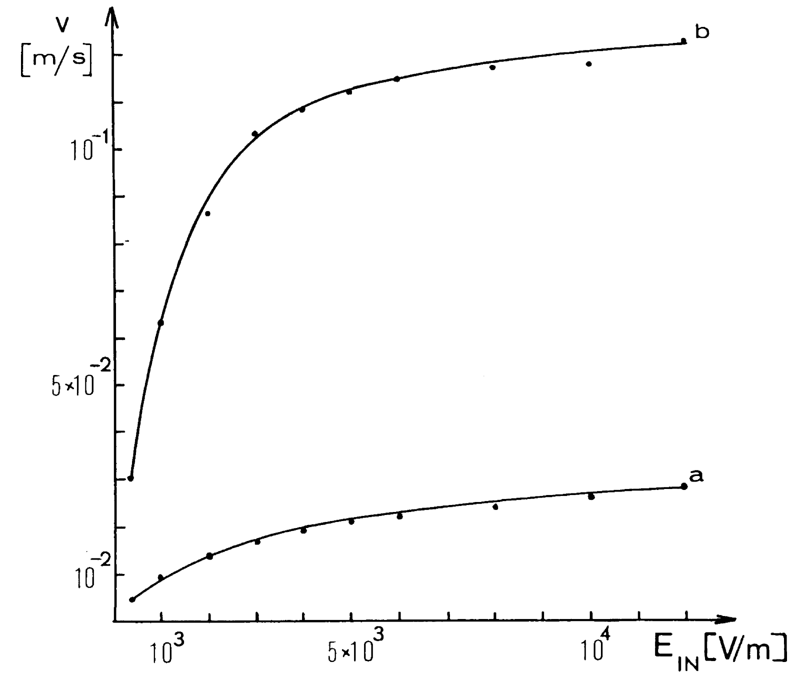

Fig. 7. Vibration velocity (rms) as a function of the input electric field. a, b — as in Fig. 6.

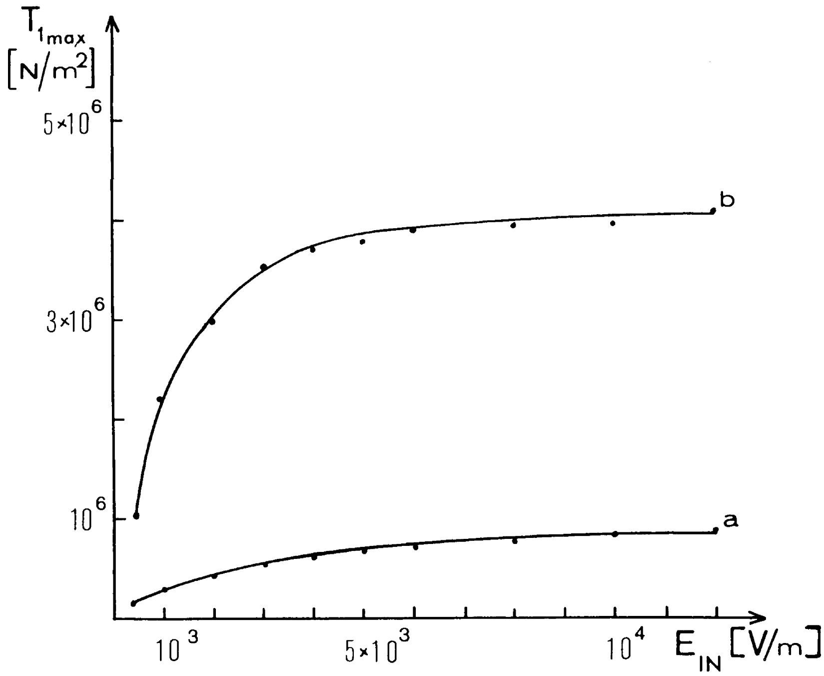

Fig. 8. Maximal stress as a function of the input electric field. a, b — as in Fig. 6.

obtained in this way tended to the saturation value for $E_{\rm IN} \geq 10^3$ V/m, similarly as in Fig. 7.

The authors of the theoretical analysis given in [15] have proved that the vibrational amplitude of a piezoelectric plate in the range of high fields is proportional to the cube root of the amplitude of the driving voltage. Therefore the vibrational amplitude (or vibrational velocity) has the tendency to saturate as the driving voltage increases. The authors of [15] confirmed this cubic relationship experimentally for plates of $LiNbO_3$ monocrystal (Z-cut, thickness-longitudinal vibration) using an interferometric heterodyne laser probe. Figure 9 presents the dependence v ($E_{\rm IN}$) for a soft and for a hard PZT-type ceramic. The continuous line presents the relation $v = A\sqrt[3]{E_{\rm IN}}$ and x denotes the values calculated using Eqs. (4.4) and (4.6). The proportionality coefficient for presented curves is equal: $A = 1.2 \cdot 10^{-3}$ for the soft ceramic and $A = 6.3 \cdot 10^{-3}$ for the hard ceramic. The proportionality coefficient depends on magnitudes of the second, third and fourth order elastic constants and the second and third order piezoelectric constants [15]. The obtained results indicate that the cubic relationship between the vibrational amplitude (velocity) and the driving voltage (electric field), foreseen by the theory given in [15], is also valid for polycrystalline piezoceramics.

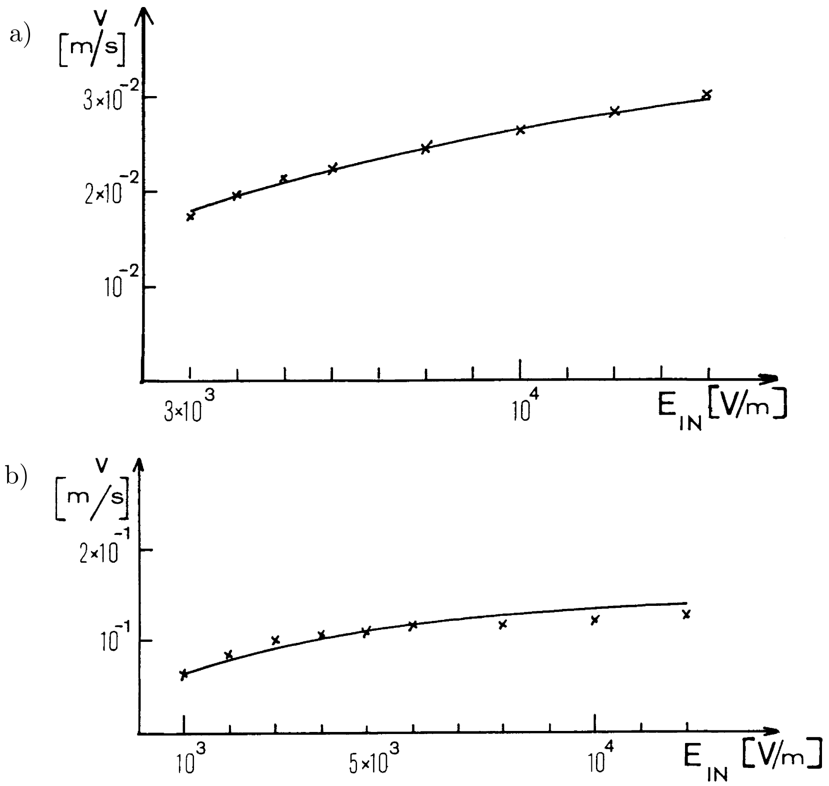

Fig. 9. Dependence of the vibration velocity on the input electric field, a) soft ceramic (as in Fig. 6a), b) hard ceramic (as in Fig. 6b). Continuous line — calculated according to the cubic relationship between the vibration velocity and the driving electric field, × — calculated using Eqs. (4.4) and (4.6).

5. Relations between losses in the piezoelectric ceramic and the magnitude of its vibration level

The dependence of the electrical and mechanical losses on the vibration velocity of the piezoelectric ceramic has been obtained using the formula given in Sec. 2,

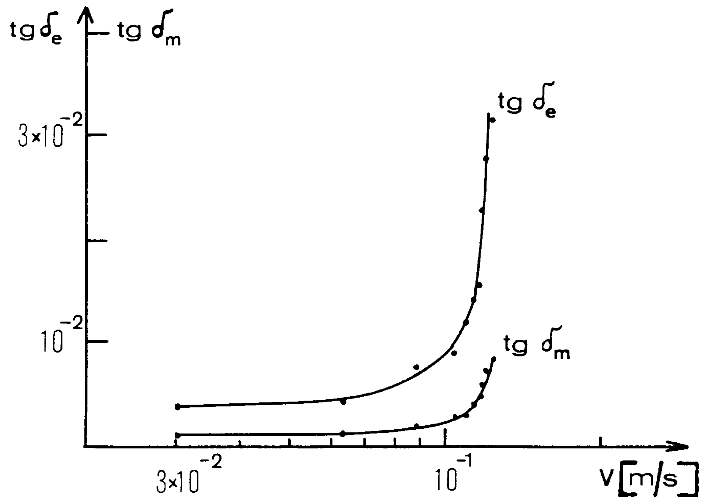

Fig. 10. Electrical and mechanical losses in the hard PZT-type ceramic as a function of the vibration velocity. Ring transformer with the dimensions as in Fig. 6b.

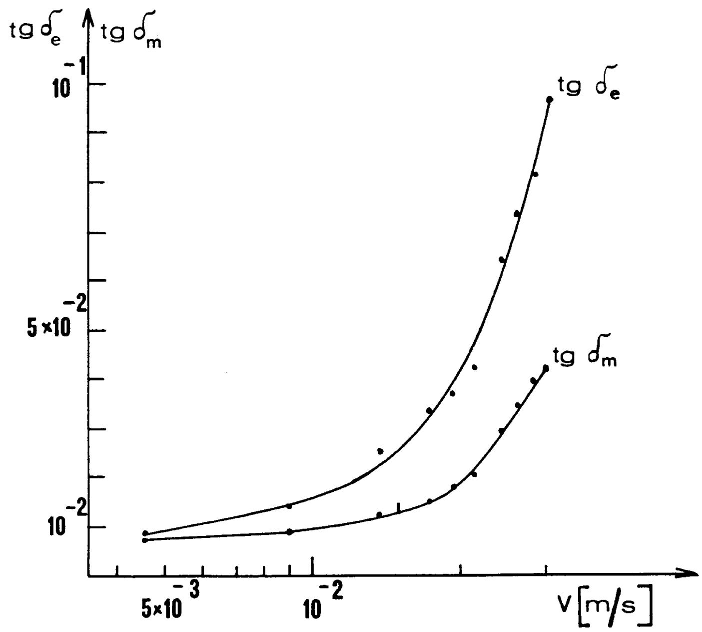

Fig. 11. Electrical and mechanical losses in the soft PZT-type ceramic as a function of the vibration velocity. Ring transformer with the dimensions as in Fig. 6a.

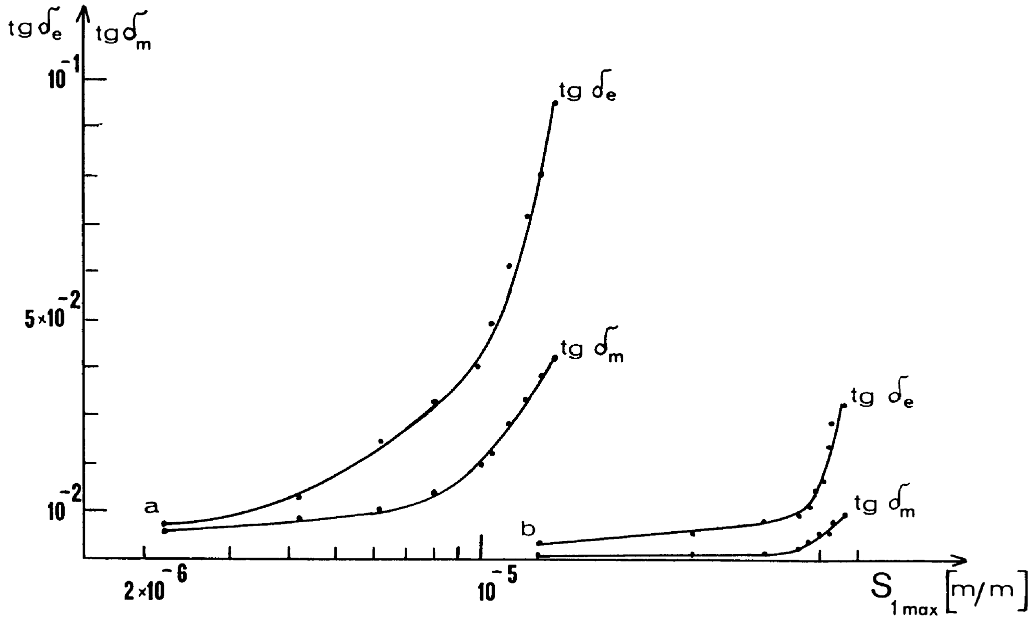

Fig. 12. Electrical and mechanical losses as a function of the maximal strain of the ring transformer, a — soft ceramic, b — hard ceramic. The dimensions of the transformers as in Fig. 6.

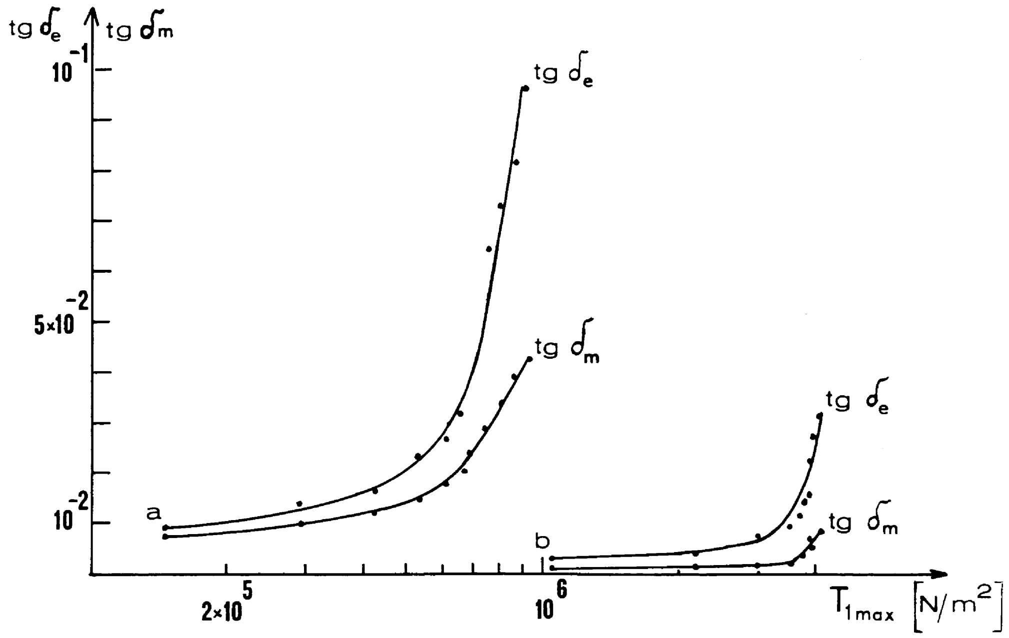

Fig. 13. Electrical and mechanical losses as a function of the maximal stress induced in the ring transformer, a — soft ceramic, b — hard ceramic. The dimensions of the transformers as in Fig. 6.

the measurements of U_{OUT} (U_{IN}) for the piezoelectric transformers, the results of the measurements of the material constants presented in Sec. 3 and the calculation results given in Sec. 4. Figure 10 presents such a relationship for the transformer made of the hard ceramic, Fig. 11 — for the transformer made of the soft ceramic with higher losses. The dependences of the losses on $S_{1\ \max}$ (Fig. 12) and $T_{1\ \max}$ (Fig. 13) have been calculated in similar way.

In Figs. 10 and 11 one can see that the large increase of the mechanical as well as electrical losses occurs for the vibration velocity $v > 10^{-1}$ m/s for the hard ceramic and $v > 10^{-2}$ m/s for the soft one. This is in accordance with the results obtained by the other authors applying different methods of loss measurements, e.g. [22, 25, 30, 31].

6. Conclusion

The realized measurements and calculations prove that the proposed earlier [24] method of the loss measurements can be also applied to determine the relations between the vibration velocity, stress, strain and the electrical and mechanical losses in the piezoelectric ceramic. The obtained results are in accordance with the results obtained by the other authors applying different measurement methods.

The analysis of the generation of harmonics of an output voltage will be necessary to apply the presented method in the range of still higher electric fields. The occurence of the second and third harmonics causes the distortion of the output voltage [8]. Output voltages of the transformers made of the ceramic with low quality factor were not distorted in the whole range of input voltages applied in the measurements described in the paper. Output voltages of the transformers made of the ceramic with high quality factor were distorted in the upper range of applied input voltages but only at the frequencies of the jump phenomenon [24] and only for $R_L \to \infty$. Similar effect has been observed in piezoceramic resonators (length extensional vibration mode) [28].

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