

Methods of synthesis of piezoceramic transducers: spatial energy force structure of piezoelement

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Abstract

In the paper the designing method piezoceramic transducers is described, which uses spatial energy force structure of a piezoelement, e. g. location of vectors \mathbf{F} , \mathbf{P} and \mathbf{E} in space. It is shown, that change of position of a vector of the electric field of the output signal \mathbf{E} in relation to the polarisation vector \mathbf{P} leads to change of dynamic characteristics of the transducer.

Keywords: piezoceramic transducer, spatial energy force of piezoelement, dynamic characteristics.

Introduction

Piezoceramic transducers are widely used in hydroacoustics and electro-acoustics, in ultrasonic, medical, measurement instruments and in other areas of science and technology [1-6].

Principle of action of piezoelectric transducers is based on piezoeffect, discovered by P. and Zh. Kjurii in 1880. Practical application of piezoelectric effect began in 1917 in a sonic depth meter, developed by P. Lanzheven.

The synthesis of piezoceramic (B. Vul, I. Goldman, 1944) stimulated development of piezotechnique [1]. Piezoelements made of piezoceramic possess by an order higher sensitivity than quartz and can be made practically of any shape.

Usually piezoelements of certain shape and sizes are used for design of piezoceramic sensors. For this purpose piezoceramic material with certain electrophysics properties is used. Thus, traditionally the vector of piezoelement forces \mathbf{F} (pressure, etc.) is parallel to the vector of polarization \mathbf{P} , e. g. vector of force is perpendicular to the surface, on coated by electrodes. Obviously, these electrodes are utilized for polarization of the piezoelement during manufacturing. Also they are utilized for the pick-up of the useful signals when measuring various physical quantities (forces, pressures, accelerations and other), and also for application to the piezoelement of an electric voltage at the use of a piezoelement as an emitter of ultrasonic waves.

Problem and approach

In work [3] for design of piezoceramic transducers it is suggested to take into account also the vector of \mathbf{E} of electric field of the output signal or the voltage applied to an emitter.

The orientation of the vectors \mathbf{F} , \mathbf{P} and \mathbf{E} in space characterizes the spatial energy force structure of a piezoelement.

Let's consider for an example a piezoelement in the shape of a rectangular parallelepiped (Fig. 1). Electrodes in this piezoelement are put on wide surfaces.

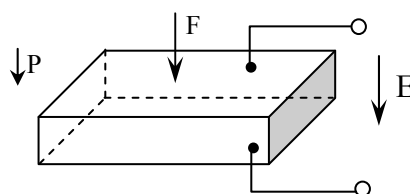


Fig. 1. A piezoelement with a traditional arrangement of vectors \mathbf{F} , \mathbf{P} and \mathbf{E}

In this drawing are shown the vectors of polarization \mathbf{P} , forces \mathbf{F} and the vector of the electric field \mathbf{E} of the output signal. Such an arrangement of vectors is the most widespread, known and traditional [1-3].

In order to change characteristics of the piezoceramic sensors constructed under the traditional scheme, earlier there was only one possibility - to apply another piezoelement - of other size, the shape or other material.

Meanwhile, it is possible to expect change of sensors characteristics by change of a relative positioning of polarization vectors \mathbf{P} , applied force \mathbf{F} and the vector of the electric field of the target signal \mathbf{E} .

Let's consider further the same piezoelement in the form of a rectangular parallelepiped (Fig. 2).

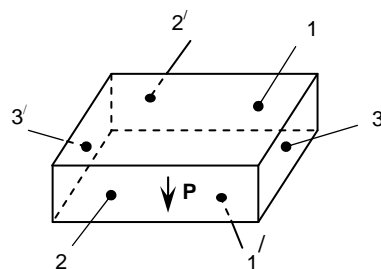


Fig. 2. A piezoelement in the form of a parallelepiped

Let us assume that the electrodes are put on all surfaces of a parallelepiped and are not connected among themselves, and the piezoelement is polarised between the surfaces 1-1'. Let us also assume that the measured force \mathbf{F} is applied in parallel to a vector of polarization \mathbf{P} , e.g.

perpendicularly to the side 1, and the pressure acts from sides 1-1'. Thus, for the given transducer all three vectors are parallel to axis Z ($\mathbf{F} \downarrow \mathbf{P} \downarrow \mathbf{E} \downarrow$).

It is necessary to notice, that change of a direction of one of vectors by 180 ° leads only to change of the phase of the signal.

The transducer considered above with a parallel arrangement of three vectors as we already pointed out, is the most widespread and known.

For it it is possible to write:

$$U_{out} = \frac{Q}{C_{1-1'}} = \frac{d_{31} \cdot F}{C_{1-1'}}, \quad (1)$$

where Q is the a charge generated by a piezoelement on sides 1-1'; $C_{1-1'}$ is the capacitance between the sides 1-1'; d_{31} is the piezomodule.

Let us assume that the polarisation vector \mathbf{P} does not change the direction and the force \mathbf{F} can be put both on the side 1, and to the sides 2 and 3, the electric voltage thus can be picked-up from sides 1-1', 2-2' or 3-3'. Thus, the vectors \mathbf{F} and \mathbf{E} can be both parallel, and perpendicular to the vector \mathbf{P} (Fig. 3).

In that case when the measured force is applied to the piezoelement in such a manner that the angle between the direction of the force \mathbf{F} and the polarisation vector \mathbf{P} is 90° (transducers b and e, Fig. 3), the transducer has been named transverse [3].

For such transducers sensitivity S is given by [7].

$$S = \frac{Q}{F} = d_{ij} \frac{h}{a}, \quad (2)$$

where Q is the a charge generated on the corresponding side; h is the piezoelement height; a is the a thickness.

Transverse piezoelements are used, for example, in gauges of the firms «Brüel and Kjer» (Denmark) and «Kistler Instrumente AG».

If the angle between the vector of electric field of the target signal \mathbf{E} and the polarisation vector \mathbf{P} makes 90° (transducers c and d, Fig. 3), such transducers have been named domain-dissipative [3].

The physics of the processes occurring in these transducers is studied insufficiently. It is supposed, that the following factors can render influence on characteristics of the transducers:

- energy dissipation on domains [3, 6];
- change of electric capacity between electrodes;
- occurrence in a piezoelement of other types of fluctuations.

Definition of the possible contribution of each of the listed factors demands further study.

Not less interesting there was a gauge, in which both vectors - \mathbf{F} and \mathbf{E} are perpendicular to the polarisation vector \mathbf{P} (transducers d and g , Fig. 3). Such transducers have received the name cross-section domain-dissipative.

When all vectors are perpendicular to each other, the transducers have been named the volume, (transducers h and i , Fig. 3) [3].

The schemes of the transducers presented in Fig. 3 of naturally, do not limit possible variants of their execution.

So, if we will change a direction of the polarisation vector so that it is perpendicular to the sides 2-2' of the parallelepipeds, we will obtain 9 more variants of execution of the transducer. At last, deflecting the polarisation vector so that it would be perpendicular to the sides 3-3', we can get 9 more variants of execution of the transducer. In total for one piezoelement in the form of a rectangular parallelepiped it is possible to get 27 variants of transducers with various characteristics.

Results

Let us determine experimentally the dynamic characteristics of the transducers shown in Fig. 3. As it is known, dynamic are such characteristics which are shown only at a transducer's operation in a dynamic mode, that when the transformed quantity is function of time (process). These parametres characterise internal (own) properties of the transducers.

Theoretically all real dynamic systems to a greater or lesser extent are not linear and not stationary, and their parametres are distributed.

Practically it is possible to consider majority of them as linear stationary dynamic systems with the concentrated parametres, except when nonlinearity is exploited as operation principle.

It is known, that the linear stationary dynamic system with concentrated parametres is described by the differential equation with constant coefficients:

$$a_n \frac{d^n y}{dt^n} + \dots + a_1 \frac{dy}{dt} + a_0 y = b_m \frac{d^m x}{dt^m} + \dots + b_1 \frac{dx}{dt} + b_0 x, \quad (3)$$

which in the operational form [8] looks like

$$(a_n p^n + \dots + a_1 p + a_0) y(t) = (b_m p^m + \dots + b_1 p + b_0) x(t) \quad (4)$$

or

$$A_n(p) \cdot y(t) = B_m(p) \cdot x(t) \quad m \leq n \quad (5)$$

where

$$y(t) = \frac{B_m(p)}{A_n(p)} x(t) = Lx(t), \quad (6)$$

where $p = d / dt$ is the operator of differentiation; L is the linear operator of stationary dynamic system.

The differential equation is the complete characteristic of a dynamic system, however its coefficients is difficult to determine experimentally.

Having applied to the differential equation under initial zero conditions the Laplas transformation, we will get the operational transfer function

$$W(s) = \frac{Y(s)}{X(s)} = \frac{b_m s^m + b_{m-1} s^{m-1} + \dots + b_1 s + b_0}{a_n s^n + a_{n-1} s^{n-1} + \dots + a_1 s + a_0}, \quad (7)$$

- where s is the complex variable of the Laplas transform; $Y(s)$ is the Laplas transform of the output quantity and $X(s)$ is the aplas transform of the input quantity.

Replacement of the complez variables in the transfer function by $j\omega$ gives the complex frequency response

| | Type of transducers | The sensor scheme | Direction of vectors | | |
|----------|--|-------------------|----------------------|---|---|
| | | | F | P | E |
| <i>a</i> | Conventional | | ↓ | ↓ | ↓ |
| <i>b</i> | Transverse | | → | ↓ | ↓ |
| <i>c</i> | Domain-dissipative | | ↓ | ↓ | → |
| <i>d</i> | Transverse domain-dissipative | | → | ↓ | → |
| <i>e</i> | Transverse | | → | ↓ | ↓ |
| <i>f</i> | Domain-dissipative | | ↓ | ↓ | → |
| <i>g</i> | Transverse domain-dissipative | | → | ↓ | → |
| <i>h</i> | The volume transverse domain-dissipative | | ↗ | ↓ | → |
| <i>i</i> | The volume transverse domain-dissipative | | → | ↓ | ↗ |

Fig. 3. Classification piezoceramic transducers depending on a direction of vectors F, P, E

$$K(j\omega) = \frac{b_m(j\omega)^m + b_{m-1}(j\omega)^{m-1} + \dots + b_1(j\omega)b_0}{a_n(j\omega)^n + a_{n-1}(j\omega)^{n-1} + \dots + a_1(j\omega)a_0} = \quad (8)$$

$$= P(\omega) + jQ(\omega),$$

where $P(\omega)$ and $jQ(\omega)$ are the real and imaginary parts of the complex transfer function.

The amplitude-frequency response is

$$K(\omega) = |K(j\omega)| = \sqrt{P^2(\omega) + Q^2(\omega)}, \quad (9)$$

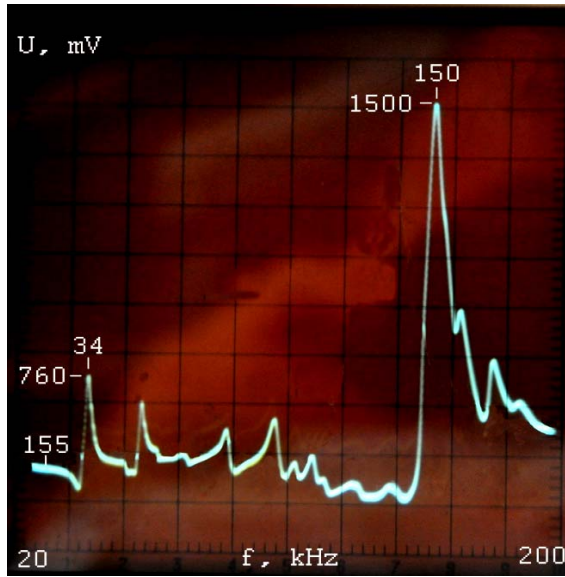
and the phase-frequency response is given by

$$\varphi(\omega) = \arctg \frac{Q(\omega)}{P(\omega)}. \quad (10)$$

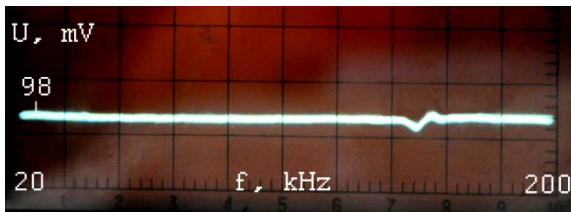
The pulse response is the response of a dynamic system on so-called δ -impulse

$$\delta(t) = \begin{cases} t & \\ 0, & \text{when } t \neq 0 \\ \infty, & \text{when } t = 0 \end{cases}$$

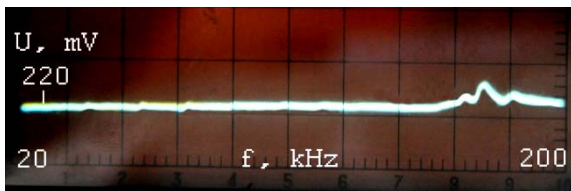
$$\int_{-\infty}^{\infty} \delta(t) dt = 1$$



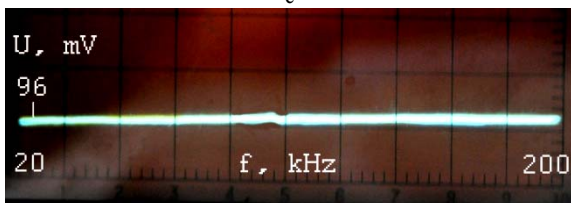
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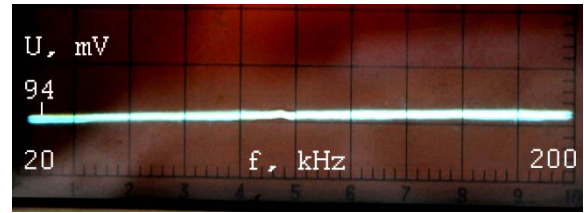
b



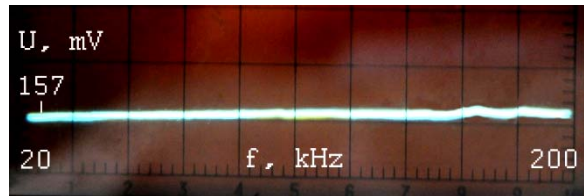
c



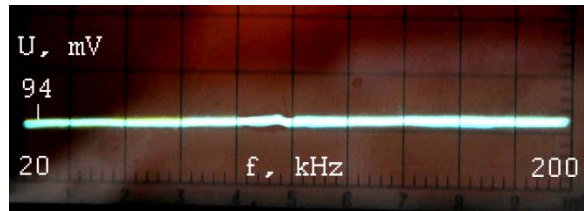
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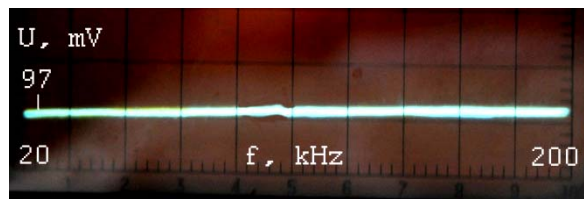
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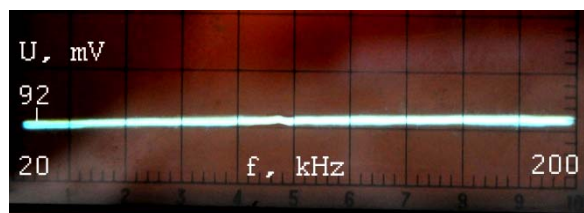
f



g



h



i

Fig.4. Amplitude-frequency responses of the transducers shown in Fig.3

Step response is the response of a dynamic system to a step at the input in the form of individual function $1(t)$, derivative from which is equal to the δ -impulse.

$$\frac{d1(t)}{dt} = \delta(t)$$

In Fig.4 experimental amplitude-frequency responses (AFR) of the transducers represented on Fig. 3 are given. These transducers have been made of a piezoelement with the sizes $9 \times 10 \times 90$ mm from LiTC-19 (analogue PZT-5A).

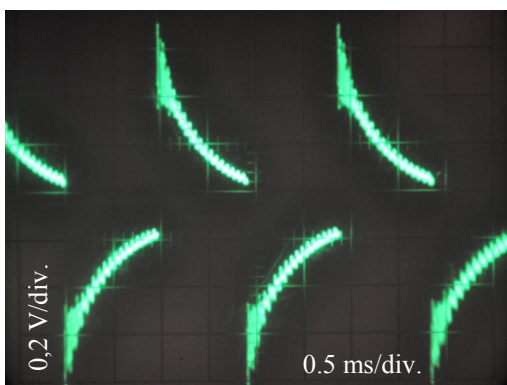
The measurements of the AFR were performed by means of the amplitude frequency response analyzer AFR X1-46, and photographing of the responses was made by the digital photocamera "Nikon-D90".

In Fig. 4 for the conventional transducer is possible to observe presence of several peaks on the amplitude-frequency response (Fig.4, a). In transverse transducers

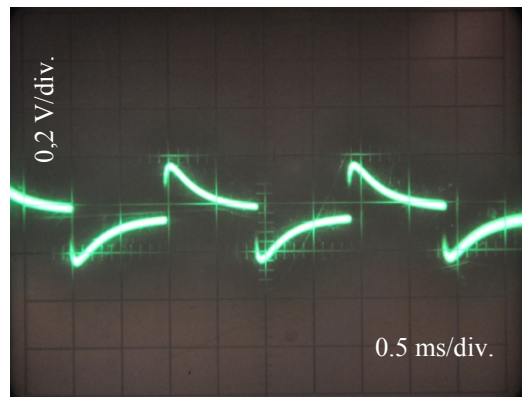
these resonances are partially suppressed (Fig.4, b). For domain-dissipative transducer AFR it is practically linear (Fig.4, c, f, g, h, i).

In this case the transfer coefficients (sensitivity) in a low-frequency area for all types of transducers are lower, than for conventional, however it is possible essential increase of the transfer coefficient for the domain-dissipative transducer.

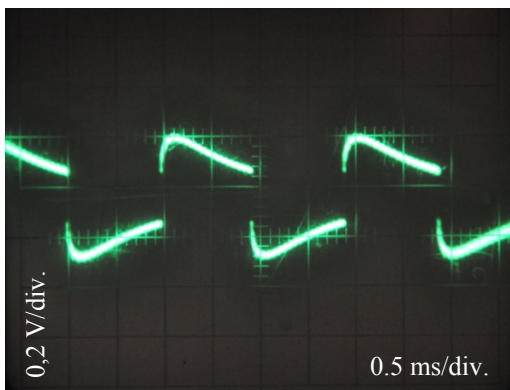
Fig. 5 shows transient responses of the transducers represented in Fig. 3. Measurements were performed in a piezotransformer, mode applying to the transducer the electric voltage in the form of a meander ($f = 500\text{Hz}$, $U = 3\text{V}$). Photographing was carried out by the digital photocamera "Nikon-D90".



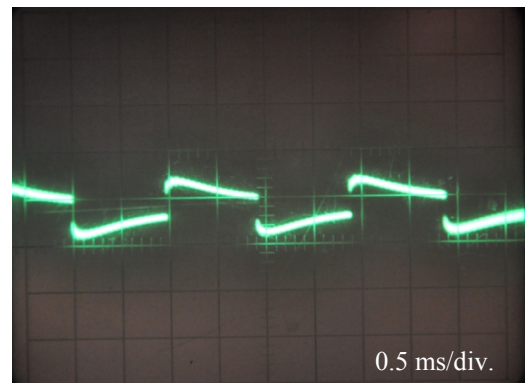
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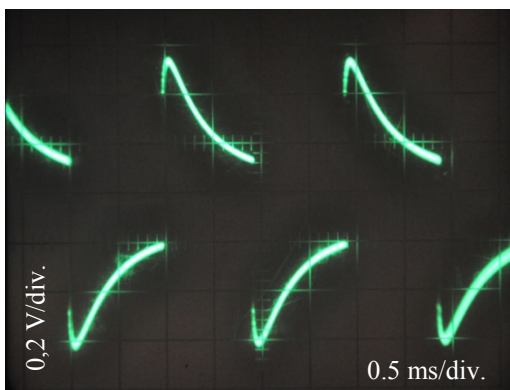
d



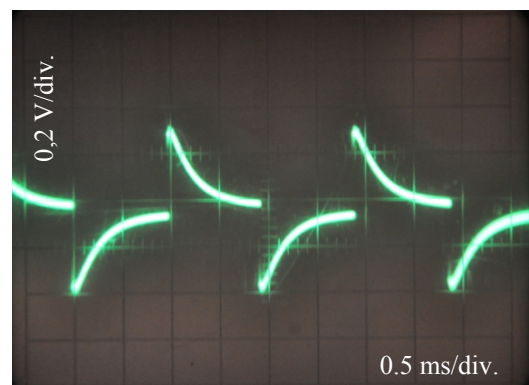
b



e



c



f

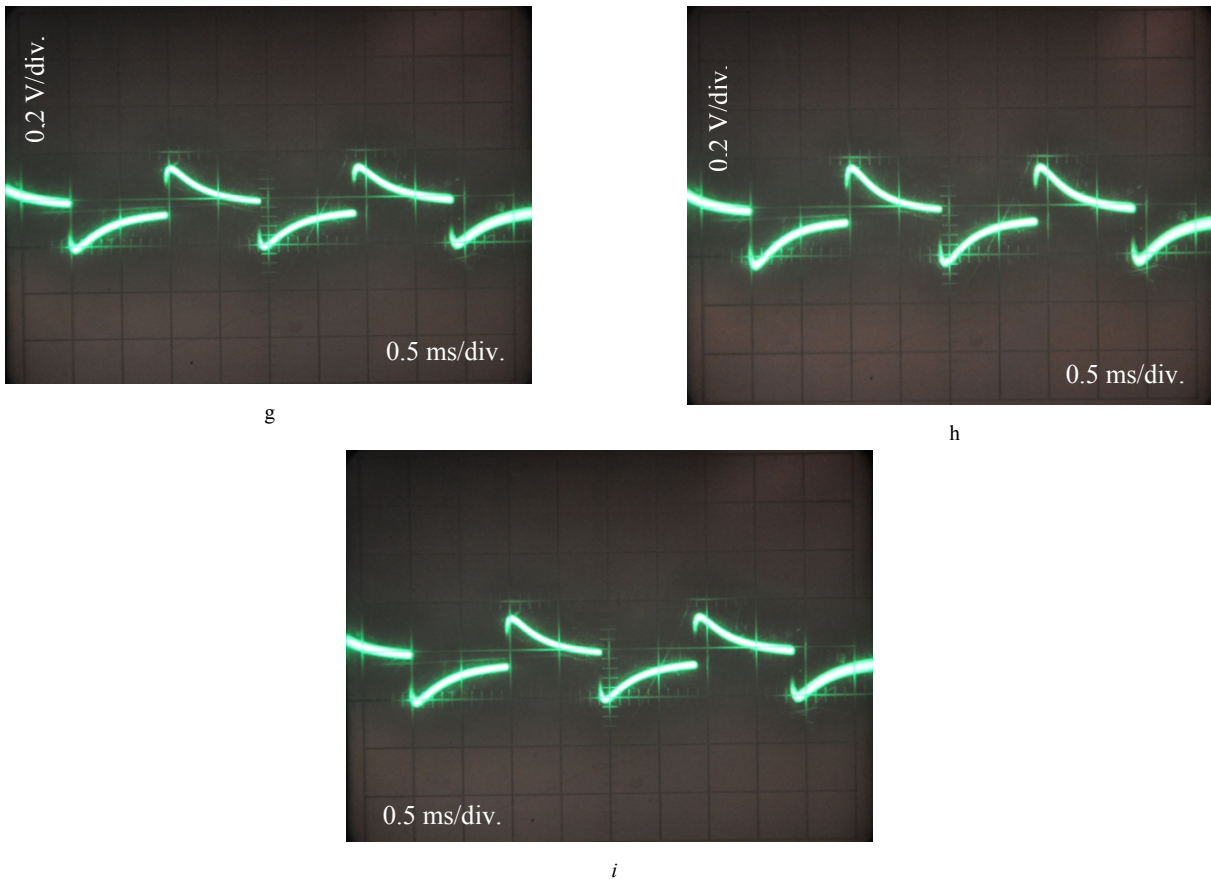


Fig. 5. Transient responses of the transducers which are shown on Fig. 3

From Fig. 5 follows, that the same piezoelement depending on the connection scheme can possess various dynamic characteristics.

As follows from Fig. 4 and 5, change of position of vectors F , P , E in space, change the spatial energy force structure (SEFS), what leads to an essential change of dynamic characteristics of the transducer.

This change SEFS is provided by a corresponding arrangement of electrodes on a surface of a piezoelement and by a choice of a place of force application.

As experiments have shown, change of responses of the transducers occurs also at angles between the vectors smaller than 90° .

Let us analyze a piezoceramic transformer further [3, 12]. As it is known, a piezotransformer is a transducer of the electric voltage of one level in to an electric voltage of an other level. The piezoceramic transformer it is made of the piezoceramic element PZT-5A with the diameter 30 mm and the thickness 0,8 mm.

The piezotransformer has five electrodes, located on face surfaces of the piezoelement and the bottom electrodes are projections of the top electrodes [13, 14].

For a piezotransformer it is necessary to consider not only an arrangement of a vector of the electric field of a target signal, but also a vector of the electric field of the input signal (generator) [3].

Thus, if to use piezoelements of a small thickness, the angle between the vectors E and P can be close to 90° .

The scheme of the piezotransformer is shown in Fig. 6 [12, 13], and oscillograms of the signals at the inputs and the output of the piezotransformer are shown in Fig. 7.

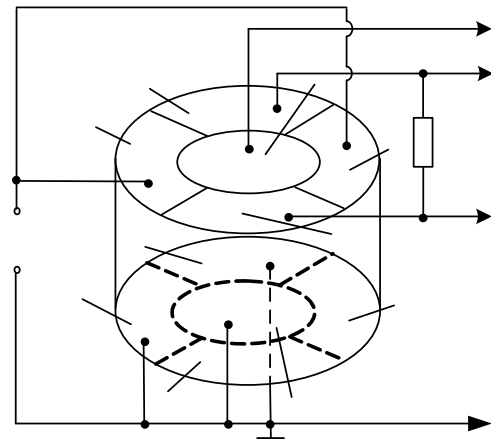
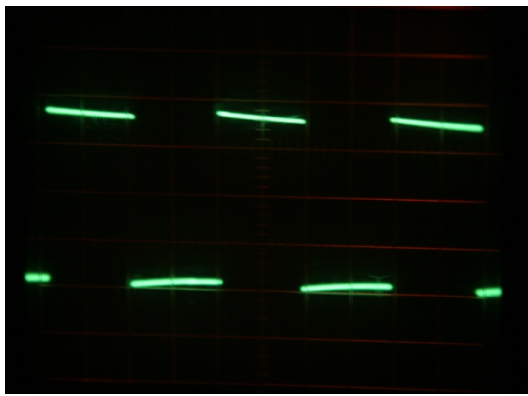


Fig. 6. Schemes of connection of electrodes

As it follows from Fig. 7, depending on the scheme of connection of the electrodes (i.e. from a relative positioning of the vectors F , P , E_{in} and E_{out}), it is possible to obtain signals corresponding to oscillatory (Fig. 7, b), differentiating (Fig.7) and to an integrating link (Fig. 7, d).

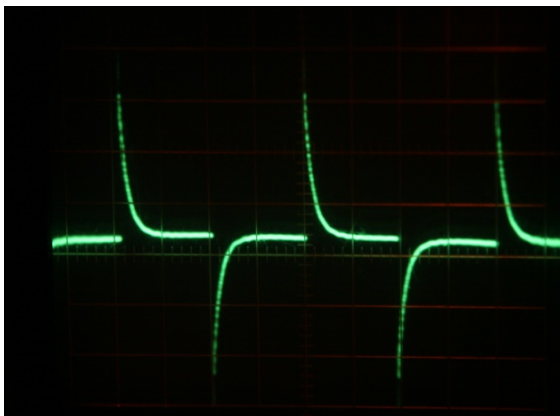
However the most curious and surprising in this case is that a piezoelement - the elastic monolithic solid body - can possess such properties simultaneously.



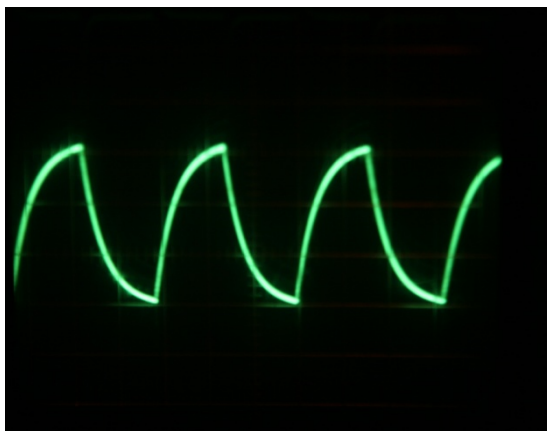
a



b



c



d

Fig.7. Oscillograms signals piezotransformer: a - input signal (meander); b - output 1; c - output 2; d - output 3

Conclusions

- 1 Spatial energy force structure (SEFS) makes essential impact on piezoelement dynamic responses.
2. Change of the SEFS is provided with a corresponding arrangement of electrodes on a surface of a piezoelement and a place of application of force.
3. The physics of processes which occur in the described transducers is still studied insufficiently.

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Pjezoelektrinių keitiklių sintezės metodai: pjezoelektrinio elemento erdvinės energijos jėgų struktūra

Reziumė

Išnagrinėtas erdvinės energijos jėgų pasiskirstymas pjezoelektriniame elemente esant įvairiems lokaliems vektoriams F , P ir E erdvėje. Parodyta, kad elektrinio lauko vektoriaus pokytis, susijęs su poliarizacija, keičia pjezoelektrinio keitiklio dinamines charakteristikas.

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