The new technologies of piezoceramic sensors synthesis

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Abstract

The new technologies of synthesis of piezoceramic sensors are described in article.

For the first time design of piezoelectric transducers and sensors consider a relative position of vectors of the polarisation op in a piezoelement force and a vector of an electric field (spatial energy force piezoelement structure). Besides, the arrangement of electrodes on a piezoelement surface also leads to change of dynamic characteristics of the sensor. The technology on the basis of a spatial electromechanical feedback allows to create sensors with the reduced error and expanded bandwidth.

Inclusion of a piezoelement scheme of the electric filters allows it to get sensors with filter dynamic characteristics.

As the piezoelement usually represents an electromechanical oscillatory system, joining it to mechanical or electric elements changes its characteristics.

Increase of the level of an output signal and expansion of a working frequencies range can be reached by using the excitation signal of the piezoelement in the form of a meander.

Keywords: piezoelectric transducer, spatial electromechanical, feedback.

Introduction

Piezoelectric transducers and sensors are widely applied in hydroacoustics, electroacoustics, ultrasonic, medical, measuring technics, in scanning probe microscopy, piezoengines and in other areas of a science and engineering [1, 2]. Piezoelectric transducers occupy a special place in hydroacoustics, being in essence, the ears and eyes of underwater and surface ships.

As it is known, transducer is a device which transforms one of energy to another type of energy. For example, thermal energy - in to electric, force - in to displacement, pressure - in to electric voltage or a current, electric voltage of one level - in t electric voltage of another level etc. [3]. The sensor is a transducer that transforms a physical quantity, as a rule, in an electric signal (voltage, current, frequency, phase, etc.) [3, 4]. In other words, the sensor is a transducer for reception of the measuring information. In the given work these terms are used as equivalent.

For designing of piezoceramic sensors usually a piezoelement of a certain form and size, from a definite piezoceramic material with certain electrophysical properties are used. Usually vector of the force **F** operating on a piezoelement (pressure, etc.) is parallel polarisation vector **P**.

Simultaneously the vector of the force **F** is parallel to the vector of electric field **E,** of creating the output signal, that is perpendicular to the electrodes which are put on a piezoelement surface (Fig. 1 a) [1, 4, 5].

These electrodes are used for piezoelement polarisation at manufacturing. Simultaneously they are used also for picking up of a useful signal paused by force, pressure, acceleration, etc., and also for application in a piezoelement of an electric voltage to use of the piezoelement as a transmitter.

These types of sensors are well known [1, 4, 5]. In this case using a certain piezoelement it is possible to develop **only one** sensor with certain characteristics. For creation of the sensor with other characteristics earlier it was necessary to use other types of piezoelements, of different dimension, shape or other piezomaterials.

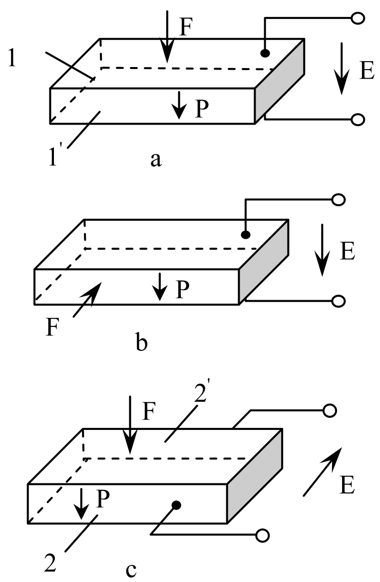


Fig. 1. **Type of spatial energy force structure of piezoelement: a - conventional; b - transverse; c - domain-dissipative**

Results

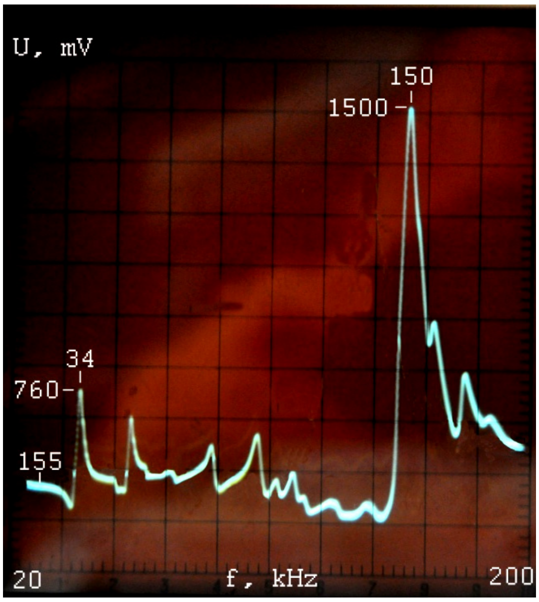
1. Spatial energy force structure of piezoceramic elements

In work [1] it was proposed to take into consideration a relative position of vectors **F, P** and **E** for sensor design. This arrangement of vectors has been named by spatial energy force structure of piezoceramic elements (SEFS).

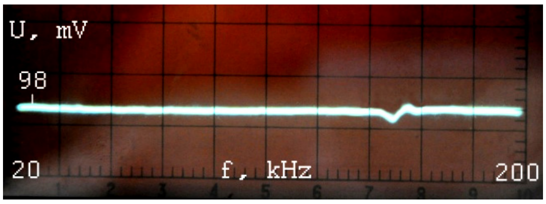
Let us consider a piezoelement in the shape of a rectangular parallelepiped (Fig. 1). Electrodes are put on all sides of a parallelepiped and are not connected among themselves, and the piezoelement is polarised between planes 1-1$^{/}$. The measured force **F** is directed in parallel to the vector of polarisation **P** (perpendicularly to the plane 1), and the output voltage acts between the surfaces 1-1$^{'}$. Thus, for the given sensor all three vectors are parallel to the axis Z (**F** ↓ **P** ↓ **E**↓) (Fig. 1 a).

As we already marked, it is a known (traditional) case of an arrangement of vectors **F** , **P**, **E** (spatial energy force structure).

The piezoelement, in which force the vector **F** is perpendicular to the vector **P,** is less often used. These types of the sensors have been named transverse [4, 5].



a



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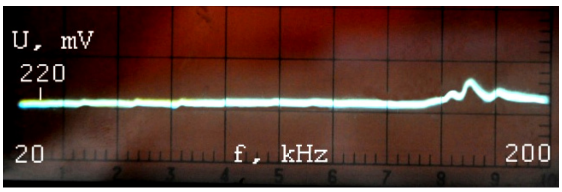

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Fig. 2. **Amplitude-frequency responses of the transducers shown in: a – Fig. 1 a; b - Fig. 1 b; c - Fig. 1 c**

Another type of the sensor is in which the output signal is picked-up by the electrodes 2-2$^{/}$ (Fig. 1 c). In this case vector the **E** is perpendicular to the vector **P.** This type of the sensor has been named a domain-dissipative [1, 2, 6]. The physics of the processes occurring in these transducers, is studied insufficiently. It is supposed, that the following factors can influence their characteristics [4, 5]:

- energy dispersion on domains;
- change of the electric capacity between electrodes;
- occurrence in a piezoelement of other types of oscillations.

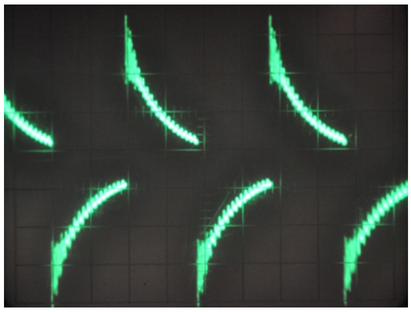
Definition of the possible contribution of each listed factors demands further study.

Schemes of transducers presented in Fig. 1, do not show possible versions of their execution. In total, for one piezoelement in the shape of a rectangular parallelepiped it is possible to obtain 27 (!) different versions of transducers with various characteristics [5].

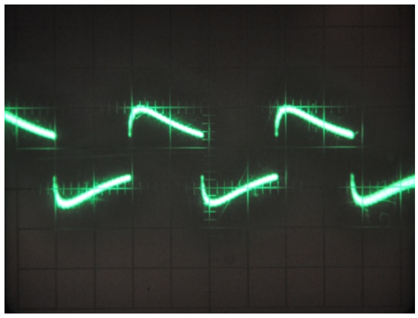
In Fig. 2 experimental amplitude-frequency responses (AFR) of transducers represented in Fig.1 are shown. These transducers were made of a piezoelement with dimensions 9×10×90 mm from the piezoceramic ЦТС-19 (analogue PZT-5A).

The measurements of AFR were performed in a piezotransformer mode by means of the frequency response analyzer AFR X1-46 and photographing of characteristics was made by the digital camera «Nikon-D90».

Transient responses of the transducers are shown in Fig. 3.



a



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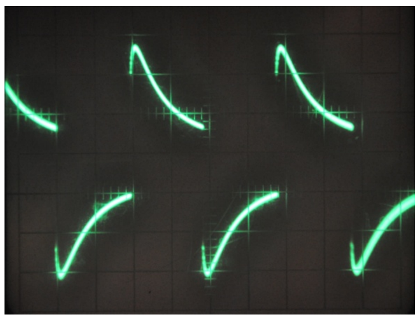

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Fig. 3. **Transient responses of the transducers which are shown in: a – Fig. 1 a; b - Fig. 1 b; c - Fig. 1 c**

According to Fig. 2 and 3, there is a change of a relative positions of vectors **P, F** and **E.** Therefore, dynamic characteristics of transducers essentially change. This circumstance opens various opportunities at designing of sensors [1, 2, 7].

2. Spatial arrangement and connection of piezoelement electrodes

Change of output signal electric field vector **E** position can be realize by division of piezoelement electrodes into parts and connection of these part so that the angle α between the vector E and the polarization vector P is $0<\alpha<90^o$

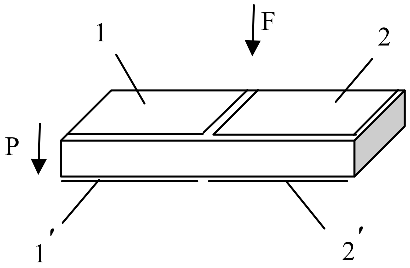

Fig. 4. **Traditional piezoelement with divided electrodes**

It is known that a piezoelement with two or more electrodes is called a piezotransformer [4].

If the piezoelement electrodes are divided two equal parts the sensor charge sensitivity will decrease twice, because the charge is proportional to the electrodes area. The voltage sensitivity remains the same as for the piezoelement with undivided electrodes.

It is quite obvious, that the capacity between the electrodes 1-2' (or 1'-2) will be less, than the capacity between the electrodes 1-1' (2 - 2'). Therefore it is possible to obtain the electric voltage several times more than on the electrodes 1-1' or 2-2' [4, 7].

The piezosensor voltage sensitivity will increase even more, if electrodes 1 and 2 are shifted from each other (for what it is possible to divide initial electrodes into three parts (Fig. 5).

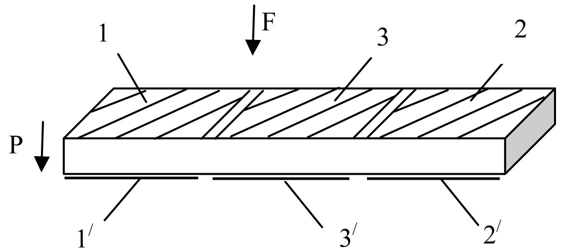

Fig. 5. **Piezoelement with system of three electrodes**

It is necessary to notice, that the spatial arrangement of electrodes and their connection results not only in change of electrodes capacity and sensitivity, but also is change of dynamic characteristics (AFR, pulse and transient responses).

Sensors can be made from piezoelements in the shape of disks or hollow cylinders with electrodes in the form of semi-disks, disks and rings [4, 7].

3. Spatial electromechanical feedback

It is known that the feedback allows to change essential characteristics of automatic control systems (input and output resistance, time constant, dynamic characteristics etc.). The feedback is also widely used in the measuring technic [1]. For example, the positive feedback allows to excite resonant oscillations in piezosensors and to build on this basis sensors of various physical dimensions [1]. A negative feedback in resonant piezotransducers gives the chance to linearize them graduation characteristics [1]. The feedback possesses unique properties and allows to improve parametres of measuring devices essentially.

In a kind of that piezosensors output size (a charge or voltage) depends not only from mechanical influence (force, pressure, acceleration, that is direct piezoeffect), but also of electric voltage (the return piezoeffect), was offered to enter a feedback into the auxiliary channel which was created by means of additional system of electrodes or the additional piezoelement which had with the core planar or coplanar.

The scheme of one of many versions a piezoceramic sensor with a feedback, implementing the offered method, is shown in Fig. 6 [1, 4].

This sensor represents the closed static automatic system [1]. It consists of the piezoelement PE and voltage amplifier A. Three electrodes 1, 2 and 3 are put on a piezoelement. The electrode 1 is connected to the input of the voltage amplifier, the electrode 2 - to the general wire of the circuit and the electrode 3 - an additional electrode on the piezoelement - to the output the voltage amplifier.

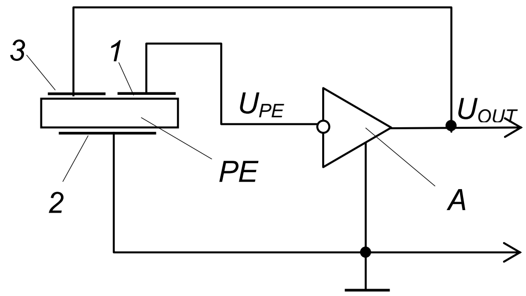

Fig. 6. **The piezoceramic sensor with a feedback**

The electrodes are placed on various sides of a piezoelement, therefore the feedback in this case is called spatial.

The transfer function of such device is given by

$$W_{FB}(p) = W_1(p)\frac{W_{TR}(p)}{1+W_{TR}(p)\beta(p)}, \tag{1}$$

were $W_1(p)$ is the transfer function of the circuit of the direct transformation; $W_{TR}(p)$ is the transfer function of the circuit of direct transformation with feedback; $\beta(p)$ is the transfer function of the feedback circuit.

Relative error γ_{FB} of the device, presented in Fig. 6, it is possible to define by [1]:

$$\gamma_{FB} = \gamma_W \frac{1}{1+W(p)\beta(p)} - \gamma_W (1 - \frac{1}{1+W(p)\beta(p)}), \tag{2}$$

were γ_W is the relative error of a circuit of the direct transformation with feedback.

From this expression it is easy to see a condition at which the error of the piezosensor with feedback will be equal to zero, $\gamma_{FB} = 0$:

$$W(p)\beta(p) = 1 \qquad (3)$$

The sensitivity of the sensor at $W(p)\beta(p) = 1$ will decrease twice.

It is necessary to note that, in this case a various arrangement of vectors **F**, **P**, $\mathbf{E}_{IN}$, $\mathbf{E}_{FB}$ allows to with a piezoelement in the shape of a parallelepiped, to obtain tens versions of sensors with various characteristics.

4. Inclusion of piezoelements in electric filters

The idea is based on development of such a piezoelements which after inclusion in the electric filter possess the amplitude-frequency responses (AFR) which will correspond to the AFR of the filter [4, 9].

Electric filters are well enough studied and described in [6-8].

As the electric filter is called the device serving for passing (or suppression) of electric voltage or currents of different frequencies. Depending on characteristics, some filters which are of the greatest interest for the given case, are by low-pass and high-pass filters frequencies are known. Low-pass filters (LPF) pass fluctuations of all frequencies from a direct current and to some cut-off frequency ω_t.

High-pass filters (HPF) pass oscillations from some cut-off frequency ω_b to infinitely high.

Two versions of the sensor with piezoelements in LPF and HPF are shown in Fig. 7 [7].

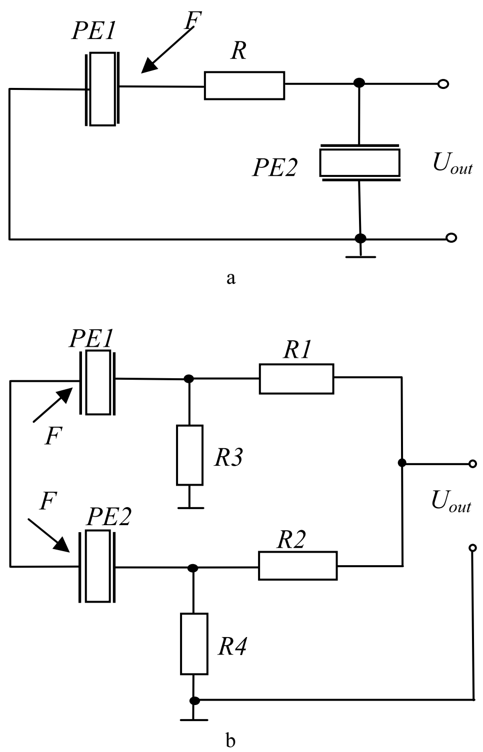

Fig. 7. **Sensors with piezoelements in schemes of electric filters: a - in LPF; b - in HPF**

Drawback of these sensors is necessity to use in some circuits two piezoelements or a piezoelement and a capacitor. To eliminate this drawback, it is offered to use in schemes of the sensors piezotransformers, that is piezoelements with two systems of electrodes. Besides, it is proposed to have electrodes on a piezoelement so that the electric field vector between these electrodes was under an angle α to the polarisation vector ($0<\alpha\leq 90°$).

It allows to obtain an electric voltage which exceeds the voltage for a conventional case when on these electrodes α=0 [4].

Two schemes of the sensors realising these ideas are shown in Fig. 8 [4, 9].

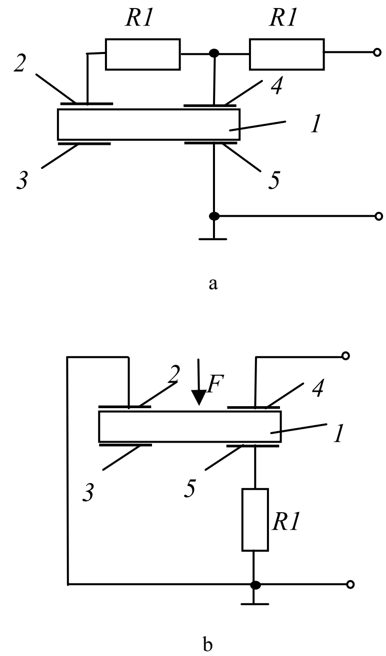

Fig. 8. **Sensors with piezotransformers in electric filters: a - in LPF; b - in HPF**

5. Technology of additional elements

The essence of this technology consists in addition to a piezoelement of elements which change sensor characteristics. Here two cases are possible, at least. In the first case the second piezoelement, a metal plate or the ultrasonic concentrator mechanically is joined to a piezoelement [1, 4].

In the second case the capacity joins a piezoelement electrical inductance, an oscillatory contour, a piezoelement or a piezoelement part [1, 7].

Two piezoelements connected among themselves mechanically and electrically (symmetric bimorph piezoelement), allow to increase sensitivity 10-20 times and at the same time to reduce a resonant frequency. Connection of a piezoelement and metal plate (asymmetric bimorph piezoelement) also leads to increase of sensitivity 10 times to and reduction of the resonant frequency.

In bimorph piezoelements arise flexural oscillations that allows to use them in microelectromechanical systems and devices (MEMS), for example, in scanners of nanomicroscopes [10-12].

Joining of the ultrasonic concentrator to a piezoelement [4] increases amplitude of the oscillatory displacement (or particle velocity), that allows to use such devices for ultrasonic cutting, washing, dispersion of liquids, and also in measuring devices on the basis of resonant piezoelements [1]. The use of concentrators for increase of performance of low-frequency ultrasonic radiators is also promising.

Because the piezoelement is the electromechanical device which may be represented by an equivalent circuit (in a specific case - a resonant circuit), connection to it of electric elements (resistors, capacitance, inductance) can change characteristics of piezosensors.

For example, connection of a resistor in series with a piezoelement, reduces quality of a piezoelement and expands a bandwidth of the transducer [1].

Inclusion f the capacitor between the input and the output systems of electrodes of piezotransformers type sensor also allows to expand a working range of frequencies [4].

Inductance connection between electrodes of the piezotransformer type sensor allows to increase level of the output voltage and acoustic power, to expand a bandwidth of the sensor, etc. Investigation results in this area will be published in a separate work.

6. Technology of synthesis of the transducers, considering electric signals

Change electric signal form applied to the transducer, can lead to change of its characteristics. For example, if to put on the electro-acoustic transducer electric voltage in the form of a meander, AFR of such transducer extends towards low frequencies [13].

Applying to piezoelement simultaneously two electric signals new properties and transducer functions can be obtained. For example, if to put on a piezoelement with two inputs two signals of the sinusoidal shape with frequencies close to its resonant frequency a powerful low-frequency signal may be obtained [4].

7. The combined technology

In this case the technologies described above are used simultaneously or in various combinations. It is easy to see, that in this case from one piezoelement hundreds of versions of sensors with various characteristics, among which it is possible to get the sensor with necessary or best characteristics (increase of accuracy, stability, sensitivity, expansion of a working range of frequencies, etc.) can be obtained.

Conclusions

Technologies of synthesis of piezoelectric transducers, exploiting spatial energy force structure, spatial electromechanical feedback, spatial arrangement and switching of electrodes of a piezoelement, technology of inclusion piezoelectric vibrators and piezotransformers into electric filters, technology of joining to a piezoelement of additional elements and others are developed.

By results of this work about 400 patents of the USSR, the Russian Federation and Ukraine have been obtained.

References

1. **Sharapov V. M., Musienko M. P., Sharapova E. V.** Piezoelectric sensors. Ed. V.M. Sharapov. Moscow: Technosphera. 2006. P. 632 (in Russian).
2. **Sharapov V.** Piezoceramic sensors. NY: Springer, 2011.P. 564.
3. Sensors. Ed. Sharapov V. and Polischuk E. Cherkassy: Brama. 2008. P. 1072 (in Russian).
4. **Fraiden J.** Modern sensors. The directory. Moscow: Technosphera. 2005. P. 592 (in Russian).
5. Piezoceramic transformers and sensors. Sharapov V., Minaev I., Sotula Zh., Bazilo K., Kunitskaya L. Ed. Sharapov V. Cherkassy: Vertical. 2010.P. 278 (in Russian).
6. **Sharapov V., Vladisauskas A., Bazilo K., Kunitskaya L., Sotula Zh.** Methods of synthesis of piezoceramic transducers: spatial energy force structure of piezoelement. ISSN 1392-2114 Ultrasound. 2009. Vol.64. No. 4. P. 44-50.
7. **Jonson D., Jonson D., Mur G.** The directory on active filters. M.: Energoatomizdat. 1983. P. 128 (in Russian).
8. **Titse У., Shenk К.** Semi-conductor circuitry. M.: Mir. 1983 (in Russian).
9. **Kaufman M., Sidman A.** Practical guidance by calculations of schemes in electronics. The directory in 2 t. T. 2: Ed. F.N. Pokrovskiy (in Russian).
10. **Sharapov V., Kazys R., Vladisauskas A., Kunitskaya L., Sotula Zh., Tuz V., Bazilo K.** Transducers with piezoelements in schemes of electric filters. ISSN 1392-2114 Ultrasound. 2010. Vol. 65. No. 1. P. 25-32.
11. **Mironov V. L.** Fundamentals of scanning probe microscopy. Moscow: Technosfera. 2004. P. 144 (in Russian).
12. **Sharapov V., Vladisauskas, Filimonov S.** Bimorph cylindrical piezoceramic scanner for scanning probe nanomicroscopes. ISSN 1392-2114 Ultrasound. 2009. Vol. 64. No. 4. P. 51-54.
13. **Sharapov V., Vladisauskas, Filimonov S.** Piezoceramic scanners on the basis of planar bimorph piezoelements for scanning probe nanomicrockopes. ISSN 1392-2114 Ultrasound. 2010. Vol. 65. No. 1. P.33-36.
14. **Sharapov V., Musiyenko M., Sotula Zh, Kunitskaya L**. About the effect of expansion of reproduced frequency band by electroacoustic transducer. ISSN 1392-2114 Ultrasound. 2009. Vol. 64. No. 3. P. 7-10.

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Naujos pjezokeraminių jutiklių sintezės technologijos

Reziumė

Sukurtosios jutiklių sintezės technologijos leidžia keisti jutiklių erdvinį elektromechaninį grįžtamąjį ryšį ir taip pakeisti jutiklių darbo dažnines charakteristikas. Tam tikslui naudojamas pjezoelementas su daug elektrodų, kai kurie iš jų jungiami į stiprintuvų grįžtamąjį ryšį arba yra du pjezoelementai, kurių vienas jungiamas į elektrinės schemos grįžtamąjį ryšį.

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