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 \( \mathbf{P} \) 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.

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 \( \mathbf{F} \) operating on a piezoelement (pressure, etc.) is parallel polarisation vector \( \mathbf{P} \).

Simultaneously the vector of the force \( \mathbf{F} \) is parallel to the vector of electric field \( \mathbf{E} \), 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.

Results

1. Spatial energy force structure of piezoceramic elements

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

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

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.
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 (\( F \parallel P \parallel E \)) (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].

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 ІТС-19 (analogue PZT-5A).

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

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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<α<90°.

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 parameters 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

\[ W_{FB}(p) = W_{1}(p) \frac{W_{TR}(p)}{1 + W_{TR}(p)\beta(p)}, \]

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 \( \gamma_{FB} \) of the device, presented in Fig. 6, it is possible to define by [1]:

\[ \gamma_{FB} = \gamma_{W} \frac{1}{1 + W(p)\beta(p)} - \gamma_{W}(1 - \frac{1}{1 + W(p)\beta(p)}), \]

were \( \gamma_{W} \) 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, \( \gamma_{FB} = 0 \):

\[
W(p)\beta(p) = 1
\]  

(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 \( F, P, E_{IN}, E_{FB} \) 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 \( \omega_c \).

High-pass filters (HPF) pass oscillations from some cut-off frequency \( \omega_c \) 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](image)

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 \( \alpha \) to the polarisation vector \( (0 < \alpha \leq 90^\circ) \).

It allows to obtain an electric voltage which exceeds the voltage for a conventional case when on these electrodes \( \alpha = 0 \) [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](image)

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
Conclusions

Electric filters, technology of joining to a piezoelement of inclusion piezoelectric vibrators and piezotransformers into switching of electrodes of a piezoelement, technology of the form of a meander, put on the electro-acoustic transducer electric voltage in can lead to change of its characteristics. For example, if to considering electric signals published in a separate work.

Investigation results in this area will be output voltage and acoustic power, to expand a bandwidth piezotransformer type sensor allows to increase level of the sensor also allows to expand a working range of output systems of electrodes of piezotransformers type expands a bandwidth of the transducer [1].

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 [4].

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

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Naujos pjezokeraminių jutiklių sintezės technologijos

Reziumė

Sukurtojos jutiklių sintezės technologijos leidžia keisti jutiklių erdvinių elektromechaninių grižtamajį ryšį ir taip pakeisti jutiklių darbo dažnines charakteristikas. Tam tikslui naudojamas pjezokerametas su daug elektrodų, kai kurie iš jų jungiamas į stiprintuvų grižtamaji ryšį arba yra du pjezoelementai, kurių vienas jungiamas į elektrinės schemas grižtamaji ryšį.

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