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Modelling of Piezoelectric Transducers for Environmental Monitoring

Constantine Bazilo[1], Alvydas Zagorskis[2], Oleg Petrishchev[3], Yulia Bondarenko[4], Vasyl Zaika[5], Yulia Petrushko[6]

[1,4–6]Department of Computerized and Informational Technologies in Instrument Making,
Cherkasy State Technological University, Cherkasy, Ukraine
[2]Department of Environmental Protection, Vilnius Gediminas Technical University, Vilnius, Lithuania
[3]Department of Acoustics and Acoustic Electronics, National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine
E-mails: [1]b_constantine@mail.ru (corresponding author); [2]alvydas@vgtu.lt; [3]om.petrischev@aae.kpi.ua;
[4]julybo@rambler.ru; [5]zavasio@mail.ru; [6]petrushko.10@mail.ru

Abstract. World Health Organization (WHO) defined health as being "a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity". Physical factors (noise, vibration, electromagnetic fields, ionized radiation, etc.) may have a negative influence on both the environment and the health of population. Piezoelectric sensors have been employed in different fields such as medical analysis, environmental monitoring, etc. The object of the research is piezoelectric sensors for environmental monitoring and their simulation. Currently, there are no reliable and valid methods of constructing of mathematical models of piezoelectric transducers, which could be used as a theoretical basis for calculating characteristics and parameters of this class of functional elements of modern piezoelectronics. In most papers the described methods of transformers simulation are mostly based on the use of equivalent electrical circuits and it does not allow analysing stress-strain state of solids with piezoelectric effects. The final goal of mathematical modelling of vibrating piezoelectric elements is a qualitative and quantitative description of characteristics and parameters of existing electrical and elastic fields. Physical processes in piezoelectric transducers which occur using axially symmetric radial oscillations of piezoceramic disk are considered.

Keywords: environmental monitoring, physical pollution, mathematical simulation, piezoelectric transducer.

Conference topic: Environmental protection.

Introduction

World Health Organization (WHO) defined health as being "a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity". Physical factors (noise, vibration, electromagnetic fields, ionized radiation, etc.) may have a negative influence on both the environment and the health of population (Vasilyev *et al.* 2013). Noise and vibration present increasing environmental problems to society. They are hazards to human when they occur at high levels, or continue for a long time (Abdel-Rahman 2008).

Noise and vibration as environmental hazards

Noise is one of the physical environmental factors affecting our health in today's world. Noise is generally defined as the unpleasant sounds (for example: produced by a machine or airplane) which disturb the human being physically and physiologically and cause environmental pollution by destroying environmental properties (Atmaca *et al.* 2005). The direct health effect known to be attributable to noise is hearing loss with noise exposure higher than 90 decibels. There are several non-auditory physiological effects of noise exposure including headaches, dizziness, high blood pressure, loss of concentration, heart disease etc.

Noise in the working environment constitutes a serious human, social and economic problem. Actions on an international scale would contribute to solving this problem and would be particularly useful to the developing countries (Abdel-Rahman).

According to EU Vibration Directive two forms of vibrations can be distinguished: whole-body vibration (WBV), which is transmitted by mobile or fixed machines where the operator is standing or seated, and hand-arm vibration (HAV), which is transmitted by hand-held or guided tools. The Directive defines the terms as follows:

- whole-body vibration': the mechanical vibration that, when transmitted to the whole-body, entails risks to the health and safety of workers, in particular, lower-back morbidity and trauma of the spine;
- hand-arm vibration': the mechanical vibration that, when transmitted to the human hand-arm system, entails risks to the health and safety of workers, in particular, vascular, bone or joint, neurological or muscular disorders (EU-OSHA 2008).

WBVs affect the drivers of heavy agricultural tractors where they are transmitted through the seat, the frame and the controls to the whole body of a driver.

There are many negative medical effects resulting from drivers being exposed to vibrations. When the influence of vibrations is short-termed, the symptoms are short breathing, nausea and disturbed balance, whereas long-term influence causes disorders in psychomotoric, physiological and psychological systems. Agricultural tractors have been identified as a hazardous machine from the aspect of the whole body vibrations. There is a risk even for those drivers who are exposed to vibrations only one hour a day.

This is why it is important to measure noise and vibration levels constantly, evaluate them and determine the risk for driver's safety. Depending on the risk, organizational and technical measures for vibration reduction should be taken (Cvetanovic, Zlatkovic 2013). An increased risk for health of persons living close to roads and railways has been found in several studies (Aasvang *et al.* 2011; Eriksson *et al.* 2012; Babisch *et al.*2005).

Undoubtedly, there is a need for further research to clarify this complex area, including better measurement of noise and vibration exposure and health outcomes (Stansfeld, Matheson 2003).

The object of current research is sensors for environmental monitoring and their simulation.

Piezoelectric sensors can be employed in different fields such as medical analysis, environmental monitoring, etc. Piezoelectric accelerometer is a device that measures the vibration, or acceleration of motion of a structure. It serves as a link between vibrating structures and electronic measurement equipment. Piezoelectric accelerometers are widely accepted as a good choice for measuring vibration. Compared to the other types of sensors, piezoelectric accelerometers have important advantages: extremely wide dynamic range, low output noise; excellent linearity over their dynamic range; wide frequency range; self-generating; acceleration signal can be integrated to provide velocity and displacement (Metra Mess- und Frequenztechnik 2001).

Piezoelectric accelerometers rely on the piezoelectric effect of quartz or ceramic crystals to generate an electrical output that is proportional to applied acceleration. The piezoelectric effect produces an accumulation of charged particles on the crystal. This charge is proportional to applied force or stress. The total amount of accumulated charge is proportional to the applied force, and the applied force is proportional to acceleration. Electrodes collect and wires transmit the charge to a signal conditioner that may be remote or built into the accelerometer. The same effects are also used in noise assessment by piezoelectric microphones that consist of a piezoelectric element attached to a diaphragm.

The method of determination of physical and mechanical constants of piezoceramic materials

Currently, there are no reliable and valid methods of constructing of mathematical models of piezoelectric transducers for environmental monitoring, which could be used as a theoretical basis for calculating characteristics and parameters of this class of functional elements of modern piezoelectronics. In most papers the described methods of transducers simulation are mostly based on the use of equivalent electrical circuits (Lineykin, Ben-Yaakov 2004; Ozeri, Shmilovitz 2006; Buchacz *et al.* 2014) and it does not allow analysing stress-strain state of solids with piezoelectric effects. The final goal of mathematical modelling of vibrating piezoelectric elements is a qualitative and quantitative description of characteristics and parameters of existing electrical and elastic fields. It is clear that to obtain informative and reliable quantitative estimates of parameters of the physical condition of piezoelectric (piezoceramic) element is not possible without reliable data on the values of the physical and mechanical constants of materials.

In the method of determination of piezoceramic disk's electrical impedance in low, medium and high frequencies is considered. The experimental scheme is shown in Figure 1 (Petrishchev, Bazilo 2016b, 2016c).

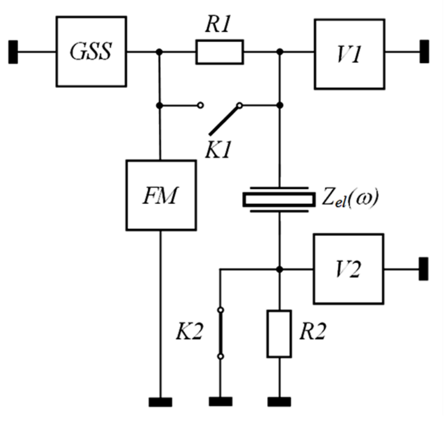


Fig. 1. Schematic diagram for measuring of piezoceramic disk's electrical impedance in a wide frequency range

Before determination ofits electrical impedance the piezoceramic disk is weighed and its thickness α and radius R are measured. According to known mass mand sizes α and R the density of the piezoceramics is determined as $\rho_0 = m\big/\left(\pi\alpha R^2\right)$, kg/m^3.

For measurements of electrical impedance it is recommended to use schematic diagram, shown in Figure 1, where *GSS* is a generator of sinusoidal signals, *FM* is a frequency meter, *V1* and *V2* are voltmeters, *K1* and *K2* are mechanical keys, *R1* and *R2* are load resistors. Investigated sample is indicated as $Z_{el}(\omega)$. Keys' position *K1* and *K2* shown in the diagram corresponds to the mode of electrical impedance measurement in the vicinity of the frequency of electromechanical resonance. For measurements in the vicinity of the frequencies of electromechanical antiresonance key *K1* must be closed and key *K2* must be open. Load resistors *R1* and *R2* are selected such that voltmeters *V1* and *V2* work in the range of their maximum sensitivity, i.e. on the scales (1÷10) mV.

Before starting the measurement in a wide range of frequencies thedynamic electric capacitance C_d^{σ} is determined on the measuring bridge at low frequencies. From the values of capacitance the dielectric permittivity is defined $\chi_{33}^{\sigma} = \alpha C_d^{\sigma}\big/\left(\pi R^2\right)$, F/m.

Upon completion of all measurements the following base of experimental data is formed:

– middle frequency range:

▪ frequencies of the first and second electromechanical resonances (f_{r1} and f_{r2}) and antiresonances (f_{a1} and f_{a2});

▪ an electrical impedance at frequencies of the first and second electromechanical resonances $Z_{el}\left(f_{r1}\right)$ and $Z_{el}\left(f_{r2}\right)$;

▪ a value of dynamic electric capacitance C_d^{*} of piezoceramic disk, which is determined by electrical impedance of the disk, measured on the frequency $f^{*} = \left(f_r + f_a\right)/2$, where $f_r = \left(f_{r1} + f_{r2}\right)/2$ и $f_a = \left(f_{a1} + f_{a2}\right)/2$;

– high frequency range:

▪ frequencies of the first and second thickness electromechanical resonances F_{r1} and F_{r2}, and cyclic frequency F_{a1} of the first thickness antiresonance;

▪ an electrical impedance at frequencies of the first and second electromechanical resonances $Z_{el}\left(F_{r1}\right)$ and $Z_{el}\left(F_{r2}\right)$;

▪ a value of dynamic electric capacitance C_d^{ε} of piezoceramic disk, which is determined by electrical impedance of the disk $Z_{el}\left(F^{\varepsilon}\right)$, where $F^{\varepsilon} \geq \left(F_{r1} + F_{r2}\right)/2$.

The procedure of experimental data processing.

1 According to the known value of C_d^{ε} the dielectric permittivity χ_{33}^{ε} is determined as

$$\chi_{33}^{\varepsilon} = \frac{\alpha C_d^{\varepsilon}}{\pi R^2}, \text{ F/m.}$$

2. According to the known value of the frequency of the first thickness electromechanical antiresonance F_{a1} the modulus of elasticity c_{33}^{D} is determined as

$$c_{33}^{D} = \rho_0\left(2\alpha F_{a1}\right)^2, \text{ Pa.}$$

3. According to known numerical values of frequencies F_{r1} and F_{a1} their ratio $\eta = F_{r1}\big/F_{a1}$ is determined and square electromechanical coupling factor K_{33}^2 for the thickness vibrations of the piezoceramic disk is defined as

$$K_{33}^2 = \frac{(\pi\eta/2)}{tg\left(\pi\eta/2\right) - \left(\pi\eta/2\right)}.$$

4. According to the known values of K_{33}^2 and c_{33}^{D} the modulus of elasticity c_{33}^{E} is determined as

$$c_{33}^{E} = \frac{c_{33}^{D}}{1 + K_{33}^2}, \text{ Pa.}$$

5. According to the known values of K_{33}^2, χ_{33}^{ε} and c_{33}^E the piezoelectric modulus e_{33} is determined as

$$e_{33} = K_{33}\sqrt{\chi_{33}^{\varepsilon} c_{33}^{E}}\text{ , C/m}^2.$$

6. According to the known values of the electric impedance of the disk $Z_{el}\left(F_{r1}\right)$ and $Z_{el}\left(F_{r2}\right)$ on the frequencies of the first and second electromechanical resonances the quality factor $Q_{mj}^{(z)}$ is determined as

$$Q_{mj}^{(z)} = \frac{K_{33}^2 \Psi\left(\Omega_{rj}\right)}{2Z_{el}\left(F_{rj}\right)\Omega_{rj} C_d^{\varepsilon}\left(1 + K_{33}^2\right)}, \qquad j = 1;2\,,$$

where:

$$\Psi\left(\Omega_{rj}\right) = \frac{2tg\left(\gamma_j \alpha/2\right)}{\left(1 + K_{33}^2\right)\left(\gamma_j \alpha/2\right)} + \frac{1 - \sin\left(\gamma_j \alpha\right)/\left(\gamma_j \alpha\right)}{\cos^2\left(\gamma_j \alpha/2\right)};\ \ \Omega_{rj} = 2\pi F_{rj};\ \ \gamma_j = \Omega_{rj}\Big/\sqrt{c_{33}^D/\rho_0}\ .$$

7. According to known quality factors $Q_{mj}^{(z)}$ the attenuation coefficients $\beta_j^{(z)}$ at high frequencies are defined as

$$\beta_j^{(z)} = \frac{\gamma_j}{2Q_{mj}^{(z)}}\text{, Np/m, } j = 1;2\,.$$

8. According to known attenuation coefficients $\beta_j^{(z)}$ at the frequencies of F_{rj} the structural coefficients $\delta_1^{(z)}$ and $\delta_2^{(z)}$ are determined as

$$\delta_1^{(z)} = \frac{\beta_1^{(z)} F_{r2}^4 - \beta_2^{(z)} F_{r1}^4}{F_{r1}^2 F_{r2}^4 - F_{r2}^2 F_{r1}^4},\ \ \delta_2^{(z)} = \frac{\beta_2^{(z)} F_{r1}^4 - \beta_1^{(z)} F_{r2}^4}{F_{r1}^2 F_{p2}^4 - F_{r2}^2 F_{r1}^4}\,.$$

9. According to known structural coefficients $\delta_1^{(z)}$ and $\delta_2^{(z)}$ the frequency dependence of the attenuation coefficient $\beta^{(z)} = \delta_1^{(z)} f^2 + \delta_2^{(z)} f^4$ at high frequencies is constructed and the frequency dependence of the mechanical quality factor $Q_m^{(z)}\left(f\right)$ within this frequency range is determined as

$$Q_m^{(z)}\left(f\right) = \frac{\pi f}{v^D\left(\delta_1^{(z)} f^2 + \delta_2^{(z)} f^4\right)},$$

where: $v^D = \sqrt{c_{33}^D/\rho_0}$ is a velocity of propagation of plane waves of compression-tension in the direction of electric polarization vector of piezoelectric disk.

10. According to the known value of dynamic electric capacitance C_d^* the dielectric permittivity χ_{33}^{ε} is determined. A check is made for compliance with the previously defined values of χ_{33}^{ε} and K_{33}^2, because of $\chi_{33}^* = \chi_{33}^{\varepsilon}\left(1 + K_{33}^2\right)$. In case of a significant difference between the calculated value χ_{33}^* and a value of χ_{33}^*, which is determined from an experiment, it is necessary to analyze the situation and, if necessary, repeat the measurement.

11. According to the known values of frequencies f_{r1} and f_{r2} their ratio $\xi_{21} = f_{r2}/f_{r1}$ is determined and according to this ratio the parameter k and the numerical value of the root x_1 are fined from Table 1 (Petrishchev, Bazilo 2016c).

12. According to the known value of x_1 the modulus of elasticity c_{11} is determined as

$$c_{11} = \rho_0\left(2\pi R f_{r1}/x_1\right)^2\text{, Pa.}$$

13. According to the known values of c_{11} and k the modulus of elasticity c_{12} is determined as

$$c_{12} = k c_{11}\text{, Pa.}$$

14. According to the known values of c_{11}, c_{12} and c_{33}^E the moduli of elasticity c_{12}^E and c_{11}^E are determined as

$$c_{12}^E = \frac{c_{33}^E}{2}\left(1 - \sqrt{1 - 4\frac{c_{12}}{c_{33}^E}}\right), \text{Pa}; c_{11}^E = c_{11} + \frac{\left(c_{12}^E\right)^2}{c_{33}^E}, \text{Pa}.$$

15. According to the known value of the parameter k and measured frequency of the first electromechanical antiresonance f_{a1} the square electromechanical coupling factor K_{31}^2 in the radial (planar) oscillations mode of the piezoceramic diskis determined as

$$K_{31}^2 = \frac{1}{2}\left[1 - k - \frac{\zeta_1 J_0(\zeta_1)}{J_1(\zeta_1)}\right],$$

where: $\zeta_1 = x_1 f_{a1}/f_{r1}$.

16. According to the known values of K_{31}^2, c_{11} and χ_{33}^* the piezoelectric modulus e_{31}^* for planar oscillations mode is defined as

$$e_{31}^* = -K_{31}\sqrt{c_{11}\chi_{33}^*}, \text{ C/m}^2.$$

17. According to the known values of e_{31}^*, e_{33}, c_{12}^E and c_{33}^E the piezoelectric modulus e_{31} is defined as

$$e_{31} = e_{31}^* + e_{33}c_{12}^E/c_{33}^E, \text{ C/m}^2.$$

18. According to the known values of the electric impedance of the disk $Z_{el}(f_{r1})$ and $Z_{el}(f_{r2})$ at the frequencies of the first and second electromechanical resonance of the radial oscillations the quality factors $Q_{mj}^{(\rho)}$ are determined as

$$Q_{mj}^{(\rho)} = \frac{R\left[\left(x_j^2 + k - 1\right)J_1(x_j) - kx_j J_0(x_j)\right]}{4x_j v C_d^* K_{31}^2 J_1(x_j) Z_{el}(f_{rj})}, \quad j = 1;2,$$

where: x_j is a numerical value of the j-th root from Table 1 (Petrishchev, Bazilo 2016c); $v = \sqrt{c_{11}/\rho_0}$ is a velocity of propagation of radial (planar) oscillations in the piezoceramic disk, determined without taking into account losses at viscous friction.

19. According to known quality factors $Q_{m1}^{(\rho)}$ and $Q_{m2}^{(\rho)}$ in analogy with the procedures 7-9 the following estimate of the frequency dependence of mechanical quality factor in the middle frequency range is provide.

20. According to the known values of the piezoceramic material parameters the dielectric permittivity χ_{33}^σ is calculated as

$$\chi_{33}^\sigma = \chi_{33}^\varepsilon\left(1 + \Delta\chi_{33}^\sigma\right), \text{ F/m}.$$

where:

$$\Delta\chi_{33}^\sigma = \frac{2e_{31}^2 c_{33}^E - 4e_{31}e_{33}c_{12}^E + e_{33}^2\left(c_{11}^E + c_{12}^E\right)}{\chi_{33}^\varepsilon\left[c_{33}^E\left(c_{11}^E + c_{12}^E\right) - 2\left(c_{12}^E\right)^2\right]}.$$

The calculated value χ_{33}^σ is compared with the value χ_{33}^σ, which is obtained by measurement of capacitance C_d^σ. In the case of a large gap between the numerical values of the dielectric permittivity χ_{33}^σ it is necessary to analyze the situation and, if necessary, repeat the measurement (Petrishchev, Bazilo 2016a).

Determined values of physical and mechanical constants of piezoceramic materials allow us to obtain informative and reliable quantitative estimates of parameters of the physical condition of piezoelectric (piezoceramic) transducers.

Results of modelling of bending vibrations of piezoelectric tranducers and their simulation

For transducers characteristics improvement the method of spatial and angular interaction, which is used in order to maximize bending vibrations, and the method of additional elements are improved (Bondarenko *et al.* 2015). The measurement for circuits with transformer decoupling, which allows us to create a traveling wave in piezoelectric element, is carried out. Traveling wave is needed to create maximal bending vibrations. To create bending deformations the cross piezoelectric modulus d_{31} is used here, which forms a larger bend of piezoelement at a lower resonant frequency. For experimental research the disk piezoceramic transducer Ø66 mm shown in Figure 2 is used.

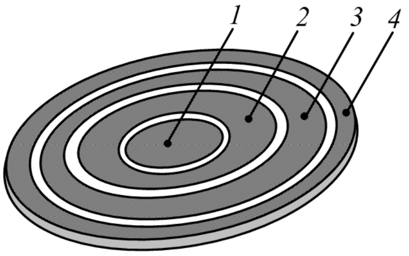
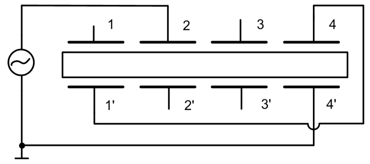
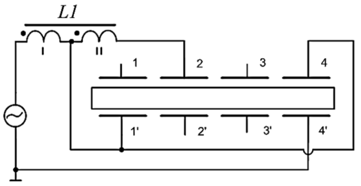
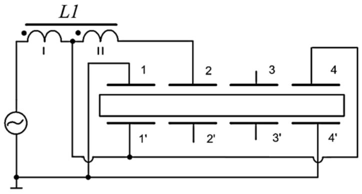


Fig. 2. Disk piezoelectric transducer with electrodes

The electrodes 1–4 on the surface of piezoelectric transducer (Fig. 2) are created by chemical etching. This design allows us to construct a great number of connections, apply different methods of characteristics improvement such as method of spatial and angular interaction, method of additional elements and transformer decoupling. The results of measurements for different connection schemes of disk piezoelectric transducer with transformer decoupling are shown in Table 1.

Table 1. Connection schemes of disk piezoelectric transducer with transformer decoupling

#	Scheme	*C*, nF	*L*, H	Sound pressure, dB
1		C_{Σ}=1.7	–	80
2		$C_{1',4-4'}$ = 1.7 $C_{2-4'}$ = 0.5	L_{I} = 0.25 L_{II} = 1.5	108
3		$C_{1',4-1,4}$= 1.8 $C_{2-1,4}$= 0.85	L_{I} = 0.12 L_{II} = 1.15	112

In Table 1 following symbols are used: *C* is an interelectrode capacitance; *L* is an additional inductance. Piezoelectric element is an electromechanical oscillation system. Thus electrical components adding can influence the characteristics of piezoelectric transducer. Exactly matched the inductance *L* to the interelectrode capacitance *C* we can greatly increase the output signal. As seen from Table 1, the use of transformer decoupling (scheme 2, 3) allows us to create bending vibrations in piezoelectric transducer which lead to an increase of output signal 108–112 dB in comparison with traditional connection 80 dB (Sharapov 2011) (scheme 1).

The most effective method of numerical simulation of complex systems is the finite element method. Physical processes which occur in disk piezoelectric transducers were simulated in COMSOL Multiphysics. The displacement of material particles of piezoceramic disk transducer with the highest output signal (Table 1, scheme 3) is shown in Figure 3.

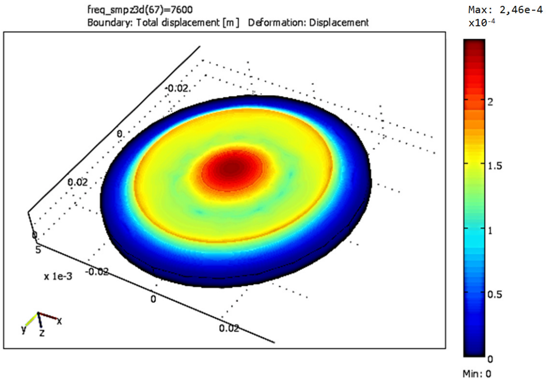


Fig. 3. Displacement of material particles of piezoceramic disk transducer

Maximum bending of proposed transducer with transformer decoupling is 250 microns, which is 4 times more than transducer with traditional connection (Sharapov 2011) has. Using such modelling it is easily to determine the characteristics sensitivity of the piezoelectric transducers to variations of their design parameters. With access to these dependences, we can implement a rational choice of products manufacturing technology, i.e. choose the least expensive technology from a number of ones. Thus, high-quality modelling can significantly reduce the time and cost of developing of the piezoelectric transducers new models.

Conclusions

1. Physical factors, such as noise and vibration, may have a negative influence on both the environment and the health of population. Piezoelectric transducers can be used for environmental monitoring, hazards assessment.
2. The method of physical and mechanical constants of piezoceramic materials determination for environmental monitoring can be applied to obtain informative and reliable quantitative estimates of parameters of the physical condition of piezoelectric element.
3. For transducers characteristics improvement the method of spatial and angular interaction, which is used in order to maximize bending vibrations, and the method of additional elements were improved. The use of transformer decoupling allows us to create bending vibrations in piezoelectric transducer which lead to an increase of output signal 108–112 dB in comparison with traditional connection 80 dB.
4. Physical processes which occur in disk piezoelectric transducers were simulated in COMSOL Multiphysics. Maximum bending of piezoelectric transducer with transformer decoupling is 4 times more than for the transducer with traditional connection. This makes it possible to obtain an increase of the output signal of piezoelectric transducers for environmental monitoring.

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