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A study of acoustic echolocation in complex gaseous environments by using acoustic antennas consisting of piezoelectric ceramic transducers in flexural vibration

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Abstract

In this article, acoustic echolocation measurement method for measurements in complex and normal gaseous environments is described in detail. The advantages of this measurement method along with information about improving the characteristics and accuracy of measurements in complex gaseous environments are presented. When measuring in a complex structural environment, the accuracy of the measurement greatly depends on the shape of the radiation pattern of the ultrasonic transducer (antenna). Most suitable transducers along with their directivity patterns are presented. When measuring in a gaseous environment, acoustic impedances of transducers and the environment should be matched. Since the impedances of the transducer and the environment are different, matching layers are necessary to increase the effectiveness of the transmission of acoustic energy. This matching directly affects the amplitudes of the transmitted and received measurement signals. Information on how the acoustic transducer operates in air is presented. In addition, main requirements for the transducers of the ultrasonic measurement instruments are given. Types of the transducers for measuring long distances are presented and parameters of different types of transducers are compared. For measurements in air or gaseous environment, piezoelectric ceramic transducers in a flexural vibration mode are widely used. Details of the specific design of such transducers for measurement in air are presented. Radiation patterns for the most effective transmission of energy are also presented. Designs of unidirectional acoustic antennas are given. Diagrams for calculating the geometric parameters of the transducers in flexural vibration mode to obtain specific radiation patterns of transducers are presented. When acoustic measurement instruments operate in complex gaseous environments, measurement of the ambient temperature along the whole measurement channel is necessary. An ultrasonic level measurement system with a detailed measurement algorithm for operation in such environments is presented.

Keywords: Echolocation, level measurement instrument, ultrasound, ultrasound velocity, ultrasonic transducer, types of transducers, design of transducers, oscillating piston, acoustic antenna, piezoelectric ceramic transducer, bimorph, flexural vibration, longitudinal vibration, matching layer, acoustic impedance, measurement algorithm, directivity pattern, nodal lines

Introduction

Acoustic measurement method based on echolocation, like the microwave measurement method [1-5], became a popular option when designing level measurement devices for various materials.

Acoustic (ultrasonic) measurement instruments have many advantages over traditional measurement methods, for example:

- have no moving components, therefore no maintenance is required for that part;
- measurement results do not depend on the physical-mechanical and chemical properties of materials that are being measured;
- comparatively low cost.

Ultrasonic measurement devices also have their disadvantages. For example, it is difficult to avoid the influence of temperature variations and vapor of liquids on measurement results, because the temperature is measured using the acoustic antenna (we later propose a measurement method, which can eliminate this shortcoming).

We will describe how to improve the characteristics of ultrasonic level measurement devices, for successful practical level measurements of materials in complex gaseous environments. Currently, many well-known companies produce ultrasonic level measurement instruments [6-14]. However, in practical use of such devices various difficulties arise. In particular, when complex vapor with high-temperature aerosols is present over the materials, which are being measured. In this case, the measurement results become unreliable. Therefore, the development of new acoustic measurement instruments is still relevant.

Metrological parameters of ultrasonic level measurement instruments depend on the parameters of the electronic circuit and on the parameters of the electro-acoustic channel.

The parameters of acoustic measurement instruments greatly depend on the shape and spectrum of the measurement signal; also on the signal-to-noise ratio of the measurement signal [3]. Currently, the electronic circuits are very well refined. The most challenging part, when developing a new measurement equipment, is the design of the measurement channel. Therefore, the priorities are: design of new transducers, evaluation of the effects of the environment, investigation of the physical properties of matching elements, and development of new measurement algorithms.

One of the most important parts of the ultrasonic measurement device is the ultrasonic transducer or antenna. We will examine the parameter requirements for electro-acoustic transducers. In instruments based on echolocation, where the time of signal propagation is measured, measurement options depend on the shape of the measurement signal's autocorrelation function and on the signal-to-noise ratio. The width of the signal's autocorrelation function gets narrower as the spectrum of the signal gets wider. To increase the accuracy of measurement, a signal with a broad spectrum is necessary. Therefore, electro-acoustic transducers with the broadest possible frequency band are used in measurement devices. This band gets broader in an absolute value when the operating frequency of the transducer increases. However, when measuring in a gaseous (air) environment there is the second power increase in attenuation of the signal's amplitude, as the frequency increases. For example, when the operating frequency is around 200 kHz, the damping coefficient is 8 dB/m [15-17]. Consequently, it is impractical to use operating frequencies higher than 200 kHz in ultrasonic measurement devices.

The characteristics of the electro-acoustic measurement channel should also be as stable as possible. Therefore, the degradation of parameters in time should not be overlooked. When measuring in a complex structural environment (various irregular-shaped objects like ladders and holders are present in the measurement tank), reliability of measurements (probability of possible errors) greatly depend on the shape of the radiation pattern of the ultrasonic transducer (antenna). Narrowest possible single-leaf radiation pattern is most suitable for such measurements [17].

By increasing the efficiency of the electro-acoustic transducer, it is possible to improve the energy parameters of the measurement signal (increase the signal-to-noise ratio). When measuring in air (gas), the main problem is the signal's transmission from the electro-acoustic transducer towards the measurement object, and the echo signal's reception using the same or other transducer. After the evaluation of the environmental factors, electro-acoustic transducers with solid radiating surfaces are often used. Acoustic impedances of such transducers and the operating environment must be matched. This matching directly affects the amplitudes of the transmitted and received measurement signals.

Peculiarities of electro-acoustic transducer operation in air

Electro-acoustic transducers with a solid radiating surface have an acoustic impedance of about ($1 \times 10^7 - 3 \times 10^7$) kg/m^{2}s [3, 18-19]. The acoustic impedance of air is 3.3×10^2 kg/m^{2}s. Only 1×10^{-4} of the signal's acoustic energy is transmitted into air. On the reception of the signal, this energy further decreases by the same amount. Consequently, decreasing the impedance of the electro-acoustic transducer is exceptionally important when measuring in gaseous (air) environment. It also needs to be noted that the signal-to-noise ratio can be increased by increasing the amplitude of the transmitted measurement signal. In this case, limits do exist because of the possibility of electrical breakdown, destruction of mechanical transducer due to excitation force and non-linear phenomena (processes) in the measurement channel.

The main requirements for the transducers of the ultrasonic measurement devices are:

- highly efficient transformation of the measurement signals;
- acoustic impedance of the transducer should be as close as possible to the impedance of the environment (air);
- broad transmission frequency band;
- minimal noise;
- narrow single-leaf radiation pattern;
- high dynamic range of signals;
- stability of parameters;
- reliability and longevity;
- simple structure;
- low cost.

Aside from these requirements, when particular measurement conditions are present, there can be specific requirements for the size and weight of the transducers, hermetic sealing, operating temperature, acceptable pressure ranges, etc.

The acoustic power, transmitted from the surface of the oscillating piston to the environment (air) is calculated using expression [3]:

$$P_A = 42\pi\xi^2 d^2 f^2 \cdot 10^{-7}, \qquad (1)$$

where P_A is the acoustic power, [W]; d is the diameter of the vibrator's surface, [cm]; ξ is the amplitude of vibration, [cm]; f is the frequency, [Hz].

One can see from Eq. 1 that the acoustic power, transmitted by the oscillating piston, has a quadratic dependency on the amplitude of vibration ξ, the diameter of the vibrator's surface d and the frequency f. The dependency of the acoustic power on the amplitude of the vibration for various $d \times f$ values is presented in Fig. 1 [18].

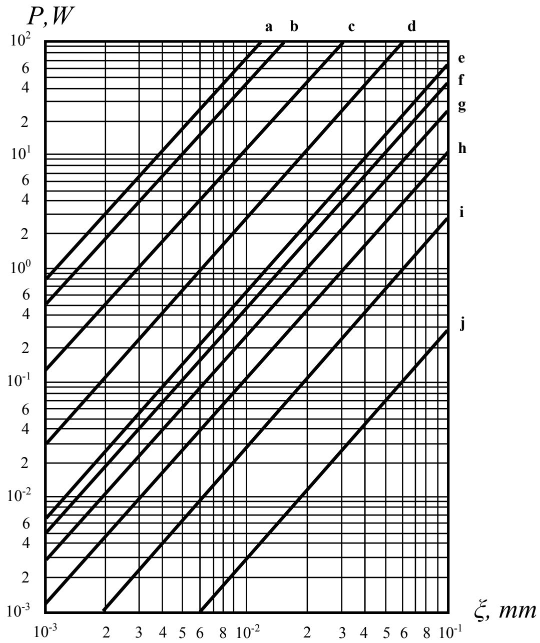

Fig. 1. **The dependency of the acoustic power, transmitted by the electro-acoustic transducer into air on the amplitude of vibration. Calculated using (1) expression for various *d·f* [cm·Hz] values: a - *d·f* = 106; b - *d·f* = 8·105; c - *d·f* = 4·105; d - *d·f* = 2·105; e - *d·f* = 105; f - *d·f* = 8·104; g - *d·f* = 6·104; h - *d·f* = 4·104; I - *d·f* = 2·104; j - *d·f* = 104**

We can mention that in order to transmit 1 W of the acoustic power into air, when the frequency of vibration is

100 kHz and the surface diameter of the oscillating piston is 1 cm, the amplitude of vibrations needs to be 1.2×10 μm. For comparison, the transmission of the same acoustic power with the same transducer into water is achieved when ξ is 3.3 × 10^{-3} μm.

The transmission of acoustic energy from the transducer's surface into air is challenging, because of the different (around 10^4 times) acoustic impedances of solids and gases. It is possible to avoid large losses of acoustic energy between the two mediums by using transitional matching layers, composed of materials with gradually decreasing acoustic impedances [3, 17, 19]. The transfer of acoustic energy from one medium to another is most efficient, when the acoustic impedance of the transitional layer is:

$$z_2 = \sqrt{z_1 z_3}\ , \qquad (2)$$

where z_1 and z_3 are the acoustic impedances of each medium respectively.

In this case, the increase of the transmitted acoustic energy is described by expression:

$$\frac{T_{123}}{T_{13}} = \frac{z_1 z_2 + z_2 z_3}{z_1^2 + 4\sqrt{z_1}\sqrt[3]{z_3^2} + z_1 z_3^2 + 5 z_1 z_3 + 4\sqrt{z_1^3}\sqrt{z_3} + z_3^2}\ , \qquad (3)$$

where T_{123} and T_{13} – coefficients of acoustic energy density transmission from one medium to another, respectively with a matching layer and without.

Currently, for transducers that operate in air, matching layers are manufactured using materials like nylon, polystyrene foam and foam glass [18]. By using such layers, it is possible to increase the transmission coefficients of acoustic energy up to 15 times [18-35]. It is impractical to increase the number of transitional layers, because of the additional losses of energy, due to acoustic wave reflections at each interface and losses inside the different matching layers. It is not possible to use polymers in electro-acoustic transducers, which operate in complex gaseous environments. When polymer-based transducer operates in such environment, deposits form on its surface, and the vibrations of the electro-acoustic transducer become significantly reduced. The level measurement devices then begin to operate unreliably.

It is known [2], that the acoustic impedance of the transducer depends on the density of the material and on the velocity of acoustic wave propagation in it. Therefore, for measurements in a gaseous environment, various electro-acoustic film-based transducers are a great choice [20]. Such transducers are frequently used for various measurements in air. Still, due to reasons mentioned above, they are not suitable for use in aggressive gaseous environment.

One can see from Eq. 1, that the acoustic power, transmitted by the transducer, depends on the vibration amplitude. By using transducers in a flexural vibration mode, vibration amplitudes in the range of hundreds of microns are possible. It is not possible to achieve such amplitudes by using transducers in a longitudinal vibration mode. When using transducers in longitudinal vibration mode, various matching elements, like transitional layers or structural elements, transforming the type of vibrations, are necessary [20, 30, 36-61].

When measuring comparatively long distances (up to few hundred meters), the operating frequency must be as low as possible. Low-frequency transducers in a flexural vibration mode have significantly smaller physical measurements and lower weight than the transducers in longitudinal vibration [3, 17, 25]. This is the reason why we recommend using transducers in a flexural vibration for measurement applications in large reservoirs.

Recently, there was a considerable progress in the development of piezoelectric transducers by using new piezoelectric materials. Various transducers with broad operating frequency range, high sensitivity, and with matching acoustic impedances between the transducer and air were developed. Parameters of various transducers are compared in Table 1 [20].

Table 1. **Comparative parameters of ultrasonic transducers**

Parameter name	Type of transducer			
	Capacitive	Piezoelectric ceramic (with matching layer)	Composite (array of layers)	PVDF (polyvinyl fluoride)
Sensitivity of reception, mV/Pa	2	1	0.1	0.4
Sensitivity of trasmission, mV/Pa	0.2	1	0.3	0.1
Operating frequency, kHz	200	500	500	200
Frequency range, %	30	2	30	30
Operating temperatures (max), °C	80	>100	>100	80
Stability to environment	low	high	high	low
Stability	medium	high	medium	high

From the data, presented in Table 1, one can see that the use of such transducers is most effective when the measurement distances are comparatively small.

To measure greater distances in industrial applications, piezoelectric ceramic transducers are most suitable [25], because they have a solid radiating surface, which is the most resistant to the influence of the environment.

Fig. 2 displays different types of electro-acoustic transducers for measurement devices, which operate in normal air environments [3]. The solid line represents the distances measured by ultrasonic measurement devices that are currently operating in practice. The dotted line represents the maximum possible measurable distances with measurement devices, which use the corresponding type of transducers. One can see from Fig. 2 that for measurements of longest possible distances, these types of transducers can be used:

- electro-dynamic transducers;
- magnetostrictive transducers with transformation of vibrations;
- piezoelectric ceramic transducers with transformation of vibrations;
- piezoelectric ceramic transducers in flexural vibration.

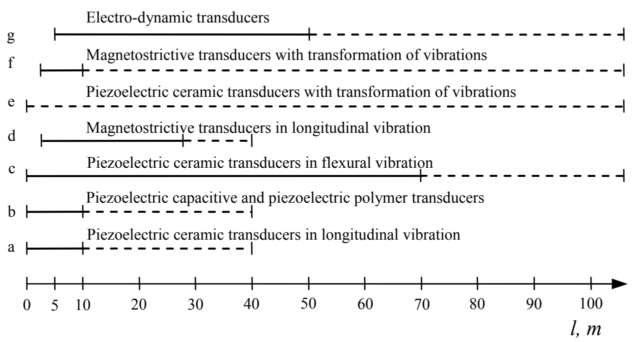

Fig. 2. **Distances measured using acoustic measurement devices with electro-acoustic transducers of different types**

The design of ultrasonic transducers in flexural vibration for echolocation in air

For measurements in air (gas) environment, piezoelectric ceramic transducers in flexural vibration are widely used [3, 15, 25]. The use of transducers in a flexural vibration mode gives the best possibility to match acoustic impedances of air and the transducer, because flexural transducers have a sufficiently low acoustic impedance. The optimal transmission of measurement signals to air is then possible.

The best way to generate flexural vibrations is by using unimorphic, bimorphic or multimophic piezoelectric transducers [3]; also by using various composite transducers with transformation of vibrations [44-47].

When measuring in air, unidirectional transmission-reception of signals is preferred. Additionally, the peripheral transmission-reception should be as minimal as possible, because it is disruptive and produces measurement errors. Because of this, acoustic antennas consisting of piezoelectric transducers in a flexural vibration mode are designed with a minimal peripheral transmission-reception.

As will be shown bellow, the unidirectional transmission using piezoelectric transducers can be achieved by using rectangular bimorph piezoelectric transducers with parallel nodal lines of vibrations [3]. In addition, it is possible to use various composite transducers with transformation of vibrations. Their operating surfaces must be thin-walled and rectangular.

Piezoelectric ceramic transducer vibrating in a longitudinal mode is limited by the highest possible stress in the vibrating elements [61]. Mechanical stress in vibrating elements depend on the type of vibrations [61]. When the transducer operates in a longitudinal vibration with a specific amplitude, the higher stress by around a factor of 10 are present, compared to a transducer, which operates in a flexural vibration [61]. Because of this, by using transducers in a flexural vibration it is possible to generate amplitudes greater by a factor of ten than with the transducers in longitudinal vibration.

The velocity of harmonic flexural waves in the elastic plate is calculated using expression:

$$v_{fl} = \sqrt[4]{\frac{Eh^2}{12\rho\left(1-\sigma^2\right)}}\sqrt{\omega}\,, \tag{4}$$

where v_{fl} is the velocity of harmonic flexural waves in the elastic plate; E is the Young's modulus of the elastic plate; h is the thickness of the elastic plate; ρ is the density of the elastic plate; σ is the Poisson's ratio of the elastic plate; ω is the cyclic frequency of the wave.

The velocity v_{fl} of harmonic flexural waves in elastic plates is significantly lower than the velocity v_l of harmonic longitudinal waves [61]. The velocity ratio of flexural and longitudinal waves in the elastic plate changes, depending on the ratio of the thickness h of the elastic plate and the wavelength λ_l of the longitudinal acoustic wave in the elastic plate [61]. This dependence is presented in Table 2.

Table 2. **The dependence of ratio v_{fl} / v_l on the ratio h / λ_l**

h / λ_l	0.0001	0.001	0.01	0.1
v_{fl} / v_l	0.0135	0.0426	0.135	0.426

The figures from Table 2 indicate that as the thickness of the elastic plate decreases, the ratio v_{fl}/v_l is also decreasing.

The radiation of the acoustic transducer depends not only on the type of vibrations, but also on the shape of vibrations on its surface [3, 17, 19]. The most effective radiation of energy happens, when nodal lines of vibrations on the surface of the rectangular transducer in a flexural vibration are parallel to one another [3, 17]. In case when the radiating surface of the transducer is circular, most effective radiation of energy happens, when nodal lines of vibrations on the transducer's surface are distributed in concentric circles [40]. If the nodal lines of flexural vibrations are distributed parallel to one another on the transducer's surface, the angle θ, between the direction of radiation of the transducer and its surface is [2, 3]:

$$\Theta = \pm\arcsin\frac{\lambda_A}{\lambda_T}\,, \tag{5}$$

where θ is the an angle between a flat transducer's surface and direction of radiation; λ_A is the length of acoustic wave in air; λ_T is the length of acoustic wave on the surface of the transducer.

The sign ± in Eq. 5 indicates that in the transducer with a finite surface, standing waves are generated and the radiation of energy is in two directions.

Rectangular piezoelectric transducers were described in [3, 47-50]. In other publications [51-53] a new look on forming of the directivity patterns of transducers exploiting flexural vibrations is presented. A paper [3] proposes that for measurements in air environment it is best to use piezoelectric ceramic rectangular bimorph transducers with parallel nodal lines of vibrations. In one plane, a radiation pattern of such transducers is the same as for an oscillating piston. In a perpendicular plane, if a flexural transducer is flat, it has a four-leaf (four-directional) radiation pattern and an inclination angle α between a normal to a flat surface and direction of radiation. This angle depends on the ratio of velocities of acoustic waves in the transducer and in air [61]:

$$\sin\alpha_{1,2} = \pm\frac{k_\delta\lambda_a}{2l}, \qquad (6)$$

where α is the an angle between a normal to a flat surface and direction of radiation; λ_a is the length of acoustic wave in air; k_δ is the number of nodal lines in a transducer; l is the length of a transducer in the direction of flexural vibrations.

As shown below, it is possible to achieve unidirectional transmission from piezoelectric transducers by using rectangular piezoelectric transducers with a four-leaf radiation pattern.

The vibration modes of flat and rod-like piezoelectric elements are theoretically analyzed in [3, 27, 62, 63].

The vibrations $\xi_\delta(x)$ of a bimorph in segment Ox_1 are described by expression [62, 63]:

$$\xi_\delta(x) = \xi_\delta(x_1)\cdot\Phi(\alpha_\delta), \qquad (7)$$

where α_δ is the argument of bending coupling factor and coordinate x_1; $\Phi(\alpha_\delta)$ is the complex expression of Prager and Krylov function [62].

The resonant frequencies of a piezoelectric bimorph are obtained using equation [3]:

$$1+\cos\alpha_\delta ch\alpha_\delta + \beta(\sin\alpha_\delta ch\alpha_\delta - \cos\alpha_\delta sh\alpha_\delta) = 0, \qquad (8)$$

where

$$\alpha_\delta = \frac{v_\delta\cdot x_1}{2\pi f}, \qquad (9)$$

where v_δ is the length of flexural wave in the bimorph; f is the frequency of vibrations.

In practice, usually the second resonant frequency of a bimorph piezoelectric transducer is used [3].

The quality of acoustic measurement devices strongly depends on radiation patterns of acoustic antennas. In most situations, the radiation pattern of antennas must be unidirectional.

In Fig. 3, a schematic cross-section of a transducer with an elastic plate, which is mounted on a rectangular frame along the whole perimeter, is presented.

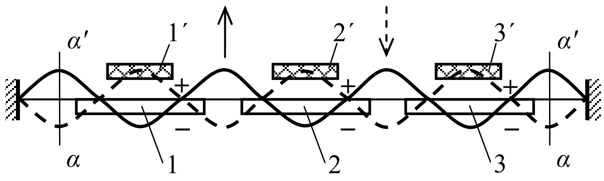

Fig. 3. **Schematic cross-section of a multi-component piezoelectric transducer: 1, 2, 3 – piezoelectric ceramic plates with same polarization; 1′, 2′, 3′ – reflectors of acoustic waves**

In case when the transducer has loose edges, the width of the multi-component transducer has to be decreased as shown in Fig. 3 by αα'. For effective operation of such transducers, vibrations of the piezoelectric ceramic plate arrays must be matched with the vibrations of elastic plates, on which the arrays are mounted. In the design of the multi-component transducer, presented in Fig. 3, three rectangular piezoelectric ceramic plates vibrate in the second mode of cosinusoidal flexural vibration and the elastic plate vibrates in the seventh mode of cosinusoidal flexural vibration.

The design of the transducer can also be either with fixed or with loose edges [64-66]. This technique can also be used to design complex transducers [64].

The cross section of a unidirectional acoustic antenna is shown in Fig. 4.

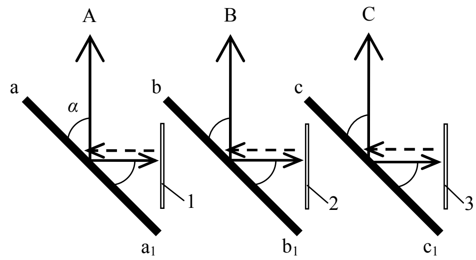

Fig. 4. **Cross-section of unidirectional acoustic antenna: aa1, bb1, cc1 – rectangular bimorph piezoelectric ceramic transducers in flexural vibration with parallel nodal lines; 1, 2, 3 – reflectors of acoustic waves**

In Fig. 5, the cross section of a different unidirectional acoustic antenna is shown [64]. The acoustic transmission in this antenna is increased by using two additional reflectors placed behind two rectangular bimorphs.

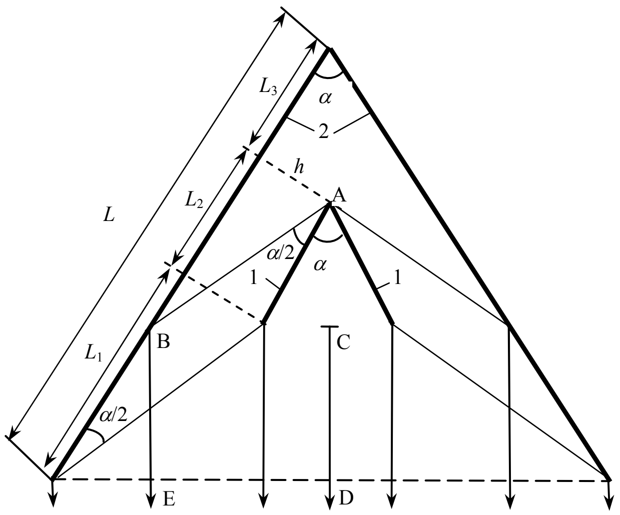

Fig. 5. **Cross section of unidirectional acoustic antenna: 1 – rectangular bimorph piezoelectric transducers; 2 – reflectors of acoustic waves**

In the aperture of the antenna (Fig. 5) the radiation of both bimorphs is summed. The distance h from the reflector to the bimorph is calculated using expression:

$$h = \frac{m\lambda_a}{2\sin(\alpha/2)}, \qquad (10)$$

where $m = 1, 2, 3, \ldots$.

The length of a reflector L (Fig. 5) must meet the following condition:

$$L \ge \frac{m\lambda_a\cos(\alpha/2)}{\sin^2(\alpha/2)} + l_2. \qquad (11)$$

In such design of the antenna, three (out of 4) leafs of the radiation pattern are used for measurement [64]. Acoustic antennas (Figs. 4, 5 and 6), consisting of rectangular bimorphs have a peripheral radiation up to 25%. Because of this radiation, difficulties arise when using such antennas in acoustic measurement devices.

The paper [64] shows that the near field zone of a bimorph in a flexural vibration is shorter than of the field, produced by an oscillating piston. It is possible to use this property to eliminate peripheral radiation by using sound-absorbing elements (Fig. 6 and 7).

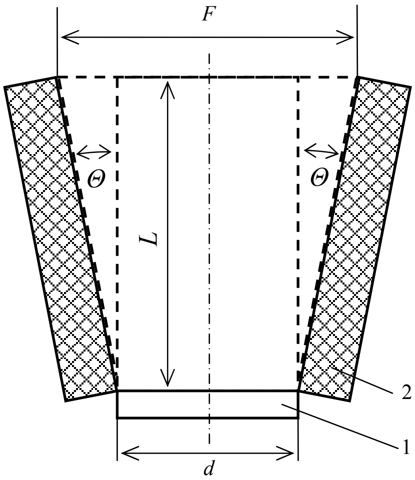

Fig. 6. **Cross section of unidirectional acoustic antenna: 1 – bimorph piezoelectric unidirectional transducer; 2 – absorber of acoustic waves.**

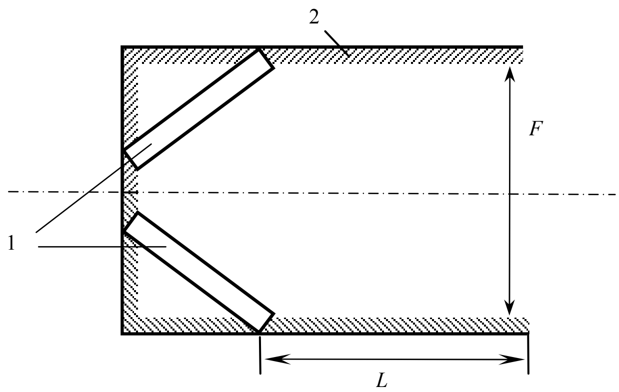

Fig. 7. **Cross section of unidirectional acoustic antenna: 1 – rectangular bimorph piezoelectric transducers; 2 – absorber of acoustic waves.**

The length L of the absorber must meet the following condition:

$$L = (F/2)\cdot \cot\Theta\,, \tag{12}$$

where Θ is the angle between maximum and the first minimum of the directivity pattern; F is the aperture of the acoustic antenna.

In the top part of the actual image of the antenna (Fig.8), one can see that it is composed of four rectangular bimorphs. This antenna operates at the frequency of 18 kHz, and the aperture is 100 mm. The radiation pattern of this antenna is presented in Fig. 9.

It needs to be mentioned that when designing acoustic antennas, other rectangular transducers in flexural vibration [3] can be used in place of bimorphs.

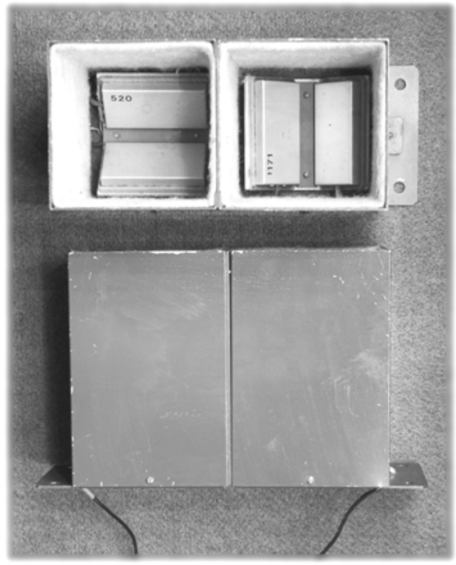

Fig. 8. **The actual image of unidirectional acoustic antenna**

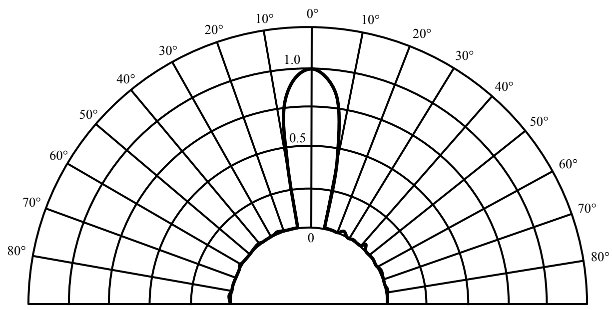

Fig. 9. **Radiation pattern of acoustic antenna (Fig. 8)**

For example, a composite transducer [3] with transformation of vibrations can be used (Fig. 10).

The antenna consists of a piezoelectric ceramic transducer, concentrator of longitudinal acoustic waves and a thin-walled rectangular elastic plate. In this case, vibrations with parallel nodal lines are excited in the thin-walled rectangular elastic plate [3]. The elastic plate operates in the same way as rectangular bimorphs mentioned above.

If the plate is bent with an angle α in the place of attachment, an unidirectional acoustic antenna is obtained [3] (Fig. 10).

Acoustic antenna (Fig. 10) is made using two rectangular elastic plates bent by the angle α:

$$\alpha = 2\arcsin(\lambda_a / \lambda_p)\,. \tag{13}$$

where λ_a is the length of acoustic wave in air; λ_p is the length of the flexural wave in the elastic plate.

In this case, two (out of 4) leafs of the directivity pattern are used to obtain a unidirectional antenna. The radiation of the antenna will be at maximum, when $\alpha = 90^\circ$, and the length of the flexural wave in a plate $\lambda_\delta \approx 1.4\,\lambda_a$.

An angular sensitivity of an electro-acoustic measurement device depends on the width of the directivity pattern of the transducer. The directivity pattern and the transmitted acoustic power of the transducer (acoustic antenna) are mutually dependant.

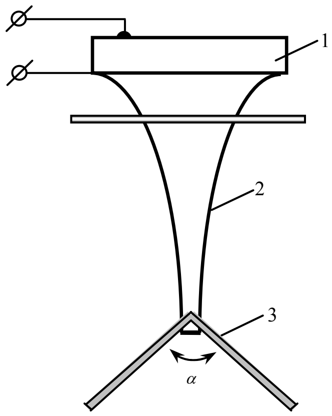

Fig. 10. **Cross section of composite transducer with transformation of vibrations: 1 – rectangular or circular piezoelectric transducer; 2 – concentrator of acoustic waves; 3 – thin-walled rectangular elastic plate bent with angle α**

In [19] is presented the dependence of the oscillating piston's aperture on the operating frequency in air environment, when the width of the directivity pattern is 1, 2, 4, 6, 10 and 20 degrees. It is possible to use these diagrams to calculate geometric parameters of transducers in a flexural vibration mode. These calculations are sufficiently accurate for a practical use.

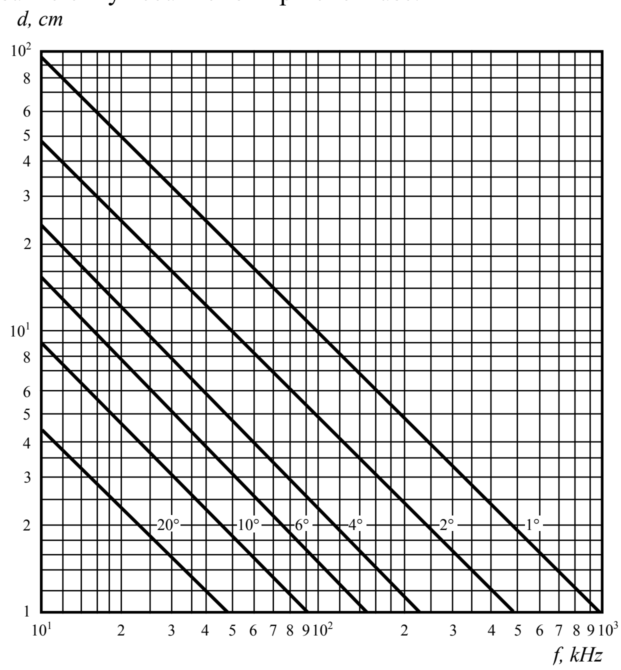

Fig. 11. **Diagram for calculating the aperture of the electro-acoustic transducer in air environment.**

Measurement algorithm for acoustic echolocation device operating in air

The distance $A = A_M$ to the surface of the object is calculated using expression [2]:

$$A_M = \frac{T_p v_U}{2} = \left(\frac{T_p}{2}\right)\left(331 + k_T \cdot t_1\right), \qquad (14)$$

where T_p is the double time of the acoustic (ultrasonic) signal's propagation from the antenna to the surface of the object; v_U is the velocity of ultrasound in the measurement environment; k_T is the coefficient of the dependency of ultrasound velocity on temperature; t_1 is the temperature of the environment at the level of antenna [°C].

The measurement device measures the distance A_M with some error, because there is a delay of the signal in the electric circuit and the measurement channel. The signal's propagation time T_M, measured by the device, is:

$$T_M = T_p + T_{cor}, \qquad (15)$$

where T_{cor} is the time interval for the delay of signal in the device's circuits.

To be able to determine T_{cor}, the distance $A = A_{test}$ needs to be measured with other precise measurement methods. Then, T_{cor} is determined using expression:

$$T_{cor} = \frac{2\left(A' - A_{test}\right)}{331 + k_t \cdot t_1}, \qquad (16)$$

where A' is the indicated distance to the surface of the object by the ultrasonic device (length of the unoccupied space from the antenna to the surface of the liquid).

The distance A is calculated using expression:

$$A = 0.50\left(T_M - T_{cor}\right)\left(331 + k_T \cdot t_1\right). \qquad (17)$$

In practice, when measuring the level of liquids in large reservoirs, there is a problem of non-uniform distribution of gas and liquid along the path of the signal's propagation. Because the ultrasound velocity is mostly dependant on the temperature t [17, 21-24], the temperature distribution along the signal's propagation path must be determined as precisely as possible.

For temperature t measurements in the reservoir, we propose to install ten or more temperature sensors along the vertical axis, as close as possible to the measurement area. The temperature sensors must constantly measure the temperature of gas and liquid. A schematic diagram of such measurement system is presented in Fig. 12.

The proposed acoustic level measurement system [67] consists of a processing unit *PU*, electronic module *EM*, acoustic antenna *AA* and temperature sensors TS_1 ... TS_N. To decrease the measurement inaccuracies in the proposed system, *EM* is mounted on the reservoir. *EM* collects data from the temperature sensors *TS* and measures the propagation time T_p. *EM* and *PU* are connected with a twin-axial cable, through which the control and information signals are transmitted. In this system, the measurement data are sufficiently reliable. The data rate is fast and overall cost is low. The measurement data is averaged in the *PU*, and data, which is outside of the acceptable range, are discarded.

The first temperature sensor TS_1 is installed on the level h above the reservoirs bottom. The acoustic antenna *AA* is also mounted on the same level. Other temperature sensors are installed below the first sensor TS_1 at a distance of $(n–1)\Delta h$, where n is the number of the temperature sensor, Δh is the distance between neighboring sensors. To determine the changes of the ultrasound velocity due to the variations in temperature of the environment along the measurement channel, the average temperature in the A range is calculated. This temperature is calculated if $TS_N \geq 2$.

Foremost, the unoccupied space A' is evaluated using only the temperature value from the top temperature sensor TS_1:

$$A' = 0.50\left(T_M - T_{cor}\right)\left(331 + t_1\right). \qquad (18)$$

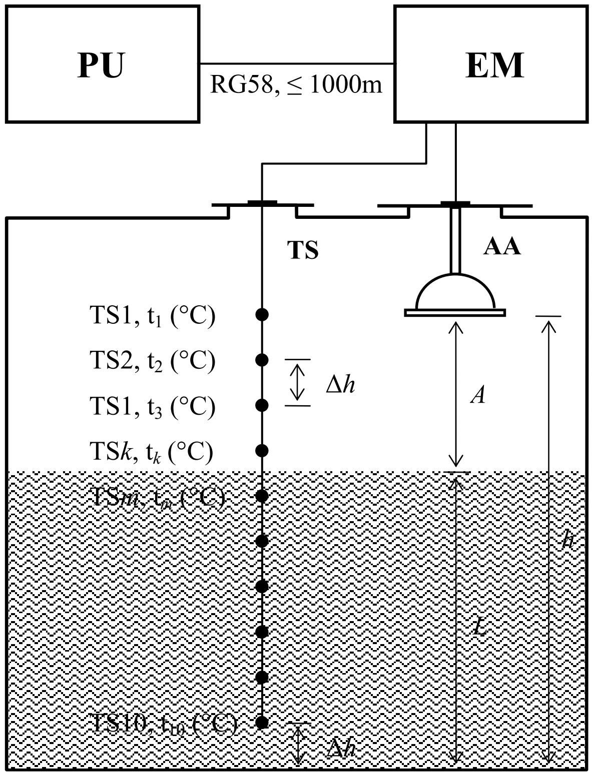

Fig. 12. **Schematic diagram of the ultrasonic level measurement system with environmental temperature evaluation: TS – array of temperature sensors; AA – unidirectional acoustic antenna**

The approximate level L' of the object is calculated:

$$L' = h - A', \tag{19}$$

where h is the distance between the reservoir bottom and the antenna AA (height at which the antenna AA is mounted).

The number of temperature sensors K above the measurement object (liquid) is determined:

$$K = \frac{L' + \Delta h}{\Delta h}. \tag{20}$$

The mean temperature t' of the unoccupied space A is calculated:

$$t' = \frac{t_K + 2t_{K-1} + \ldots + 2t_2 + t_1}{2K}. \tag{21}$$

The unoccupied space A'' in the reservoir is revised:

$$A'' = 0.50(T_M - T_{cor})(331 + k_T \cdot t'). \tag{22}$$

The revised level of the object is determined: $L'' = h - A''$.

The number M of temperature sensors TS is determined. This numbers consists of all temperature sensors above the liquid and one submerged sensor. The M-th temperature sensor is the first sensor, submerged in the object at the level L_M:

$$(L'' - \Delta h) < L_M \le L''. \tag{23}$$

The level L_M of the sensor TS_M is given by:

$$L_M = h - (M - 1)\Delta h. \tag{24}$$

The surface temperature of the object is selected as the temperature t_M of the M-th temperature sensor. The mean temperature t in the unoccupied space of the reservoir is calculated using expression:

$$t = \left[1 - \frac{\Delta h(M-2)}{h - L''}\right] \cdot \frac{t_M + t_{M-1}}{2} + \frac{(t_{M-1} + 2t_{M-2} + \ldots + 2t_2 + t_1)\Delta h}{2(h - L'')}. \tag{25}$$

Finally the length A of the unoccupied space is calculated using expression:

$$A = 0.50(T_M - T_{cor})(331 + k_T \cdot t). \tag{26}$$

For air, $k_T = 0.590$. However, when vapor from oil or from other materials is present in air, k_T can be slightly larger. Therefore there is an option in the *PU* to specify the function $k_T = f$ (t, °C). In practice, eight values are sufficient. Between the neighboring values a linear extrapolation is made.

Conclusions

Electro-acoustic transducers in flexural vibration are a good choice when designing acoustic measurement devices for operation in gaseous (air) environments. By using bimorph piezoelectric ceramic transducers in flexural vibration with elastic plates, it is possible to measure the broadest range of distances.

By arranging bimorph transducers at certain angles to one another, unidirectional radiation of energy by acoustic antennas is achieved. It is also possible to achieve unidirectional radiation by using reflectors of acoustic waves.

To decrease the peripheral radiation, electro-acoustic transducers in flexural vibration must have absorbers of acoustic waves with specific lengths and apertures.

When acoustic measurement devices operate in complex gaseous environments, measurement of the environmental temperature along the whole measurement channel is necessary to achieve accurate results.

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A. Petrauskas

Apie akustinės lokacijos kompleksinėje dujų aplinkoje ypatybes, kai naudojamos iš pjezoelektrinių keraminių lankstymosi virpesių keitiklių sudarytos akustinės antenos

Reziumė

Aptartos elektroakustinių keitiklių darbo oro aplinkoje ypatybės, atsižvelgta į keitiklių ir darbo aplinkos akustinių pilnutinių varžų skirtumus. Darbui oro aplinkoje geriausiai tinka elektroakustiniai keitikliai, sudaryti iš įvairių pjezoelektrinių polimerinių plėvelių, ir lankstymosi virpesių pjezoelektriniai keraminiai keitikliai. Išnagrinėti akustinių antenų, sudarytų iš lanksčiai virpančių stačiakampių pjezoelektrinių keraminių keitiklių, kryptingumo charakteristikų pagerinimo, siekiant išvengti matavimams trukdančio periferinio spinduliavimo-priėmimo, klausimai. Apžvelgtos labiausiai tinkančios matuoti ore pjezoelektrinių keraminių keitiklių konstrukcijos. Pateikta siūlymų dėl lanksčiai virpančių keitiklių naudojimo akustinėse antenose. Pasiūlyti akustinės lokacijos prietaisuose naudotinų akustinių antenų su vienlape kryptine charakteristika konstravimo principai, be to, pasiūlytas atstumo matavimo algoritmas, kai matuojama sudėtingoje kompleksinėje dujų aplinkoje.

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