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Evaluation of vibrations of acoustic spherical antenna by laser interferometer

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Introduction

The metrological properties of acoustic location devices are determined by the parameters of electronic circuits and parameters of acoustic channel. Electronic circuits are now well developed and all attention is paid to investigation of physical properties of acoustic measurement part in designing new acoustic location devices. Investigation of physical properties of sensors, work environment and transitional layers is very important.

One of principal parts of ultrasonic measurement devices is an electroacoustic transducer (antenna). It should have broad frequency band and should have narrow directivity pattern [1].

In measurements by echolocation method in complex engineering structures (in fuel tanks there are various supporting elements, holders, ladders etc) reliability of results (probability of errors) significantly depends on directivity pattern of electroacoustic transducers. The unidirectional and as narrow as possible directivity pattern of antenna is most suitable for distance measurements by ultrasound.

Improvement in energy output of measurement signals (increase of S/N ratio) is achievable by increase of efficiency coefficient. The vibration modes of flat and rod-like piezoelements can be analyzed theoretically [2]. However, when measurement is performed in air or in other gases the significant problems are the radiation of acoustic measurement signals only towards target and reception of echo signals by the same or other transducers. Working surfaces of electroacoustic transducers are made of rigid (metal) sheet as they operate in partially aggressive environment and therefore it is necessary to match acoustic impedances of transducers and work environment. Matching quality has great influence on the amplitude of radiated and received signals.

From many possible types of vibrations of antenna's surface the flexural waves (antisymmetric Lamb waves) are most widely used for measurements in air. These waves can be excited by piezoceramic transducers of flexural vibrations. Flexural transducers are characterized by sufficiently low acoustic impedance. However the main problem in designing acoustic antennas using such electroacoustic transducers is forming of unidirectional directivity diagram. This problem appears because the phases of flexural vibrations in the vicinity of different sides of vibration's nodal lines on the surface of piezoelectric transducer are opposite one to other. Therefore if flexural transducer is flat it reveals four-leaf (four directional) directivity pattern and inclination angle from a flat surface depends on the ratio of velocities of acoustic waves in the transducer and in air. For formation of a unidirectional radiation the phasing of radiated waves should be performed either by placing transducers in the space in specified angular position [3] or by making concave surface of the transducer. In the latter case the waves from different points of the surface can reach the far zone of an acoustic field in the same phase. These transducers are axis symmetrical, technology for production is easy and theoretical investigation is comparatively simple.

Description of vibrations

Flexural vibrations with distribution of node lines along parallels and meridians of the sphere are best for excitation of unidirectional radiation and reception of reflected acoustic waves by shell-like axis-symmetrical electroacoustic transducers. Different areas of spherical part of the transducer along parallels and meridians vibrate in opposite phases and therefore shell reveals "*m*" parallel and "*n*" meridian nodal lines [4].

An electroacoustic active element should not distort own resonant vibrations of the sphere. This is the main requirement in designing the optimal spherical resonant transducer. To fulfill this condition it is necessary to match resonant frequencies of a piezoceramic element and own frequencies of the spherical segment. More precisely we should reach coincidence of nodal lines. This can be made when velocities of acoustic waves are the same in the active element and in the spherical segment. This coordination is the best when the segment itself is the electroacustical active element. For example, it can be done from bimorph parts of which can be piezoceramical segments or combination of piezoceramic and elastic (passive segment) segments. We can design a number of acoustic antennas having one dominant leaf of directivity pattern by changing shape and dimensions of one of two segments.

In optimization of the acoustic antenna we are interested in vibrations, nodal lines of which are concentric rings with radii r_1, r_2, r_3, …. Distribution of vibrations amplitude on the round plate can be described by equation:

$$\xi(r) = AJ_0(kr) + BJ_0(ikr) \qquad (1)$$

where A and B are the constants evaluating boundary conditions, $J_0(kr)$ is the Bessel function of the first kind and the zero order.

In the case when the edge of a transducer is loaded against transversal displacements by the impedance Z (Fig.1), distribution of flexural vibrations on the bimorph element can be written:

$$\xi(r) = \frac{M_E}{G_{ef}} \left\{ \frac{i\left[G_{ef} \cdot J_3(ika) - \omega Z J_0(ika)\right]}{R} \cdot J_0(kr) + \frac{G_{ef} J_3(ka)}{R} J_0(ikr) \right\}, \qquad (2)$$

where

$$M_E = \frac{2}{\pi} e_{31} \cdot U \cdot r \left(\frac{h_1}{2} - h_0 \right) \tag{3}$$

is the bending momentum of a round bimorph element,

$$G_{ef} = G - \frac{k_{31}^2}{S_{11}^D} \left(\frac{h_1}{2} - h_0 \right)^2 h_1 r \cdot \frac{2}{\pi} \tag{4}$$

is the effective bending elasticity of a round bimorph element,

$$G = \frac{2}{3\pi} \cdot \frac{1}{S_{11}^D} h_1 \left(h_1^2 - 3h_1 h_0 + 3h_0^2 \right) + \\ + Eh_2 \left(h_2^2 + 3h_2 h_0 + 3h_0^2 \right) \tag{5}$$

is the bending elasticity of a passive plate,

$$R = J_2(ka) \left[iG_{ef} J_3(ika) - i\omega Z_0(ika) \right] - \\ - G_{ef} J_3(ka) J_2(ika), \tag{6}$$

U is the applied effective voltage, h_1,h_2 are thicknesses of elastic and piezoceramic plates, h_0 is average thickness of the transducer for bending vibrations, k_{31} is the electromechanical coupling coefficient of piezoceramic plate for longitudinal vibrations perpendicular to the vector of a electrical field, S_{11}^D is the mechanical flexibility of a piezoceramic plate in the case of a constant electric induction, e_{31} is the piezoelectric constant.

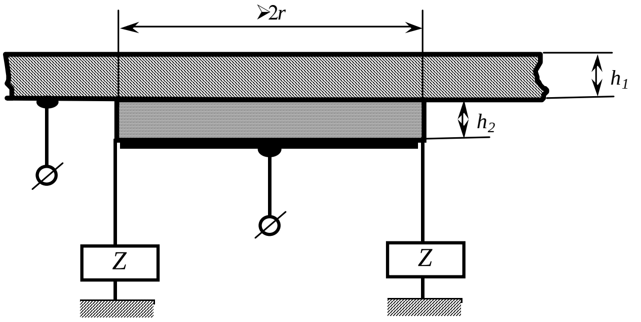

Fig.1 **Section of circular transducer attached to an elastic plate: h_1 is the thickness of the elastic plate, h_2 is the thickness of the piezotransducer, Z is load impedance against transversal displacement**

The surface displacement for the given radiator depends on the applied electric voltage in accordance with equation [5]:

$$\xi(\bar{r}) = \frac{e_{31} U h_2}{\omega \sqrt{G_{ef}(\rho_1 h_1 + \rho_2 h_2)}} \dot{K}(\bar{r}), \tag{7}$$

where $\dot{K}(\bar{r})$ is the complex quantity depending on the loading impedance Z value, $\bar{r}$ is the normalized radius.

Experimental optical measurements

The investigation of real flexural vibrations of an acoustic antenna was carried out by a laser interferometer. Efficiency of radiation of acoustic waves depends on amplitudes of vibrations in direction out of plane. An optical interferometer has the best sensitivity to normal displacements too. Therefore, this method of measurements is suitable for solution of the problem.

We used the home made laser interferometer for measurements of vibrations distribution along the radii of a parabolic antenna. The diagram of experimental setup is shown in Fig.2.

There were no problems with selection of vibrations amplitude. We were able to adjust the amplitude of mechanical vibrations by tuning the amplitude of the exciting electrical pulse. In conditions of real measurements it is known that the mechanical amplitude exceeds several optical wavelengths. We reduced the amplitude of electrical pulses to satisfy conditions of linear sensitivity in measurements.

We encountered problems in obtaining the sufficient intensity of the optical beam reflected from the acoustic antenna's surface. In this case a retroreflecting coating is used [6]. Such coatings were necessary in several cases in our investigations too. This additional mass did not influence flexibility of a surface, because there was no influence to the resilience and the additional mass density was about 1/20 part of initial mass density.

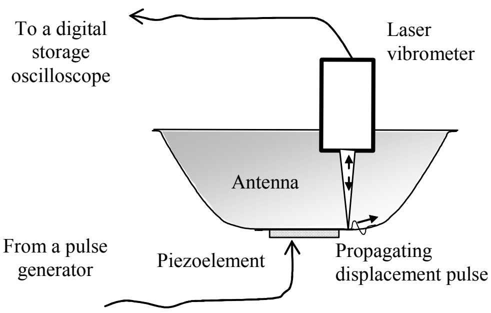

Fig.2. **Diagram of experimental setup for optical investigation of real vibration distribution on the surface of acoustic antenna**

We used the electrical pulse generator developed in our laboratory and had possibility to change not only the amplitude but also shape and duration of pulses. The digital storage oscilloscope PCS500 was used for acquisition of obtained signals.

Results of experimental measurements

One period electrical excitation signal was used for investigation of propagating displacement waves. One of purposes in optimization of acoustic distance meters is to obtain steep rise of acoustic pressure in the initial phase of sound pulse. Oscilloscope pictures in Fig 3 show the signals obtained in different places on the surface of the concave ultrasonic transducer. The upper curve shows shape of the electrical pulse and the lower curve is the electrical signal from the photodiode. The resonant frequency of this antenna was 17 kHz. The duration of one period pulse shown is 60 µs and p/p voltage is 7…10 V. The sweep of mechanical vibrations in the center of antenna's body is about 250nm. The important parameter in these investigations was the time delay of initial vibrations in surface points along the antenna's radius.

The time delay graphs of the first peak of displacement and the second peak of displacement at different points along the antenna's radius are shown in Fig.4. We can see that the time delay increases nonlinearly with distance from the antenna's center. This means changes of the velocity of shear waves along the radius of the antenna. These changes occur because of a complex shape of the surface.

It can be seen from the oscilloscope traces that in the center of the antenna the growth rate of the first peak is higher then at other points at some distances from the center. The reason of this difference may be in interaction of waves of different directions and types. The shape of the initial phase of the propagating transversal displacement pulse changes with the increasing distance from the antenna's center.

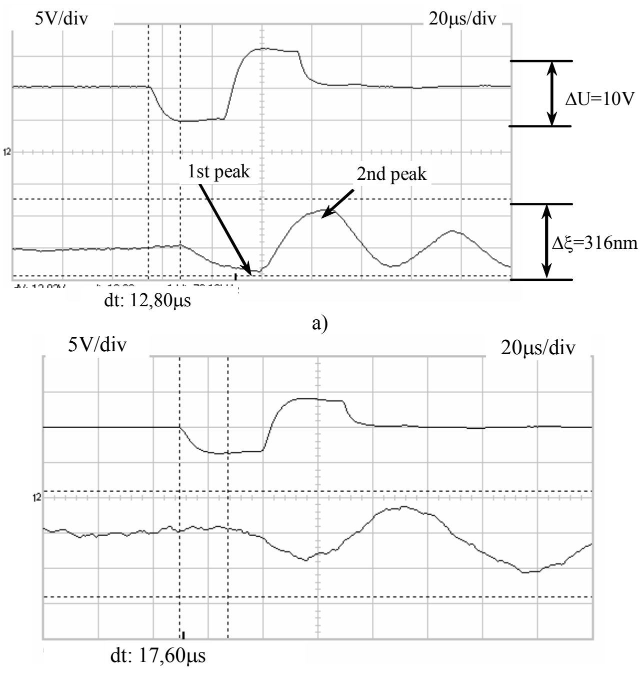

Fig.3. **Oscilloscope traces of initial phases of shear displacements propagation at different points of antenna's radius. The upper trace shows change of the excitation voltage and the lower one the signal from laser interferometer according to surface shift out of plane. Distance between two dashed horizontal lines means displacement of 316 nm: a) in the center of the antenna; b) at the point at distance 1/5 of the antenna's radius from the center**

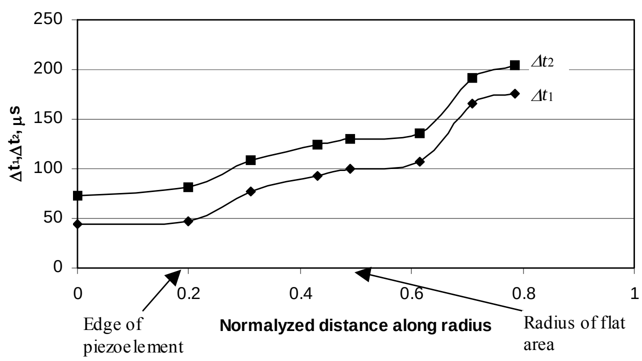

Fig.4.**Time delay of the first peak (Δt_1) and of the second peak (Δt_2) of shear displacement wave along the radius of the antenna's body**

Conclusions

Application of a laser interferometer enables us to measure by non-contact method the parameters of transients at different points of the antenna's body surface. The coordinate error of the measurement point depends on the dimensions of laser beam focus point.

Pulse distribution measured by the laser vibrometer allows evaluation of origin places of different types of waves and interaction between them.

Measurements by a laser reveal shape of mechanical out of plane vibrations during the initial phase and its dependence on the distance from a center. This result is very important in design of new piezoelectrical antennas for measurements in gaseous environment.

The resonant frequency of transducer's vibrations, quality of glue junction, coefficient of electromechanical coupling and overall quality of a piezoelectrical transducer can be checked by pulse measurements using the laser vibrometer.

The measurements of front distribution in the acoustic wave propagating to a target in air and the reflected wave can be planned after evaluation of reliability of information obtained by a laser.

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Akustinės sferinės antenos virpesių įvertinimas lazeriniu interferometru

Reziumė

Optimizuojant sferinių akustinių antenų išspinduliavimo parametrus esant impulsiniam režimui reikia įvertinti skersinių akustinių bangų sklidimą sferiniu paviršiumi. Ypač aktualu išmatuoti akustinės bangos sklidimo greitį ir jo kitimą sužadinančio elektrinio impulso fronto atžvilgiu. Šiam tikslui siūloma naudoti bekontaktį lazerinį interferometrą, pritaikytą kreivų paviršių skersinių virpesių tyrimams. Pateikiami eksperimentiniai sferinės antenos skersinių virpesių sklidimo matavimo rezultatai.

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