Sensitivity and directivity measurement of ultrasonic transducer with polymer-powder matching layer

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Abstract. The results of an experimental study of the sensitivity and directivity pattern of the ultrasonic transducers are presented. Data was obtained for transducers with central frequency at 2.5 and 5 MHz with protective matching layers, in comparison with transducers without matching layers. Increase of transducer sensitivity is shown. In addition, it is shown that the directivity patterns for transducers with the matching layer and without it are practically identical. Also was observed that the directivity pattern gets sharper as the frequency of the transducer increases.

1. Introduction
Ultrasound is the most popular method of non-destructive testing and diagnostics in various fields including medicine. In [1,2] it is shown results of new methods and apparatus development for non-destructive testing multiphase and biological objects.

Ultrasonic transducer is a critical component that used for the transformation of acoustic energy and electric energy in ultrasonic nondestructive detection system. Despite significant advances in the development of new materials that have piezoelectric properties in recent years, such as polymers with a piezoelectric effect [3], relaxor ferroelectrics PMN-PT, PZN-PT, etc. [4], the most common are piezoceramic materials based on lead zirconate titanate (PZT). The specific acoustic impedance of the PZT ceramics ranges from 22×10⁶ to 35×10⁶ Rayl. This is a limiting factor for immersion and medical sensors. The specific acoustic impedance of water and biological tissues about 1.5×10⁶ Rayl [5]. To improve the acoustic impedance matching of medium with piezoceramics matching layers (ML) are used. According to the theory of transmission lines, to ensure the transmission of 100% acoustical energy, the thickness of the matching layer should be equal to a quarter of the wavelength in the layer. The specific acoustic impedance of the matching layer ($Z_m$) is defined by the equation [6]:

$$Z_m = (Z_1 Z_2)^{1/2},$$

where $Z_1$ – the specific acoustic impedance of the piezoceramics, $Z_2$ – the specific acoustic impedance of the media.

For most tasks of ultrasound diagnostics and probing the frequency range 0.5-15 MHz is used. Ultrasonic vibrations in this frequency range provide sufficient resolution in the low-level vibration damping. In previous paper [7] it was shown that the thickness of the matching layer the piezoceramic at these frequencies is 10-300 um.
Various polymers are used as the material for the protective matching layer: polycarbonates, polyester films, polytetrafluoroethylene, acrylonitrile-butadiene-styrene, poly-para-xylylene, polypropylene, polystyrene, etc. In Russian medical devices, a copolymer of vinyl chloride and ethyl acrylate was widely used. Despite a large number of developed materials, there is currently no long-term matching protective coating capable of ensuring a long service life of the transducer.

In [8], a method for applying a matching layer of polymer powder coatings in an electrostatic field of corona discharge is proposed. Polyester, epoxy-polyester and polyurethane powder coatings are considered.

In this paper, we report the results of the sensitivity and directivity pattern studies of ultrasonic transducers with protective matching layers, in comparison with transducers without matching layers.

2. Methods

2.1. Sensitivity measurement

Sensitivity is an important parameter to describe the electro-acoustic transducer energy conversion efficiency, and is a key indicator of transducer performance [9].

Sensitivity is simply defined as the ratio of an output quantity to an input quantity. For an ultrasonic transducer characterized as a two-port network, there are the mechanical quantities of force and velocity ($F$, $v$) at the acoustic port and quantities of voltage and current ($V$, $I$) at the electrical port. Since an ultrasonic transducer can be used as either a transmitter or a receiver, there are a variety of sensitivities that can be defined from these quantities [10].

A complete theory of the ultrasonic waves propagation and the description of the transducers characteristics is described in detail in [9,11].

There are several common methods for measuring the ultrasonic transducer sensitivity. In 1940s was developed a first method of measuring electro-acoustic transducer sensitivity based on the reciprocity principle. In the process, a reciprocal transducer is used. In [12] it was proposed an improved reciprocal method. During the measurement, three transducers were arranged in a straight line along a calibrated support. The measured transducer is placed in the middle of the transmitter and the reciprocity transducer. In [13] it was proposed a pulse-echo technique. The transducer was excited by electrical pulses, and the ultrasonic waves were reflected by the reflector and received by the measured transducer. In another method a laser interferometer was used to measure the particle vibration displacement in the acoustic field [14]. Method of measuring the transducer sensitivity by using a calibrated hydrophone is described in [15]. In laboratory tanks, the pressure is usually measured with a calibrated hydrophone by reference to its sensitivity curve. The direct field of the sound source is obtained by time-gating the signal sent to the transducer so that the hydrophone receives the direct signal in the absence of reflections.

In this paper, the author used a simplified method of measuring sensitivity. Method based on reciprocity and pulse-echo methods. One transducer always used as receiving. Two another transducers were used sequentially as transmitters. The radiating sensitivities of these transducers were compared with each other.

The sensitivity in logarithmic units can be written as [16]:

$$S = 20 \log_{10} \left( \frac{V_{\text{out}}}{V_{\text{in}}} \right),$$

where $V_{\text{in}}$ – voltage applied to transmitting transducer, $V_{\text{out}}$ – amplitude of voltage recorded at receiving transducer.

2.2. Directivity pattern measurement

Beam directivity is the most fundamental aspect used in characterizing the transducer. Each ultrasound transducer has its own specific directivity pattern. The directivity pattern, also known as beam pattern
or radiation pattern, is an important far-field characteristic of a transducer. Directivity pattern consists of a main lobe and side lobes. Radiation intensity is dominant mainly in the front region of the transducer source, so the main lobe is directly in front of the ultrasound transmitter, followed by side lobes sidewise with null region in between these lobes. In general, the directivity patterns are the same whether the transducer is used as a transmitter or as a receiver [17].

The sound pressure of the plane rectangular transducer is no longer symmetrical, but elliptical in the far field. The mathematical expression for the normalized directivity pattern in far-field of the plane rectangular transducer is:

\[ I = \frac{S \sin(a_1k \sin \theta_1) \sin(a_2k \sin \theta_2)}{\lambda r a_1 \sin \theta_1 a_2 \sin \theta_2}, \]

where \( k \) – is the wave number, \( r \) – distance from the transmitting transducer, \( \lambda \) – wavelength, \( a_1, a_2 \) – length and width of the transducer, \( \theta_1 \) – beam divergence on length direction, \( \theta_2 \) – beam divergence on width direction.

Transmitter and the receiver should be separated by the minimum acceptable distance, called far-field distance, to minimize interference from reflections. The far-field distances were determined to be approximately beyond 20 cm and 40 cm for the 2.5 MHz and 5 MHz transducers, respectively. These distances were obtained using the following equation, which are the standard criteria for uniform rectangular transducer:

\[ X > \frac{\pi S}{\lambda}, \]

where \( X \) – the far-field distance, \( S \) – the square of the transducer, \( \lambda \) – the wavelength of the ultrasound waves in the medium.

The boundary of the field is conventionally considered to be the locus of points where the amplitude falls by a factor of 10 compared to its value on the axis, i.e., by 20 dB. The width of the directivity pattern in the far zone is in practice characterized by a 2-fold decrease in amplitude, i.e., by 6 dB.

3. Experimental setup

To measure the sensitivity and the directivity pattern, two sets of transducers were made. Central frequency of them 2.5 and 5 MHz. Each set consists of one transducer with the matching layer and two without the matching layer. The transducers are made of piezoceramics PZT-19 (the closest analogue of PZT-5A) (Aurora-ELMA, Volgograd, Russia).

Piezoelements with a central frequency of 2.5 MHz (±5%) are rectangular shape with geometric dimensions of 10×5×0.8 mm. Piezoelements with a central frequency of 5 MHz (±5%) are rectangular shape with geometric dimensions of 10×5×0.4 mm.

The specific acoustic impedance of such a piezoceramic is 22.4×10⁶ Rayl. To match with water or biological tissue, the specific acoustic impedance of the coating should be about 5.8×10⁶ Rayl [6]. The damper material is an epoxy resin with the addition of red lead and tungsten powder.

All sensitivity and directivity pattern measurements here were made at a temperature of 25 °C.

3.1. Emitter circuit

The electrical circuit are shown in figure 1 emits electrical pulses to excite the emitting transducer. Power to the circuit is supplied from the line power source AKIP-1137 (PriST, Russia).

Transducer X1 emit ultrasonic pulses with a filling frequency of 2.5 to 5 MHz. The operation of the circuit is based on the effect of avalanche breakdown of transistor Q1.

The capacitor C1 starts charging through the resistor R2 when the supply voltage is turned on 150 – 200 V. The time constant of the chain R2C1 determines the charge time of the capacitor C1. The transistor Q1 is closed at the initial moment. Voltage at the collector Q1 increases, approaching the
supply voltage. However, when the voltage on the collector reaches the avalanche breakdown value of the p-n junction, the resistance of the transistor between the collector and the emitter drops sharply and the capacitor $C_1$ is connected to the ground by the left terminal. The voltage at the capacitor $C_1$, equal to the breakdown voltage of the transistor (about 130 – 140 V), at this moment is applied to the transducer $X_1$ and resistor $R_3$. $X_1$ – is a resonant circuit with a center frequency of 2.5 or 5 MHz. $X_1$ emits a short pulse with a filling frequency equal to the resonance frequency.

After $C_1$ is quickly discharged through $X_1$ and $R_3$, the voltage on it falls and the transistor $Q_1$ closes. Further, $C_1$ is recharged through $R_2$ and the process is periodically repeated.

The simulation of the described emitter circuit was carried out. To take into account the process of avalanche breakdown of transistor, an equivalent circuit is developed (figure 2).

The KT312B transistor in the simulation circuit has been replaced by an analog.

The following results of the simulation were obtained. The shape of the signal on the equivalent resistor of the replacement circuit of the resonant emitter is shown in figure 3. Damped oscillations at the resonant frequency are seen.

### 3.2. Sensitivity measurement

The measurements were carried out in a tank with transformer oil. To measure the sensitivity, the reciprocity method (figure 4a) and pulse-echo method (figure 4b) were used. Other of the described methods can not be implemented because of the lack of a calibrated hydrophone and a laser vibrometer. Reciprocity method uses three sensors. One transducer is constantly used as a receiver. The transducer with matching layer and then the transducer without matching layer is alternately used.
as a transmitter. The transmitting and receiving transducer were placed opposite each other at a
distance of 20 to 100 cm. For emitting transducer, short electrical pulses with an amplitude of up to 70
V were applied. As the emitter the circuit is based on the effect of avalanche breakdown of a KT312B
series transistor was used.

To receive electrical signals the Agilent DSO 9104A digital oscilloscope was used (Agilent
Technologies, US).

The second method uses a reflector instead of a receiving transducer. The transmitting transducer is
also receiving a reflected signal. A metal plate with dimensions 20×20 cm was used as a reflector. The
distance from the transducer to the reflector also varied from 20 to 100 cm.

![Diagram of sensitivity measuring system: a) reciprocity method, b) pulse-echo method](image)

**Figure 4.** Sensitivity measuring system: a) reciprocity method, b) pulse-echo method

### 3.3. Directivity pattern measurement

In this work, the beam directivity was analyzed by assuming values of the sound pressure radiated
from transmitting transducer and redirected by receiving transducer.

Testing was done by mounting the receiving transducer in a motorized fixture driven by a step
motor. The scheme of the measuring system is shown in figure 5.

The pair of transducers with an identical resonance frequency were used in each measurement. One
transducer was used as a transmitter and the other as a receiver. Then transmitting transducer was
changed to another from the set. After the one set of transducers having the same resonance frequency,
the second set was placed in the measurement system.

![Diagram of directivity pattern measuring principal scheme](image)

**Figure 5.** Directivity pattern measuring principal scheme

Directivities were obtained from –45 degrees to 45 degrees by plotting the peak amplitude on the y-
axis. The alignment was based on the recording of the maximum amplitude of the received signal on
the oscilloscope. Next, the directivity pattern measurement was carried out with the fixed receiver. The transmitter was rotated using program based on Arduino from –45 to 45 degrees in 1 degrees increments (a total of 91 readings). For each angle, the peak-to-peak voltage of the received signal was recorded and the data were saved. The obtained data were normalized and then compared to the theoretical results using the directivity pattern model provided in equation 3. This procedure was repeated for two sets of transducers, having resonance frequencies of 2.5 MHz and 5.0 MHz.

4. Experimental results and discussion

The results of sensitivity measurements are shown below. Figure 6 and 7 shows the results for 2.5 MHz transducers without matching layer and with matching layer respectively. Signal amplitude for the transducer with the matching layer is about 1.8 V, while for the transducer with the matching layer is about 1.1 V.

![Figure 6. 2.5 MHz without matching layer](image)

![Figure 7. 2.5 MHz with matching layer](image)

Figure 8 and 9 shows the results for 5 MHz transducers without matching layer and with matching layer respectively. Signal amplitude for the transducer with the matching layer is about 3.5 V, while for the transducer with the matching layer is about 1.7 V.

![Figure 8. 5 MHz without matching layer](image)

![Figure 9. 5 MHz with matching layer](image)

The obtained results shows increasing of transducers with a matching layer sensitivity in 1.6 ... 2 times in comparison with transducers without matching layer. The next step will be an experimental comparison with transducers coated with lavsan and a two-component epoxy polymer EPOTEK 301.

Then directivity pattern measurements of transducers were made. Figure 10 shows the signal along the sensor axis, i.e. for $\theta = 0^\circ$. Figure 11 shows the signal for $\theta = 30^\circ$.
Figure 10. 2.5 MHz with matching layer θ = 0°

Figure 11. 2.5 MHz with matching layer θ = 30°

The assuming results of the directivity pattern are presented for transducers with matching layer and without matching layer in figures 12-13.

Figure 12. Directivity pattern of transducers with central frequency at 2.5 MHz

Figure 13. Directivity pattern of transducers with central frequency at 5 MHz

The results of the measurements show that the directivity patterns for transducers with a matching layer and without it are practically identical. This indicates that the proposed coating does not spoil the radiation pattern.

Figure 12 and 13 shows that the directivity pattern gets sharper as the frequency of the transducer increases. Half power beam width of 2.5 MHz transducer is about 12 degrees, 5 MHz transducer is about 8 degrees.

5. Conclusions

In conclusion, the sensitivity and directivity patterns were measured experimentally. The key aspect of this study was described by the directivity, which shows amplitude as a function of radiation angle at a specific radius. The analytical expressions for beam directivity were derived from the far field pressure distribution.

The results of the experiments showed increase of the transducers sensitivity by 1.5 ... 2 times in the case of using a polymer powder coating as a matching layer. It was also shown that using the matching layer does not change the radiation pattern of the transducers.
In addition, the results presented above confirmed that the beam pattern of ultrasound waves emitted from transducers of varying resonance frequencies is dependent on the frequency of the transducers. Also was observed that the directivity pattern gets sharper as the frequency of the transducer increases.

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