Highly directional ultrasonic emitters with reflectors and horns

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Abstract. The article presents the research of the efficiency of the modernized directional ultrasonic disk radiators equipped with reflectors, phase-aligning cones and horns. Using the experimental setup consisting of two directional ultrasonic radiators operating at a close resonant frequency, the data for constructing the radiation patterns, determining the acoustic power and calculating the linear attenuation were obtained. It was found that the reflectors allow to increase the sound pressure of the radiator array by 3.5 dB, providing the angle of the main lobe of the radiation pattern within ±7.5 degrees. The installation of phase-aligning cones not only cut off the oscillations in antiphase, but also increased the resulting sound pressure by 9 dB. It was noted that with the simultaneous operation of two directional ultrasonic radiators, a region of difference frequency beats with the angle of the main lobe of the radiation pattern of ±10 degrees and the maximum sound pressure of 97.6 dB is formed.

1 Introduction

The use of mechanical vibrations of sound and ultrasonic frequencies is a promising means of non-lethal impact on organisms and technical devices. Ultrasonic vibrations can be used as such radiation, which, due to the low propagation speed (about 340 m/sec), are characterized by a small wavelength (tens of millimeters) and can, almost like light waves, be focused, directed in specified directions, reflected from obstacles.

The relevance and prospects of such impacts are due to the peculiarities of the impact of vibrations on the performance of equipment and human behavior. The problem of creating such systems of impact on technical objects and living organisms, creating security alarm systems has not been solved to date. The reason is the lack of low-energy, compact and autonomous emitting devices capable of generating ultrasonic vibrations in the air with a sound pressure level of more than 150 dB at a frequency of at least 22 kHz and ensuring their narrow-focus propagation (having a directivity pattern of no more than 5 degrees).

It is necessary to take into account that the sound pressure level generated by a single ultrasonic emitter is usually insufficient for solving most practical problems, so there is a need to use an array of directional ultrasonic emitters [1-2].

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The simultaneous action of several emitters at close resonant frequencies allows for the effective use of difference frequency beats, which are characterized by high radiation directivity, broadband, and suppression of side lobes of the directional pattern. The beat effect is often used to compare the frequencies of two signal sources in order to adjust one source to the frequency of the other.

2 Materials and methods

For practical implementation of the proposed method, package piezoelectric transducers based on Langevin can be used, which allow obtaining significant oscillation amplitudes with high efficiency of electroacoustic conversion [3]. The use of ultrasonic oscillations with a high sound pressure level (more than 150 dB) ensures the highest possible efficiency (minimum energy costs) of settling smoke and dust particles. However, these oscillations must be transmitted into the air with the highest possible efficiency and narrow radiation directionality. And, since the air environment is characterized by low acoustic resistance, the transmission of oscillation energy from a unit of the emitter surface area is significantly limited. Therefore, it is advisable to use a disk as an emitter, which performs bending oscillations and has a developed surface for radiating oscillations into the air.

This form of oscillations provides the maximum possible output of ultrasonic oscillation energy, since the wave resistance of the bending-oscillating emitter is better matched with the wave resistance of the gas medium. Figure 1 schematically depicts the distribution of bending oscillations over the surface of a flat disk and the radiation of individual points of the disk surface into the air.

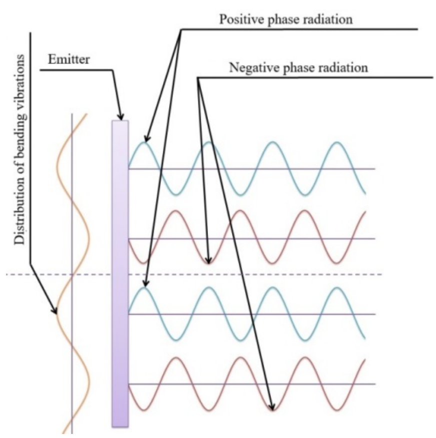

Fig. 1. Approximate distribution of bending vibrations over the surfacing of a flat disk and radiation of individual points of the surfacing disk into the air.

It is seen how different points of the disk surface emit oscillations in opposite phases. This leads to the fact that at some distance from the disk the acoustic radiation is mutually compensated and cannot provide the required ultrasonic effect on the processed objects. In practice, this leads to the impossibility of forming ultrasonic oscillations with a sound pressure level of more than 130 dB already at a distance of 1 m from the emitter.

To solve this problem, special devices are used - reflectors and phase-aligning cones. The reflector is two coaxially located truncated cones [4, 5]. Using the back side of the flexural-oscillating disk allows increasing the sound pressure and reducing the divergence of the generated ultrasonic radiation. To minimize the loss of the useful area of the emitter, it was proposed to use a special horn with phase-aligning cones [6-9]. As a result, an acoustic field of predominantly one phase is formed at the output of the device.

To measure the directivity pattern of directional ultrasonic emitters, a setup shown in Fig. 2 was assembled. The directional ultrasonic emitter (Fig. 2, pos. 1) was positioned vertically. The microphone (Fig. 2, pos. 4) of the noise meter (Fig. 2, pos. 6) was positioned on the acoustic axis of the ultrasonic emitter. The verticality and horizontality of the devices in the setup under consideration were controlled using a laser level. The ultrasonic emitter stand (Fig. 2, pos. 2) was rigidly fixed. The microphone stand (Fig. 2, pos. 5) could move, changing the angle of the microphone relative to the symmetry axis. The angle varied from 0° to 90°. In this case, a distance of 1000 mm was maintained between the radiating surface of the ultrasonic emitter and the microphone.

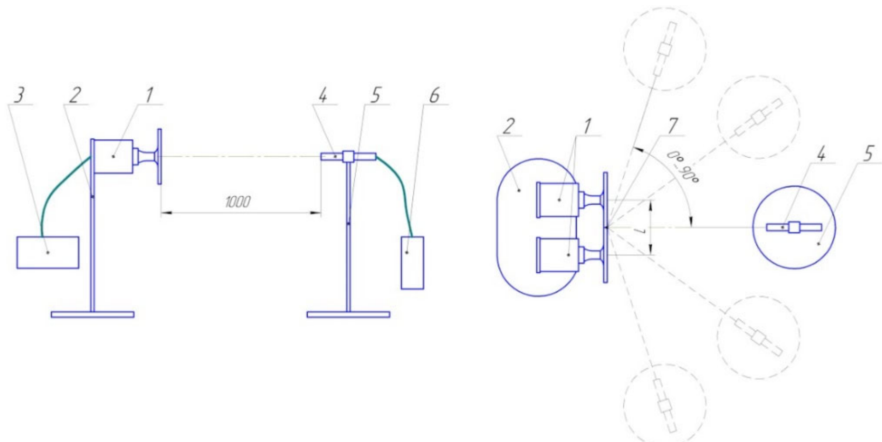

Fig. 2. Structural diagram of the stand for measuring the directional pattern of an ultrasonic emitter: 1 – ultrasonic acoustic system, 2 – emitter stand, 3 – electronic generator, 4 – microphone, 5 – microphone stand, 6 – noise meter measuring unit.

The electronic generator [10] supplied voltage with a frequency corresponding to the natural resonant frequency of each ultrasonic emitter. Sound pressure was measured using an Ecophysics-110A noise meter.

To measure the attenuation of sound pressure along the acoustic axis of the directional ultrasonic acoustic system, the setup described earlier and shown in Fig. 3 was assembled.

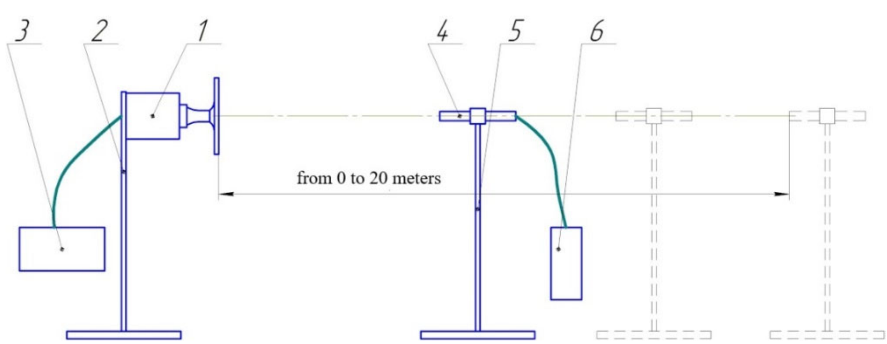

Fig. 3. Structural diagram of the stand for measuring the attenuation of sound pressure of an ultrasonic emitter: 1 - ultrasonic acoustic system, 2 - emitter stand, 3 - electronic generator, 4 - microphone, 5 - microphone stand, 6 - measuring unit of the noise meter.

The microphone stand (Fig. 3, pos. 5) could move along the acoustic axis. The position of the microphone on the acoustic axis was controlled using a laser level. The distance from the radiating surface of the directional ultrasonic emitter in the near field (up to 500 mm) was measured using a ruler, and in the far field (from 0.5 m to 20 mm) using a laser rangefinder.

The acoustic power of the directional ultrasonic emitter was determined as the difference between the total consumed electrical power of the emitter and the power of its own losses in the emitter (1). The power loss was determined by measuring the power consumed by the emitter when operating without a load. For this purpose, the emitter was placed in a vacuum chamber. Air was pumped out of the vacuum chamber to a residual pressure not exceeding 1000 Pa. The efficiency of the directional ultrasonic emitter was determined as the ratio of the acoustic power to the total consumed power of the emitter (2).

$$P_{ac} = P_{total} - P_{losses} \; , \tag{1}$$

where Pac – acoustic power of the ultrasonic emitter; Ptotal – total consumed electrical power of the emitter; Plosses – power of the emitter’s own losses.

$$\eta = \frac{P_{ac}}{P_{total}} 100\% \; , \tag{2}$$

where η – efficiency of ultrasonic emitter.

The measurement of the electrical power consumed by the emitter was carried out using the MT-1010 meter.

3 Results and discussion

To conduct the research, two directional ultrasonic emitters with flexural-oscillating disks with close resonant frequencies were developed and manufactured. Then, comparative measurements of the directional patterns were carried out between a separate disk emitter and an array of two ultrasonic emitters with natural resonant frequencies of 22634 and 22934 Hz, respectively. Figure 4 shows the external appearance of the stand.

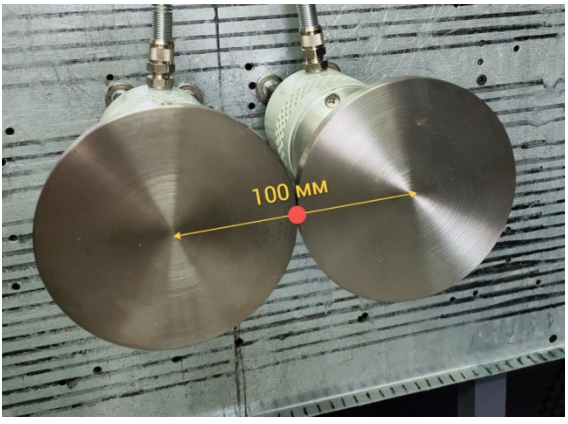

Fig. 4. A stand of two ultrasonic emitters.

The created stand was used to measure the directivity diagram of the acoustic field created by two identical directional ultrasonic emitters operating simultaneously at different frequencies. During the measurements, the microphone was located at a distance of one meter from the point shown in Fig. 4.

Similar measurements were also carried out for comparison, but using one emitter with a frequency of 22634 Hz. Figure 5 shows comparative directivity diagrams of one directional ultrasonic emitter (blue curve) and two simultaneously operating emitters (orange curve).

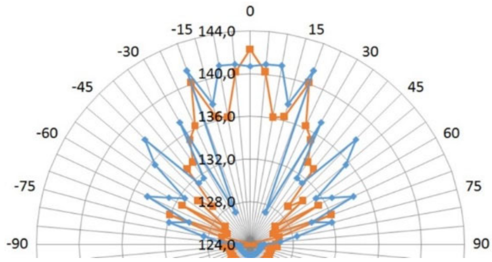

Fig. 5. Comparative radiation patterns of one ultrasonic emitter (blue curve) and two emitters (orange curve).

As can be seen from the diagram, when using two simultaneously operating directional ultrasonic emitters, the radiation angle decreased to ±10 degrees, compared to a single emitter (±20 degrees). At the same time, the sound pressure level increased by 1.9-2.2 dB and reached 142.0-142.3 dB. Also, the diagram clearly shows two peaks at measurement angles of ±20 degrees, which corresponds to 140.1 dB for each ultrasonic emitter. Further studies should show the effect of reflectors.

The appearance of the stand of two directional ultrasonic emitters with reflectors is shown in Fig. 6.

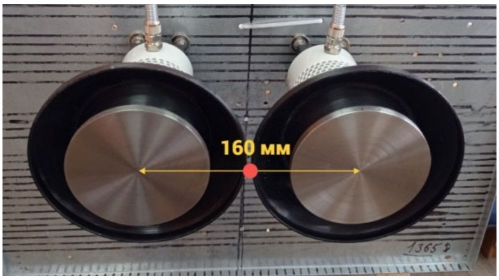

Fig. 6. Two ultrasonic emitters with reflectors.

Figure 7 shows comparative results of measurements of one directional ultrasonic emitter and a system of two emitters using reflectors.

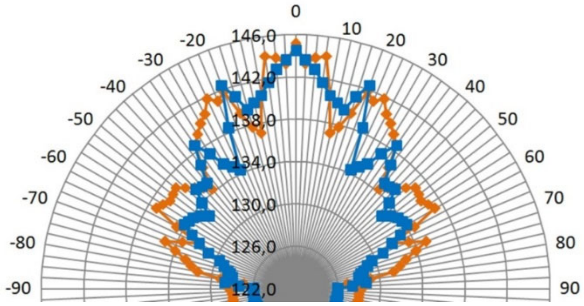

Fig. 7. Comparative radiation patterns of one ultrasonic emitter (blue curve) and two emitters (orange curve) using reflectors.

Analysis of the operation of the system of two emitters (orange curve) shows that the diagram shows two peaks at angles of ±7.5 degrees, which corresponds to 144.0 dB for each directional ultrasonic emitter. The total sound pressure from two ultrasonic emitters increased to 145.1-145.5 dB, i.e. by 3.1-3.5 dB compared to the version of the stand without reflectors.

A single directional ultrasonic emitter showed lower values - the angle of the main lobe was ±10 degrees, and the sound pressure at a distance of 1 m reached 144.5 dB.

Thus, the use of the reverse side of the bending-oscillating emitter made it possible to increase the sound pressure and reduce the divergence of the generated ultrasonic radiation. Further studies were conducted to study the effect of radiation from different sections of the disk emitter, oscillating with different phases and using a reflective screen.

The use of special devices – screens, which allow minimizing the impact of acoustic oscillations in opposite phases (Fig. 8), together with a reflector also allows increasing the sound pressure created by the directional ultrasonic emitter. Zone 1 of the disk emitter oscillates in one phase, and zone 2 – in the opposite phase.

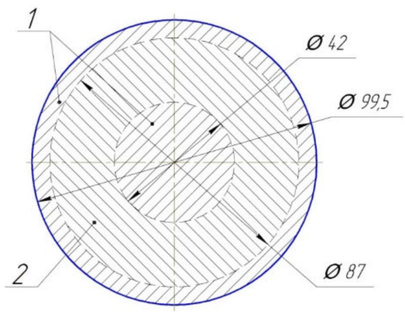

Fig. 8. Radiation zones of a flexural-oscillating disk.

Since it is most effective to close zone 2, studies were conducted using these types of screens (Fig. 9).

Fig. 9. Two ultrasonic emitters with reflectors and screens.

Figure 10 shows comparative directional diagrams of one ultrasonic emitter with a reflector and a screen (blue curve) and two simultaneously operating emitters with reflectors and screens (orange curve).

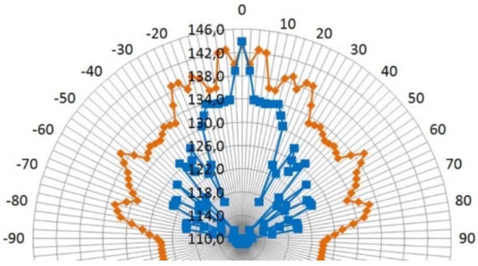

Fig. 10. Comparative radiation patterns of one directional ultrasonic emitter (blue curve) and two emitters (orange curve) using reflectors and screens.

For the case of two simultaneously operating emitters, the diagram shows two peaks at angles of ±5 degrees, which corresponds to 142.6 dB for each directional ultrasonic emitter. The total sound pressure decreased to 143.0-143.4 dB. If we consider the measurements for one ultrasonic emitter, it is noticeable that the sound pressure level remained at the same level and amounted to 144.5 dB, while the radiation angle of the directional diagram decreased to ±5 degrees.

The obtained results indicate that the use of screens that close the zones of acoustic oscillations that occur in antiphase is inappropriate. It is necessary to fully utilize the radiation formed in zones with opposite oscillation phases.

The use of special devices – horns, allowing to create acoustic vibrations in one phase from vibrating surfaces in different phases, together with a reflector allows to increase the sound pressure created by a disk emitter. A photo of a stand with two simultaneously operating directional ultrasonic emitters is shown in Fig. 11.

Fig. 11. Two directional ultrasonic emitters with reflectors and horns.

Figure 12 shows comparative directional diagrams of one directional ultrasonic emitter with a reflector and a horn (blue curve) and two simultaneously operating emitters with reflectors and horns (orange curve).

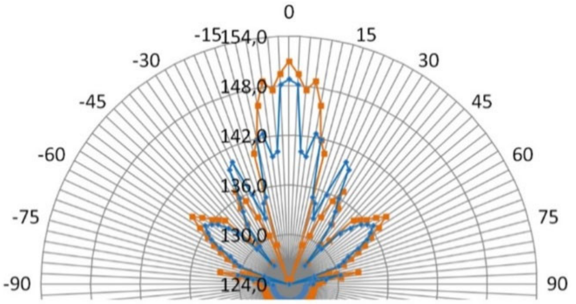

Fig. 12. Comparative radiation patterns of one directional ultrasonic emitter (blue curve) and two emitters (orange curve) using reflectors and horns.

As can be seen from Fig. 12, the angle of the main lobe of the directional pattern of two simultaneously operating radiators is ±5 degrees. The total sound pressure on the main lobe of the directional pattern when using reflectors and horns increased to 150.5-151 dB. On both sides of the main lobe of the directional pattern there are secondary peaks at angles of ±7.5 degrees, the sound pressure level at which corresponds to 149 dB. The secondary peaks can be eliminated using an additional horn device common to both radiators.

The sound pressure of a single emitter was lower and did not reach 150 dB, while the directivity angle of the main lobe was ±4 degrees.

Next, the acoustic power and efficiency of the system of two emitters (3), (4) were calculated:

$$P_{\text{ак}} = 155 - 95 = 60\,Wt\ , \tag{3}$$

$$\eta = \frac{60}{155}\,100\% = 39\ \% \tag{4}$$

When several directional ultrasonic emitters act simultaneously on the air environment, the directional patterns intersect and a zone of beats is formed at a low frequency of acoustic vibrations. Figure 13 shows a structural diagram of the formation of a beat zone for a system of two emitters.

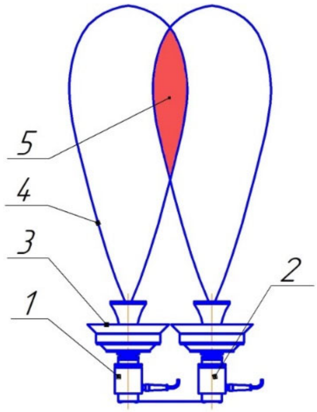

Fig. 13. Formation of the beat occurrence zone for two emitters: 1, 2 – ultrasonic emitters, 3 – system of phase-equalizing horns and reflectors, 4 – area of ultrasonic vibration formation, 5 – interaction zone of ultrasonic vibrations.

To form a zone with a difference frequency, two directional ultrasonic emitters with reflectors and horns and an interaxial distance of 210 mm were used. The resonant frequency of the first emitter is 22634 Hz, the second - 22934 Hz. As a result, a beat region with a frequency of 300 Hz was formed. Figure 14 shows the directional diagram of the difference frequency.

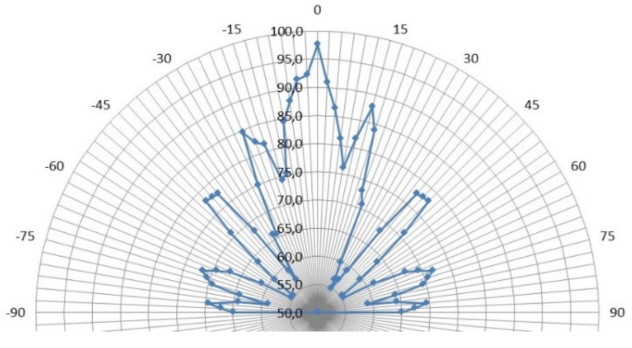

Fig. 14. Directional pattern of difference frequency.

The angle of the main lobe of the directional pattern was ±10 degrees, while the sound pressure on the main lobe of the directional pattern reached 97.6 dB.

The results of measuring the linear attenuation of a system of two directional ultrasonic emitters with reflectors and horns are shown in Fig. 15.

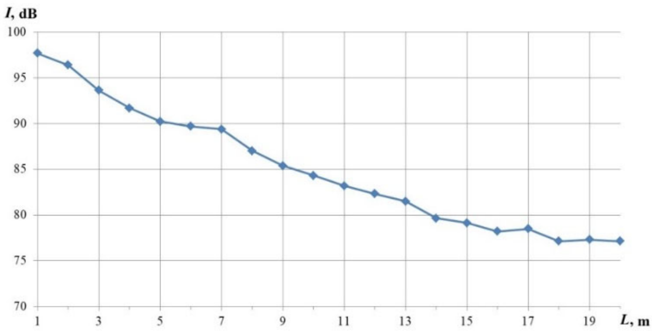

Fig. 15. Attenuation of sound pressure of a system of two ultrasonic emitters.

At a distance of 1 m from the radiating surface of the directional ultrasonic emitters, the sound pressure intensity was 97.6 dB, at a distance of 20 meters – 77.1 dB.

4 Conclusion

As a result of the conducted research, directional ultrasonic disk emitters were developed, consisting of a piezoelectric modernized transducer, made according to the Langevin design scheme and a bending-oscillating emitter, equipped with reflectors, phase-aligning cones and horns. An experimental stand was created, consisting of two simultaneously operating ultrasonic disk emitters and a sound pressure meter.

The conducted experimental studies made it possible to show the prospects of using two emitters operating at close frequencies. It was shown that the use of reflectors allows for the efficient use of the vibration energy of the back side of the bending-oscillating disk. The total sound pressure of two directional ultrasonic emitters increased by 3.1-3.5 dB. The angle of the main lobe of the directivity pattern was ±7.5 degrees. The use of phase-aligning cones ensured the formation of acoustic vibrations in one phase from oscillating surfaces in different phases. Together with the reflectors, the phase-aligning cones provided an increase in the sound pressure created by two disk emitters by 8.5-9 dB compared to the radiation of disks without cones.

It was shown that with the simultaneous action of two directional ultrasonic emitters on the air environment, a zone of occurrence of beats at a low frequency of acoustic vibrations (300 Hz) is formed, while the sound pressure reaches 97.6 dB at a distance of 1 m and 77.1 dB at a distance of 20 m.

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References

1. C.M. Harris, The Journal of the Acoustical Society of America **40**, 148-159 (1966).
2. A.P. Efimov, A.V. Nikonov, M.A. Sapozhkov, V.I. Shorov, *Acoustics* (Moscow: Radio and Communications, 1989).
3. J.M. Goodson, *Ultrasonic transducer with sleeve,* Pat. US, No 6924585 (2004).
4. G. Phanomchoeng, R. Rajamani, J. Hourdos, IEEE Transactions on Vehicular Technology **59(5)**, 2266-2276 (2010).
5. M. Toda, Ultrasonic transducer assembly having a vibrating member and at least one reflector, Pat. US, No 20080007142 (2008).

6. V.V. Furduev, *Electroacoustics* (Moscow; Leningrad: Gostekhizdat, 1948).
7. G.I. Sokol, O.V. Alkhimov, T.S. Molnar, E.O. Zagrevskyi, Journal of Nano- and Electronic Physics **15(5)**, 05026(6pp) (2023).
8. P. Rai, R. Patel, NanoWorld Journal **9**, 144-147 (2023).
9. M. Douglas, Y. Feng, Acoustical Society of America **118(6)**, 3457-3464 (2005).
10. V.N. Khmelev, R.V. Barsukov, D.V. Genne, D.S. Abramenko, A.R. Barsukov, *Ultrasound. Principles of construction, algorithms and control systems of ultrasonic devices* (Biysk, 2021).