www.czasopisma.pan.pl www.journals.pan.pl

ARCHIVES OF ACOUSTICS
Vol. 45, No. 4, pp. 747–752 (2020)
DOI: 10.24425/aoa.2020.135280

Technical Note

High-Directional Sound Propagation Over the Earth's Surface

Denis S. RAKOV[(1),(2)*], Aleksandr S. RAKOV[(1),(2)], Yury A. CHURSIN[(3)]
Vsevolod V. PAVLICHEV[(3)], Artyom O. IGUMNOV[(3)]

[(1)] *Institute of Monitoring of Climatic and Ecological Systems SB RAS*
Tomsk, Russia

[(2)] *Tomsk State University of Control Systems and Radioelectronics*
Tomsk, Russia

[(3)] *National Research Tomsk Polytechnic University*
Tomsk, Russia
*Corresponding Author e-mail: rds@tpu.ru

(*received June 19, 2020; accepted January 24, 2020*)

The article discusses the issues of accounting the direction pattern of parametric antenna array the propagation of sound over the Earth's surface. As a radiator, a parametric antenna array is used. A description is given of measuring equipment and experimental research methods. The Delaney-Bezley model was used as a model of the Earth's surface impedance. The research results showed the importance of accounting the direction pattern of parametric antenna array in predicting the sound pressure level of a propagating acoustic signal over the Earth's surface. On the example of a difference signal with a frequency of 2 kHz, the calculation of the sound pressure level on a 100-meter path with the influence of the Earth's surface is shown. The results obtained showed a good agreement between the theoretical calculation and experimental data.

Keywords: parametric loudspeaker; ultrasound; primary frequency; difference frequency; radiation pattern; outdoor propagation of sound; sound attenuation.

1. Introduction

In recent years, many actions have been undertaken worldwide to develop highly directional acoustic transducers or air parametric acoustic array loudspeakers. They are used in museums, exhibition halls, advertising boards, safety systems and also for measuring the environmental parameters, especially in the field of hydroacoustics (Shi *et al.*, 2010; Reis, 2016). Separately, it is worth noting the use of air parametric antennas as the main antennas for acoustic sensing of the atmospheric boundary layer (Adachi *et al.*, 2019; Muir *et al.*, 1979). Also, parametric antenna can be used when transmitting voice data one hundred meters or more.

The development of parametric loudspeakers is based on the works of Westervelt (1963), who studied the non-linear interaction between two finite-amplitude acoustic waves with closely spaced frequencies. Westervelt showed that such an interaction enables the propagation of acoustic wave with difference frequency. In his calculations, Berktay (1965) used the amplitude modulated signal as a reference signal. The first theoretical and practical investigations of parametric loudspeakers were conducted for underwater acoustic systems, since the achievement of the parametric effect in air had been deemed to be problematic. In (Bennett, Blackstock, 1975) was found however a possibility to create the parametric effect in air. The practical implementation of parametric loudspeakers was connected, first of all, with the names of Japanese researchers. Thus, Yoneyama *et al.* (1983) proposed the parametric aerial assembled from piezoceramic electro-acoustical transducers.

Russian scientists engaged in the investigation of the non-linear propagation of acoustic waves are Zabolotskaya, Khokhlov, Zverev, Rudenko (Zabolotskaya *et al.*, 1966; Zverev *et al.*, 1970; Rudenko, 1974) and others.

In works (Aoki *et al.*, 1991; Kamakura *et al.*, 1994; Gan *et al.*, 2011; Bouллosa *et al.*, 2016), the authors presented the implementation and research results of parametric aerials, measurements of their radiation patterns and the level of the sound pressure on the primary and difference frequencies, depending on the distance to the transducer.

Ju and Kim (2010) identified the importance of studying the parameters of parametric loudspeakers within the near-field wave radiation, where listeners are usually located. This statement is based on the fact that most of parametric loudspeakers are used in closed space, for example, apartments, studios, libraries.

At the same time, the development of the acoustic information transfer at a distance of tens or hundreds of meters is important for the creation of such systems as alerting, sound broadcasting, emergency warning and requires the calculation taking into account the influence of the Earth's surface.

It is known that the propagation of sound in the surface layer of the atmosphere is influenced by such parameters as the characteristics of the propagation path, wind speed and direction, meteorological conditions, the level of background environing noise.

An interest in studying attenuation of sound waves propagating near the Earth's surface arose at the turn of the 60–70s of the XX century. The main successes were made by American and Japanese reserchers (Attenborough, 2007; Albert, 2003; Miki, 1990; Piercy *et al.*, 1977; Li, 1994).

Additional attenuation of sound to date is well studied in the literature. To determine the attenuation of sound due to the Earth's surface, with the known geometry of the propagation of sound from the source to the receiver, knowledge of the impedance properties of the underlying surface is necessary. Which, in turn, depend on the frequency of sound and the type of surface (snow, sand, asphalt, loose soil, etc.).

When propagating sound waves with a frequency above 1000 Hz, it is necessary to take into account the molecular attenuation of sound in air and attenuation due to its viscosity (classical).

In addition to these factors, in order to predict the sound pressure level at the sounding point, it is necessary to take into account the direction pattern of the emitter itself.

In this paper, we present the results of experimental path measurements of sound pressure from a highly directional emitter.

This paper proposes the parametric loudspeaker consisting of the parametric antenna array made up of 110 elements, a control unit and power amplifier, which is a further step in the research described in (Rakov *et al.*, 2019). The aim of this paper is to develop a highly directional acoustic transducer capable of operating at a distance of up to 100 meters. An example of a 2 kHz differential frequency signal shows the calculation of the sound pressure level on a 100-meter path. This calculation includes information on sound attenuation due to the Earth's surface. Based on this development, we plan to create the similar underwater acoustic transducer.

2. Theoretical

2.1. Theory of parametric antenna arrays

During the operation of a parametric loudspeaker, the low-frequency audio signal forms due to the nonlinear interaction between the primary acoustic waves and the propagation medium. A parametric loudspeaker is usually an antenna array driven by ultrasonic waves with closely spaced primary frequencies. Therefore, the primary frequency difference matches the low-frequency acoustic signal. Another method for producing the difference frequency is based on the fact that the parametric antenna array induces the modulated signal the carried frequency of which is primary, whereas the signal envelope is the required low-frequency signal. Since the low-frequency signal component forms within the interaction zone of high-frequency components, the direction of the difference frequency signal is very narrow.

Depending on the interaction zone of the primary acoustic waves, the wave radiation of the difference frequency occurs in different ways. Thus, when the nonlinear interaction occurs in the near-field of the primary wave radiation, the area of demodulation is determined by the length of intensity absorption

$$l_n = \frac{1}{2\alpha}, \tag{1}$$

where α is the sound attenuation coefficient on the primary frequency due to the atmospheric sound absorption [1/m].

In this case, the wave amplitude of the difference frequency in the far-field region is expressed by (Westervelt, 1963)

$$P_d = \frac{\left(\beta P_0^2 a^2\right)}{16\rho_0 c_0^4 \alpha r}\frac{\partial^2 E(t)^2}{\partial t^2}, \tag{2}$$

where β is the nonlinearity factor of air; a is the effective radius of the sound source; P_0 is the sound pressure at the primary frequency; ρ_0 is the air density; c_0 is the speed of sound in air; $E(t)$ is the envelope of the high-frequency signal; r is the distance between the sound source and receiver.

When the signal envelope $E(t)$ is a modulation function with Ω frequency, the difference frequency signal can be written as

$$P_d(r,\theta) = \frac{\left(\beta P_0^2 a^2 \Omega^2 m\right)}{8\rho_0 c_0^4 \alpha r} D(\theta), \tag{3}$$

where $D(\theta) = \left[1 + k_\Omega^2 \alpha^{-2} \sin^4\left(\frac{\theta}{2}\right)\right]^{-1/2}$ is the radiation pattern of the difference frequency signal; k_Ω is the wavenumber of the difference frequency signal.

2.2. Sound propagation over the Earth's surface

The information given in the previous section describes the calculation of the sound pressure from the source in free space.

In the propagation of sound in the real atmosphere above the ground we need to take into account attenuation due to the influence of the Earth's surface, as well as the atmospheric absorption of sound.

The total sound pressure level at the reception point can be written as

$$p = p_d + R_p \cdot p_r, \tag{4}$$

where p_d is sound pressure of the directly transmitted wave, p_r is sound pressure of the specularly reflected wave, R_p is the coefficient of reflection of sound from the Earth's surface. For monochromatic radiation the phase difference between the directly transmitted and reflected waves is

$$\Delta\varphi = k \cdot (r_d - r_r) + \varphi, \tag{5}$$

where $k = 2\pi/\lambda$ is wave number, φ takes into account the change in the phase of the wave that occurs upon its reflection from the Earth's surface, r_d and r_r are the distances from the source to the receiver and from the imaginary source to the receiver (Fig. 1).

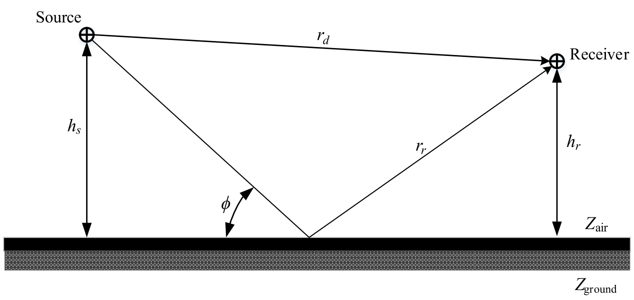

Fig. 1. The geometry of the propagation of sound above the Earth's surface.

The reflection coefficient is written in the form: r_r

$$R_p(\varphi) = \frac{\sin\phi - \frac{Z_{\text{air}}}{Z_{\text{ground}}}}{\sin\phi + \frac{Z_{\text{air}}}{Z_{\text{ground}}}}, \tag{6}$$

where ϕ is the angle of reflection of the wave from the surface.

For a spherical sound wave, both the directly transmitted wave and the reflected wave will experience additional sound attenuation. The magnitude of this attenuation can be expressed in terms of the field at the reception point, in analogy with the theory of electromagnetic waves, which is written in the form (Attenborough, 2007; Albert, 2003):

$$\frac{p}{p_0} = \frac{1}{r_d} \cdot e^{-i \cdot k \cdot r_d} + \frac{R_p}{r_r} \cdot e^{-i \cdot k \cdot r_r} + (1 - R_p) \cdot \frac{F(w)}{r_r} \cdot e^{-i \cdot k \cdot r_r}, \tag{7}$$

where p is the sound pressure at the reception point, p_0 is the sound pressure measured at a distance of 1 m from the source, r_d and r_r are the distances from the source to the receiver and from the imaginary source to the receiver, $F(w)$ is the coefficient of surface losses.

The coefficient of surface losses, which describes the interaction of the spherical wave front of the incident wave with the flat underlying surface, is written in the form (Piercy *et al.*, 1977)

$$F(w) = 1 + 2 \cdot i \cdot (\pi \cdot w)^{1/2} \cdot e^{-w} \cdot \int_{-i \cdot w^{1/2}}^{\infty} e^{-u^2} \, du, \tag{8}$$

where w is the numerical distance:

$$w^2 = \frac{2 \cdot i \cdot k \cdot r_r}{(1 - R_p)^2 \cdot \cos^2\phi} \cdot \frac{\left(\sin\phi + \frac{Z_{\text{air}}}{Z_{\text{ground}}}\right)^2}{\left(1 + \sin\phi \cdot \frac{Z_{\text{air}}}{Z_{\text{ground}}}\right)}. \tag{9}$$

For short path lengths and large values of the impedance of the Earth's surface ($|w| < 1$) expression (8) has the form:

$$F(w) = 1 + i \cdot \sqrt{\pi} \cdot w \cdot e^{-w^2}. \tag{10}$$

For long path lengths and small values of the surface impedance ($|w| > 1$):

$$F(w) = 2 \cdot i \cdot \sqrt{\pi} \cdot w \cdot e^{-w^2} \cdot H[-\text{Im}(w)] - \frac{1}{2 \cdot w^2}, \tag{11}$$

where $H[x]$ is the Heaviside step function, $\text{Im}(w)$ is the imaginary part of the numerical distance w.

The sound attenuation due to the influence of the Earth's surface:

$$\alpha_{\text{ground}} = 20 \cdot \log\left|1 + \frac{r_d}{r_r} \cdot Q \cdot e^{i \cdot k \cdot (r_r - r_d)}\right| \ \text{[dB]}, \tag{12}$$

where $Q = R_p + (1 - R_p) \cdot F(w)$.

Since this model was calculated for the case of an omnidirectional sound source, we made allowance for the influence of the radiation pattern of the parametric emitter to calculate the sound pressure level of the reflected wave. As a result, the formula for calculating the value of sound attenuation was written as follows:

$$\alpha_{\text{ground}} = 20 \cdot \log\left|1 + D(\theta_{\text{mirror}}) \cdot \frac{r_d}{r_r} \cdot Q \cdot e^{i \cdot k \cdot (r_r - r_d)}\right| \ \text{[dB]}, \tag{13}$$

where $D(\theta_{\text{mirror}})$ is normalized value of the radiation pattern of the emitter for the angle of reflection of the specularly reflected wave.

As a model of the Earth surface impedance model Delaney-Besley was used (Attenborough, 2007; Miki, 1990; Krasnenko *et al.*, 2014; Delany *et al.*, 1970):

$$Z_c = \rho_0 \cdot c_0 \cdot \left(1 + 0.0571 \cdot \left(\frac{\rho_0 \cdot f}{\sigma}\right)^{-0.754} - i \cdot 0.087 \cdot \left(\frac{\rho_0 \cdot f}{\sigma}\right)^{-0.732}\right), \tag{14}$$

where ρ_0 is the air density [kg/m^3], f is sound frequency, c_0 is the speed of sound in air [m/s], and σ is the static air flow resistivity [N $\cdot$ s/m^4].

The sound pressure level for difference frequency at the receiving point was calculated by:

$$P_r = P_d(r,\theta) + \alpha_{\text{ground}} - \alpha_{\text{atm}}, \tag{15}$$

where $P_d(r)$ is sound pressure level of the difference frequency signal at a distance r (Eq. (3)), α_{ground} is attenuation due to the influence of the Earth's surface (Eqs (1) and (3)), α_{atm} is attenuation due to atmospheric sound absorption (calculated according to the ISO 9613-1 standard).

3. Development of the parametric loudspeaker

3.1. Description

The development of the parametric loudspeaker is aimed at selecting different operating parameters. It is composed of the control unit, the Yamaha P-2500S power amplifier, and the parametric antenna array. The control unit is installed using the Altera Cyclone II FPGA Starter Development Kit.

The parametric antenna (Fig. 2) array is made up of 110 Prowave 400ST160 ultrasonic transducers having a 16 mm diameter, 2400 pF nominal capacity, 40 ± 1 kHz resonance frequency and not less than 120 dB sound pressure level. These transducers are arranged on a hexagonal mesh. The size of the proposed antenna array is 190×180 mm.

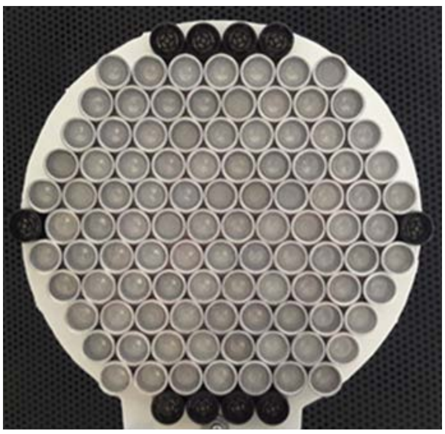

Fig. 2. Parametric antenna array.

3.2. Experimental setup

The radiation pattern was measured on the experimental setup, the flow-chart of which is shown in Fig. 3. The measurements were performed in open space with a minimum of background noise. The height of the parametric antenna array and the measuring microphone was 5 meters. This height provides a minimal effect of the Earth's surface on the measurements of directional pattern.

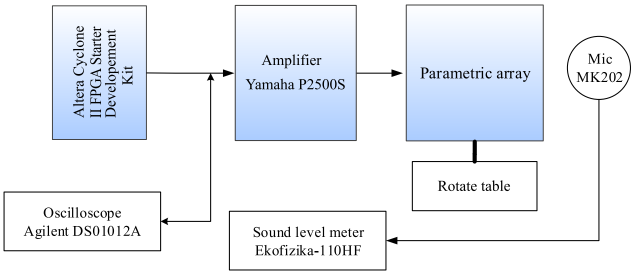

Fig. 3. Flow chart of the experimental setup.

The amplified signal was then applied to the channels of the parametric antenna array. The Ekofizika 110HF sound level meter of the first accuracy class with a MK202 microphone was used to measure the sound pressure level both on the primary and difference frequencies.

The radiation pattern of the proposed antenna array was measured at the far-field distance for the primary frequency. Measurements were performed through the rotation of the parametric antenna array on a rotate table. Angular measurements range from −20 to 60 degrees at 2 degrees of pitch. In the angular region between 60 and 90 degrees, measurements were performed at 5 degrees of pitch. The microphone was placed at an angle of 0° toward the direction of the sound propagation.

The sound pressure level was measured at a distance ranging from 0.5 to 100 m in the direction of the sound propagation. The measurement microphone was moved over the distance at a 1 m interval for the amplitude modulated signal. The parametric antenna array and the microphone were placed at the distance of 2 m from the ground surface. The signal propagated over a dirt road with insignificant bumps. This experiment is shown schematically in Fig. 4.

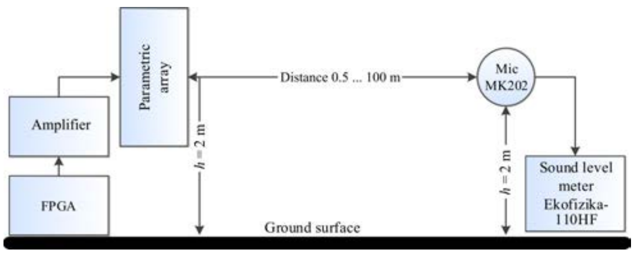

Fig. 4. Flow-chart of the experimental measurements of the sound level pressure over a long distance.

4. Results and discussion

4.1. Measurement results of the radiation pattern

The radiation pattern for the second case is calculated as $D(\theta) = \left[1 + k_\Omega^2 \alpha^{-2} \sin^4\left(\frac{\theta}{2}\right)\right]^{-1/2}$. Figure 5 presents the results of measuring the radiation pattern for a modulation frequency of 2 kHz. It is seen that the radiation pattern agrees well with the theoretical calculation.

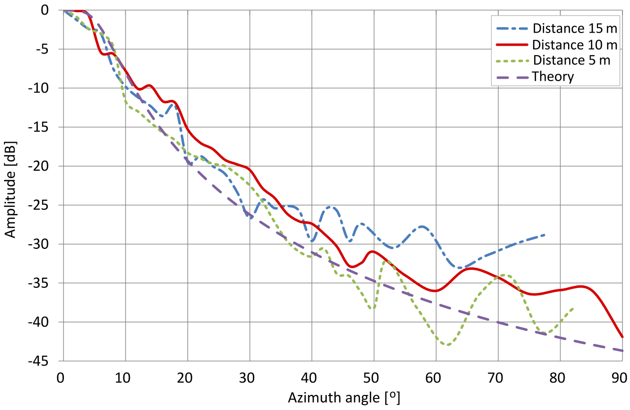

Fig. 5. The results of measuring the radiation pattern for a modulation frequency of 2 kHz and result of calculating the radiation.

4.2. Measurement results of the sound pressure level

The sound pressure level created by the parametric antenna array was 128 dB at a distance of 1 m, on a 40 kHz frequency. Under the experimental conditions of 20°C air temperature and 20% humidity, the sound attenuation coefficient was 0.6 dB/m on a 40 kHz frequency due to the atmospheric absorption. The length of primary wave propagation is therefore $l_n = 7.24$. The far-field boundary is 3.3 m.

For the difference frequency and the fundamental frequency of the signal, a theoretical calculation was made of the sound pressure level as a function of distance according to Eq. (15).

In addition to the substantial influence of meteorological conditions, near-ground propagation of sound is also influenced by the underlying surface of the Earth, or, more accurately, its impedance properties and relief, which determine the magnitude of the coefficient of reflection of sound waves from the Earth and, in the final analysis, the magnitude of their attenuation.

The dependences of the sound level pressure on the distance of 0.5 to 100 m are shown in Fig. 6 for the difference frequency signal, primary frequency. It is clear that the theoretical calculations and experimental data are in good agreement. To increase the accuracy of the calculation, we calculated the sound pressure level for the specularly reflected wave. For this, expressions (13) and (3) were used. The correction is the radiation pattern of the parametric emitter to calculate the level of sound attenuation, it was possible to increase the accuracy of the theoretical calculation.

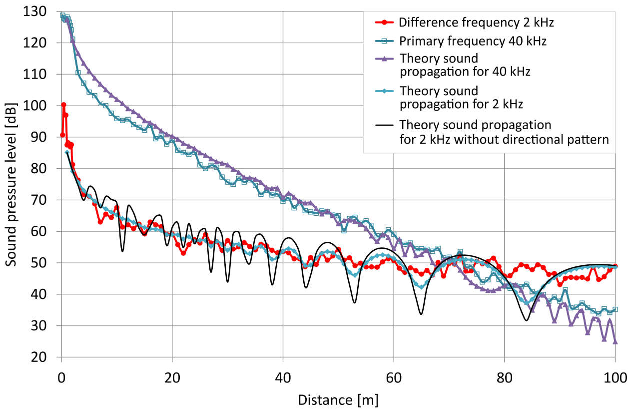

Fig. 6. Dependences of the sound level pressure for the amplitude modulated primary signal, demodulated signal of the difference frequency signal and the result of a theoretical calculation of a sound signal of 2 kHz, 40 kHz above the Earth's surface.

According to Fig. 6, the sound pressure level of the primary frequency signal is higher and attenuates more rapidly than that of the difference frequency signal. The main influence in attenuation of the signal at the primary frequency occurs due to the influence of atmospheric absorption of sound vibrations. At a distance of 70 m, the sound pressure level of the primary signal is lower than that of the difference frequency signal.

5. Conclusions

The proposed parametric acoustic array loudspeaker consisted of the parametric antenna array made up of 110 elements, a control unit and power amplifier. A hexagonal configuration was used for the transducers arrangement. The control unit was installed using the Altera Cyclone II FPGA Starter Development Kit. As an example, the article cited the results of measuring the directivity of a parametric antenna array for a difference frequency of 2 kHz. Good agreement between theoretical and experimental data is shown.

The sound pressure level on the difference frequency was measured at a distance of 0.5 to 100 m to the antenna array. Good agreement was found between the theoretical calculation of the propagation of an acoustic signal over the Earth's surface with experimental data. Taking into account the influence of the direction pattern of the emitter for calculating the attenuation level due to the Earth's surface made it possible to increase the accuracy of the theoretical calculation. The developed parametric loudspeaker is designed to study the propagation of acoustic signals along paths up to 100 meters long and can serve as a laboratory model for teaching undergraduate and graduate students to study the construction of acoustic antenna arrays and the propagation of acoustic waves.

Acknowledgement

This research was supported by Tomsk Polytechnic University Competitiveness Enhancement Program VIU ISHITR 180/2020.

References

1. Adachi A. Hashiguchi H. (2019), *Application of parametric speakers to radio acoustic sounding system*, Atmos. Mcas. Tech. Discuss. Discussion started: 10 May 2019.
2. Albert D.G. (2003), Observations of acoustic surface waves in outdoor sound propagation, *Journal of the Acoustical Society of America*, **113**(5): 2495–2500, doi: 10.1121/1.1559191.
3. Aoki K., Kamakura T., Kumamoto Y. (1991), Parametric loudspeaker – characteristics of acoustic field and suitable modulation of carrier ultrasound, *Electronics and Communications in Japan (Part III: Fundamental Electronic Science)*, **74**(9): 76–82, doi: 10.1002/ecjc.4430740908.
4. Attenborough K. (2007), *Predicting Outdoor Sound*, London– New York: Taylor & Francis.
5. Bennett M.B., Blackstock D.T. (1975), Parametric array in air, *Journal of the Acoustical Society of America*, **57**(3): 562–568, doi: 10.1121/1.380484.
6. Berktay H.O. (1965), Possible exploitation of nonlinear acoustics in underwater transmitting applications, *Journal of Sound and Vibration*, **2**(4): 435–461, doi: 10.1016/0022-460X(65)90122-7.
7. Boullosa R.R., Pérez-López A., Dorantes-Escamilla R., Rendón P.L. (2016), An airborne parametric array, *Applied Acoustics*, **112**: 116–122, doi: 10.1016/j.apacoust.2016.05.015.
8. Delany M.E., Bazley E.N. (1970), Acoustical properties of fibrous absorbent materials, *Applied Acoustics*, **3**(2): 105–116, doi: 10.1016/0003-682X(70)90031-9.
9. Gan W., Tan E., Kuo S. (2011), Audio Projection, *IEEE Signal Processing Magazine*, **28**(1): 43–57, doi: 10.1109/MSP.2010.938755.
10. Ju H.S., Kim Y. (2010), Near-field characteristics of the parametric loudspeaker using ultrasonic transducers, *Applied Acoustics*, **71**(9): 793–800, doi: 10.1016/j.apacoust.2010.04.004.
11. Kamakura T., Tani M., Kumamoto Y., Breazeale M.A. (1994), Parametric sound radiation from a rectangular aperture source, *Acta Acustica united with Acustica*, **80**(4): 332–338.
12. Krasnenko N.P., Rakov A.S., Rakov D.S., Shamanaeva L.G. (2014), Influence of impedance properties of the earth's surface on sound attenuation during near-ground propagation, *Russian Physics Journal*, **57**(1): 100–109, doi: 10.1007/s11182-014-0213-y.
13. Li K.M. (1994), A high-frequency approximation of sound propagation in a stratified moving atmosphere above a porous ground surface, *Journal of the Acoustical Society of America*, **95**(4): 1840–1852, doi: 10.1121/1.408699.
14. Miki Y. (1990), Acoustical properties of porous materials – modifications of Delany-Bazley models, *Journal of the Acoustical Society of Japan (E)*, **11**(1): 19–24, doi: 10.1250/ast.11.19.
15. Muir T.G., Vestrheim M. (1979), Parametric arrays in air with applications to atmospheric sounding, *Journal de Physique Colloques*, **40**(C8): C8-101–C8-110, doi: 10.1051/jphyscol:1979819.
16. Piercy J.E., Embleton T.F.W., Sutherland L.C. (1977), Review of noise propagation in the atmosphere, *Journal of the Acoustical Society of America*, **61**(6): 1403–1418, doi: 10.1121/1.381455.
17. Rakov D.S., Rakov A.S., Kudryavtsev A.N., Krasnenko N.P., Chursin Y.A., Murin M.A. (2019), A study of directional patterns of ultrasonic parametric array, *Archives of Acoustics*, **44**(2): 301–307, doi: 10.24425/aoa.2019.128493.
18. Reis J. (2016), Short overview in parametric loudspeakers array technology and its implications in spatialization in electronic music, *Proceedings of ICMC 2016 – 42nd International Computer Music Conference*, pp. 241–248, retrieved from www.scopus.com.
19. Rudenko O.V. (1974), On parametric interaction of progressive sound waves [in Russian], *Akusticheskij Zhurnal*, **20**(1): 108–111, http://www.akzh.ru/pdf/1974_1_108-111.pdf.
20. Shi C., Gan W.S. (2010), Development of parametric loudspeaker, *IEEE Potentials*, **29**(6): 20–24, doi: 10.1109/MPOT.2010.938148.
21. Westervelt P.J. (1963), Parametric acoustic array, *Journal of the Acoustical Society of America*, **35**(4): 535–537, doi: 10.1121/1.1918525.
22. Yoneyama M., Fujimoto J., Kawamo Y., Sasabe S. (1983), The audio spotlight: an application of nonlinear interaction of sound waves to a new type of loudspeaker design, *Journal of the Acoustical Society of America*, **73**(5): 1532–1536, doi: 10.1121/1.389414.
23. Zabolotskaya E.A., Soluyan S.I., Khokhlov R.V. (1966), Ultrasonic parametric amplifier [in Russian], *Akusticheskij Zhurnal*, **12**(2): 188–191, http://www.akzh.ru/pdf/1966_2_188-191.pdf.
24. Zverev V.A., Kalatchev A.I. (1970), On the crossmodulation effects by inlersection of sound beams [in Russian], *Akusticheskij Zhurnal*, **16**(2): 245–251, http://www.akzh.ru/pdf/1970_2_245-251.pdf.