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Application of the Partial Domain Method to the Determination of the Directional Properties of a Finite-Length Cone Horn for a Broadband Acoustic Ear Echo Spectrometer

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The paper considers and shows the extension of the partial domain method to the formulation and solution of the problem of forming the spatial selectivity of a radiating acoustic horn of a fixed length, operating in an ideal elastic medium, and which is used in the original device for objective express diagnostics of human hearing – a broadband ear spectrometer. The application of the specified method provides the possibility of avoiding the inaccuracies and conventions of the classical wave approach to the formulation of radiation problems, as well as the use of traditional boundary conditions (Neumann and Dirichlet type) and conjugation conditions at the boundaries of partial domains of canonical forms, or as close as possible to the existing ones. The pressure directivity function is determined by solving the Helmholtz equation in each domain in partial domains, followed by determining the maximum and minimum pressure at the field points of the outer domain because of the interference of acoustic waves emitted by the elements of the horn mouth surface areas. Thus, an angular pressure function is formed, which, after normalization, is converted into a directivity characteristic. In this case, the individual solutions of the pressure field components in the selected partial domains are determined from a system of linear algebraic equations with unknown coefficients recorded for the horn throat, its cavity, mouth, and vicinity. The proposed approach is relevant and up to date because it allows increasing the reliability of the modeling of horns of canonical and complicated geometric shapes using boundary conditions and conjugation conditions of selected partial domains. Calculated and experimental results are presented in the form of directional diagrams, amplitude-frequency characteristics of sound pressure, and phase-frequency characteristics.

Keywords: Acoustics, Broadband Acoustic Ear Echo Spectrometer, Interaction of Fields, Connectivity, Radiation Mode, Partial Domains, Directivity Characteristic, Frequency Characteristic, Electroacoustic Transducer.

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1. INTRODUCTION

So far, electroacoustic devices for technical acoustics have been widely and fully considered as a set of combination elements of passive and active types [1, 2]. That is, such a device should have movable and fixed elements whose functions include the formation of acoustic fields of scalar and vector types, namely, pressures, oscillatory velocities, and intensities. One of these elements is a well-known acoustic horn [3].

The acoustic horn is also used in the original device for objective diagnosis of human hearing - a broadband ear echo spectrometer - a device for early objective diagnosis of hearing impairment, which can be used to diagnose the middle ear of a person without the participation of the sensorineural system [4]. It allows to determine, by measuring the frequency dependence of the coefficient of sound reflection from the eardrum, the following: flexibility of the eardrum; resonant frequencies of the mechanical system of the ear; weight of the ossicles; ratio of the active component of the mechanical impedance of the ear to the air impedance; coefficient of transformation of acoustic pressure by the ossicles into the fluid of the inner ear cochlea; and the normal parameter - the invariant of the human middle ear in normal state [4].

The advantages over multifrequency acoustic impedance meters, which are widely used to diagnose the human middle ear, are as follows: the absence of a closed volume of the external auditory canal between the ear insert and the eardrum and, as a result, greater accuracy of acoustic impedance determination; significantly lower average sound pressure levels over time; absence of a pneumatic system that can damage the hearing system of newborns during screening studies directly in the maternity hospital, or in the case when the a hearing test is performed after a mine-explosive injury.

The principle of operation of an ear echo spectrometer [5] is to emit short sound pulses into a tube of small diameter compared to the sound wavelength at a selected frequency, and to determine, by comparing its amplitude and the amplitude of the echo signal, the coefficient of sound reflection from the eardrum. All other parameters listed above are determined from the frequency dependence of the reflection coefficient.

The acoustic part of the ear echo spectrometer consists of a flexible tubular sound guide, one end of which is tightly inserted into the external auditory canal, and an acoustic probe containing a miniature telephone and microphone is inserted into the elastic entrance of the other end through a conical horn (Fig. 1). By changing the frequency and repetition time of the pulses fed to the telephone, it is possible to obtain a change in parameters of the norm and resonant frequency, both during fast (e.g., swallowing) movements and during slower influences (e.g., medical tests).

Let us consider in more detail the principle of operation of the conical radiating horn, which is part of the

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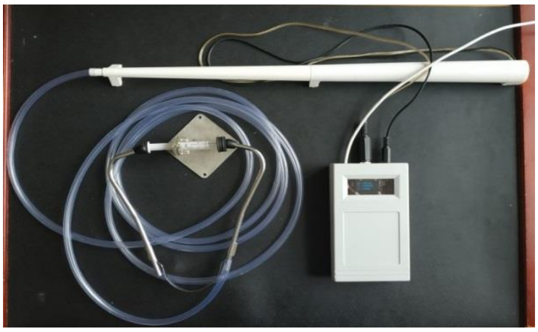
acoustic part of the ear electroacoustic echo spectrometer, which, according to [3], consists in performing the following main functions:

- function of selecting the oscillating source system in the form of a circular flexible diaphragm;
- the function of disturbing the diaphragm and setting the mode of forced mechanical vibrations at frequencies higher than the critical frequency of the horn;
- function of transformation of mechanical vibrations into acoustic vibrations by the oscillating system in the horn throat;
- function of determining the working environment in the form of an elastic adiabatic space that can be divided into parts - internal and external areas.



(a)

(b)

Fig. 1 – (a) – A prototype of the original broadband ear echo spectrometer; (b) – Acoustic conical horn for the ear echo spectrometer made by 3D printing

From the comments to the references [6, 7], it follows that formally, a horn is a device that connects the throat and mouth by a channel with acoustically rigid surfaces. The use of a horn makes it possible to increase the efficiency of the resulting acoustic system by achieving a compromise between the desire for the highest possible radiation resistance and the inevitable increase in the mass and size characteristics of the oscillating system.

Such a compromise approach extends the series of spatial and energy conventions associated with determining the desired directivity characteristics (DC) of an electroacoustic device and maximizing the concentration factor [8].

In addition, the terms of the expansion series of the acoustic fields of the electroacoustic transducer should be considered within the framework of the wave problems of forming the acoustic radiation field [9, 10] for each defined partial domain.

The result of solving these problems of technical electroacoustics [9, 10] with a certain degree of arbitrariness regarding the configuration and number of partial domains, as well as the relative simplicity and clarity of applying such formulations, can lead to the correction of the results of solving traditional problems on the directionality of horns.

In addition, the results of the solution in terms of acoustic field formation will allow to determine the mode composition and structure of the pressure field in the internal and external spaces of the horn.

Thus, as a way to further develop the theoretical and practical aspects of the development and use of horns, the method of partial domains, which is known from the practice of solving differential equations of mathematical physics, can be applied [9]. In addition, another reason for using the method of partial domains is the possibility of correct selection and application of boundary conditions and field conjugation conditions in the modes of static and dynamic deformation of the transducer. Examples of works on this topic include the article [11].

Separately, sources [7, 9] should be noted, which initiate the formulation and organize the results of solving the problems of sound radiation by a plane wave source in the form of a conical horn limited in length with acoustically rigid walls.

Thus, the attractive qualities of the partial domain method are the consideration of the size, configuration, and types of tubes, canals, the presence of holes and branches, as well as the vibrational modes of the horn body and flexible structural elements. At the same time, we will assume that the use of objects of complex geometric shapes as acoustic sources can distort the results obtained.

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It so happened that until recently, the input conditions for the problem of determining the spatial selectivity of a horn were the assumption that the horn's frequency response is approximated by a rotational ellipsoid whose vertex (major axis) touches the geometric center of the mouth. This simplification is rather conditional because the side and rear radiation of the horn are not considered here. Neglecting these factors does not allow us to obtain a complete picture of the formation of acoustic fields in the cavity, in the horn outlet cross section, and in the external space.

The purpose of the work is to extend the range of possibilities of applying the method of partial domains in terms of formulating and solving wave problems of acoustics as a branch of mathematical physics using the general provisions of the working medium dynamics and the theory of elastic wave propagation in liquids or gases. In this case, the determination of the acoustic pressure distributions in the domains of the internal and external working space of the horn is performed using the Fourier method and the orthogonality property of trigonometric and cylindrical wave functions.

The expected results are presented as an improvement of the approaches to studying the peculiarities of the horn acoustic field formation in the working space when operating in the radiation mode.

2. MATERIALS AND METHODS

The problem of sound radiation by horn devices has been studied for a long time, and the procedure for forming an acoustic field by a horn corresponds to the procedure for solving traditional boundary value problems of mathematical physics [9]. For a more in-depth study of the process of forming the spatial features of the horn, it is proposed to consider an approach based on the use of the partial domain method. The partial domains are formed, with a certain degree of assumptions, by dividing the working space of the horn system into domains in which the equations for the acoustic field correspond to the canonical ones in form.

The most successful solution is to divide the system into three domains, where I is a flat semi-infinite waveguide; III is a wedge-shaped waveguide; and II is a partial domain of coordination of domains I and III.

2.1 Problem Statement

After dividing the horn system into domains I-III, the solution method involves determining the sound fields in each domain so that any boundary or conjugation conditions can be fulfilled at the boundaries of the domains.

It is noted that a separate element of the horn system is the transient conjugation domain in the vicinity of the horn throat. The wave structure of the system and the external space are filled with an ideal medium with the density ρ_0 and speed of sound c_0. The surfaces of the system are acoustically rigid.

Suppose that a given sound source in the domain of a plane-parallel waveguide creates an acoustic disturbance in the q-mode in the form of a pressure wave traveling along the plane waveguide in the direction of increasing x coordinate. Such a disturbance is represented by the acoustic wave field formed by the source and the superposition of normal acoustic waves of the plane waveguide.

As a result of the interaction of the incident acoustic wave with domain II, a reflected wave is formed in domain I and a penetrating wave is formed in domain III.

Let's introduce the cartesian xOy and polar $Or\theta$ coordinate systems. The points O of the coordinate systems coincide. The sound source is represented by an electro elastic object of small wave size ka with fully electrified inner and outer surfaces. The generating sources are perpendicular to the plane xOy.

Thus, we consider the problem to be plane. The coordinates are reduced to polar coordinates, and the oscillatory velocity on the source surface will not depend on the angle.

Thus, the wave that has passed into domain III is represented as a superposition of the normal waves of a wedge-shaped waveguide. Then, in accordance with the method of partial domains, it is necessary to write down the expressions for the sound fields in each domain - for each domain in general form.

For domain I, this expression contains the incident wave and the full set of reflected homogeneous and inhomogeneous waves.

Thus, in the problem of sound radiation by a conical horn, the acoustic fields in each domain are determined with the fulfillment of boundary conditions on the surfaces - the boundaries and the conjugation condition between the domains. Therefore, the problem assumes the presence of sources with fully electrified inner and outer surfaces. The electrodes are connected to an external electric potential difference generator, which forms an axisymmetric electric field in the body volume, which in turn causes radial and axial displacements of the body surface points and generates axisymmetric deformations of its surface.

2.2 Functional Equations and Problem Solving

In general, the expression defining the radiation of the horn in a free medium can be given based on one of two pressure expressions:

$$p = \frac{p_0}{r_{\,0}} (\exp(-i(\omega t - kr)),$$

or: (1)

$$p = \frac{p_0}{\sqrt{r}_{\,0}} (\exp(-i(\omega t - kr)),$$

which characterizes the specified harmonic pressure change and produces a normal sound wave with amplitude p_0 and frequency $f > f_{cr}$, where f_{cr} is the critical frequency of the waveguide.

Let's use the second formula from system (1).

Further, in accordance with the basic provisions of the partial domain method [10], the partial solutions of the Helmholtz equation for each of them (I, II, III) should be written in terms of sound pressure by modes. The values of the pressure amplitudes outside and inside of such acoustic system are to be determined.

Next, based on the obtained distribution of acoustic pressure values and generalized relations for spatial selectivity, the amplitude and phase characteristics of the pressure and its normalized angular distributions are determined for each mode – the actual amplitude and phase directivity characteristics (DCs).

The result of using the partial domains should show the coincidence or differences between the horn directivity characteristics ($D(\theta)$) obtained in this work and ($D(\theta)$) using traditional approaches (e.g., given in monographs and reference books [1]):

$$D(\theta) = \frac{p(u)}{p(u_0)} = \frac{\sum\limits_{n=0} A_n exp(-(\omega t - kr))}{\max\left\{ \sum\limits_{n=0} A_n exp(-(\omega t - kr_0)) \right\}}, \quad (2)$$

where $p(u)$, $p(u_0)$ are, respectively, the current and the largest fixed pressure value in the far field, which are determined by the generalized coordinates $\mathbf{u}(r, r_0, \theta)$ when the angle changes; n is the addition operator $n = 1, 2, 3, \dots N$, and k is the wave number of the wave in the working medium (domain III).

Provisions for the formation of an acoustic field in a horn system are the following.

For domain I:

$$p_I = \cos(\alpha_q y) e^{(tk_q(x - x_0))} + \sum_{n=0}^{\infty} A_n \cos(\alpha_n y) e^{(-tk_n(x - x_0))}, \quad (3)$$

where q is the number of a normal wave that runs into the domain of conjugation of I with II; α_n is a value that has the meaning of a wave number and is determined according to the following boundary conditions: $\partial p_I / \partial y = 0$; $\left.\frac{\partial p}{\partial n}\right|_s = 0$, when $y = \pm h$ and cases:

$$\alpha_n = \frac{n\pi}{h}, \; k_n = \sqrt{k^2 - \alpha_n^2}, \qquad k > \alpha_n^2,$$
$$k_n = \sqrt{\omega_n^2 - k^2}, \qquad k < \alpha_n^2, \tag{4}$$

s is the area of the front of the active surface; n is the normal; A_n are unknown coefficients, which together allow to fulfill the conditions of conjugation at the boundaries of domains I and II.

For domain III:

$$p_{III}(r,\theta) = \sum_{m=0}^{\infty} D_m \cos(\beta_m \theta) H^{(1)}_{\beta_m}(kr), \tag{5}$$

where field (5) is the field of normal waves of a wedge-shaped waveguide recorded in polar coordinates, $\partial p_{III} / \partial \theta = 0$ as follows: $\beta_m = m\pi / \theta_0$ is the value that has the content of the wave number for the wave front at the outlet of the horn mouth at $\theta = \pm\theta_0$;

$$H^{(1)}_{\beta_m}(kr) - \tag{6}$$

is a radial Hankel function of the first kind of the first order; D_m are unknown coefficients that are determined by the boundary conditions.

For domain II, let's use the orthogonality property of trigonometric functions $\cos(\alpha_n y)$ on the boundaries of domains I and II, as well as functions $\cos(\beta_m \theta)$ on the boundaries of domains II and III. Thus, the field in domain II is represented as the expression:

$$p_{II} = p^{(1)}_{II} + p^{(1)}_{II} = \sum_{n=0}^{\infty} B_n \cos(\alpha_n y) e^{(-tk_n(x - x_0))} + \\ + \sum_{n=0}^{\infty} C_m \cos(\beta_m \theta) J_{\beta_m}(kr), \tag{7}$$

where $J_{\beta_m}(kr)$ is Bessel function of the first kind; C_m, B_n are unknown coefficients.

The solution of the system of functional equations considers the boundary conditions on the surfaces and the conditions of conjugation of the domains on the above boundaries of the domains.

Groups of functional equations, expansions (1), (3)-(7) and the above boundaries and domains are considered by the following inequalities:

$$p_I = p_{II}, \frac{\partial p_I}{\partial x} = \frac{\partial p_{II}}{\partial x}, \; x = x_0, \; |z| \le h,$$
$$p_{II} = p_{III}, \frac{\partial p_{II}}{\partial x} = \frac{\partial p_{III}}{\partial x}, \; r = r_0, \; |z| \le h. \tag{8}$$

The first group of terms of functional equations (8) establishes the order of conjugation of such characteristics of the acoustic field as power and kinematic for rectangular coordinates. The second group of terms requires the use of formulas for coupling the cartesian and polar coordinate systems. Fundamentally, the added impedance conditions and Sommerfeld's principle conditions close the system of functional equations for finding the unknown coefficients $A_m, B_m.C_m, D_m$ of the field expansions (3), (5), (7).

Using the orthogonality properties of trigonometric functions and the relationship between polar and rectangular coordinates, it is possible to algebraize the system. Or in other words, the formation of an infinite system of algebraic equations of the second kind. After performing a few cumbersome transformations, we will have four equations for four unknowns $A_m, B_m.C_m, D_m$:

$$1 + A_n = B_n + C_n \cos(\beta_n \theta) J_{\beta n}(kr),$$

$$1 - A_n i k_n = B_n + C_n J^{`}_{\beta n}\left(k \frac{x}{\cos\theta}\right) \cos(\beta_n \theta) \frac{k}{\cos(\theta)}, \tag{9}$$

$$B_n + C_n J_{\beta n}(kr_0) \cos(\beta_n \theta) = D_n \cos(\beta_n \theta) H^{(1)}_{\beta n}(kr_0),$$

$$C_n J^{!}_{\beta n}(kr_0) \cos(\beta_n \theta) = D_n \cos(\beta_n \theta) H^{(1)!}_{\beta n}(kr_0). \tag{9}$$

The determination of the unknown coefficients (system of equations (9)) allows to find the expansion of the required pressure fields using formulas (3), (5), (7).

3. RESULTS OF SOLVING THE RADIATION PROBLEM

The results of the calculations in the form of the distribution of amplitude-frequency responses (AFR) and phase-frequency responses (PFR) for a frequency of 6.1 kHz from the sound range (20 – 20,000) Hz are shown in Figs. 2, 3.

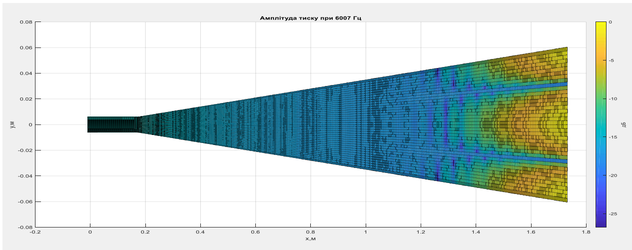


Fig. 2 – General distribution of acoustic pressure amplitudes in the working space of a conical horn

Figs. 4, 5 show the distribution of pressures in the mouth cross-section at the given frequencies of the specified range.

The initial parameters of the problem are: the selected type of horn is conical, the length of the horn is $L = 41\ mm$, or $L1 = 45\ mm$, the angle of the horn opening is α = (1-2) degrees.

The paper also calculates the amplitude distributions of acoustic pressure in the horn cavity in accordance with the selected frequency range areas and phase distributions of acoustic pressure (Figs. 4, 5).

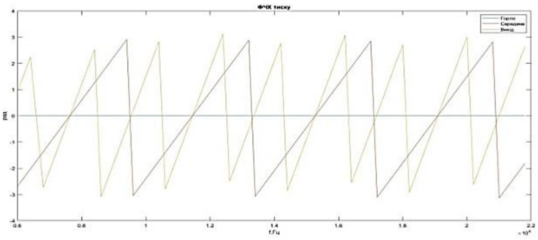


Fig. 3 – General distribution of acoustic pressure phases in the working space of a conical horn

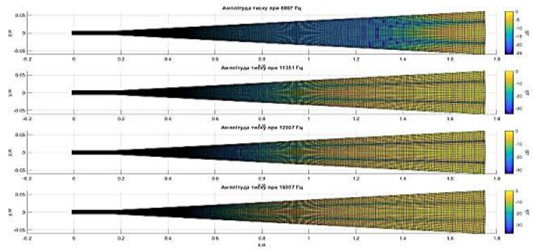


Fig. 4 – AFR (short horn)

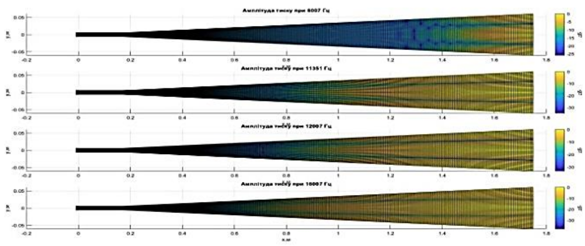


Fig. 5 – AFR (elongated horn)

In this case, the spatial selectivity of the horn is considered in accordance with the pressure distributions obtained in this paper and compared with the directivity characteristic of circular-type interferential acoustic antennas as shown by a blue dashed line (Fig. 6). Calculations of the horn directivity characteristic are shown by a red solid line (Fig. 6).

3.1 Amplitude-Frequency Response and Phase-Frequency Response

Consider the obtained results.

The frequency dependences of the amplitudes and phases of the acoustic pressure in the horn cavity show that the use of the partial domain method reveals several effects that affect the structure of the pressure field in the horn and its outlet cross-section.

The phase-frequency response (Fig. 3) illustrates the change of the pressure phase in the volume of the horn working space and shows the coincidence of the pressure phases in the cross-sections: "throat", "middle area" and "mouth" for the above input calculation data. Thus, the acoustic field, because of calculating the series (3), (5), (7) by formula (2), demonstrates the features of the fields in domains II and III. At the same time, the range of the high interference area increases with increasing frequency, while maintaining the overall field structure.

The feature of the process of forming an axis-centered (along the horizontal axis of the horn) acoustic field in the outlet cross-section, in the internal space of the horn and in the external environment is the transformation of acoustic waves as they travel from one domain to another (Fig. 4):

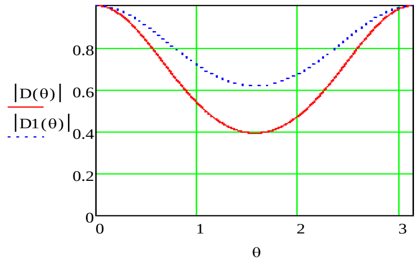
- high-pressure zone is a ring of outer radius r_1 and inner radius r_2,

- a central high-pressure zone in the form of a circular piston with radius r_3;

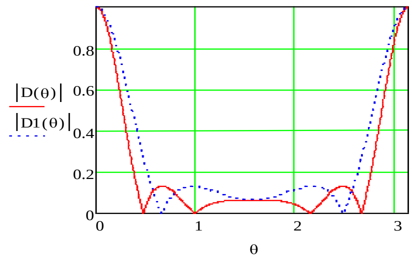
- small ring zones with the radiuses r_2 and r_3.

In this case, the formation of increased pressure areas occurs both for a short horn (Fig. 4) and an elongated horn (Fig. 5).

3.2 Directivity Characteristic of an Interferential Circular Continuous Antenna



(a)



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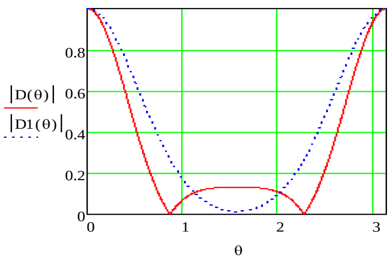
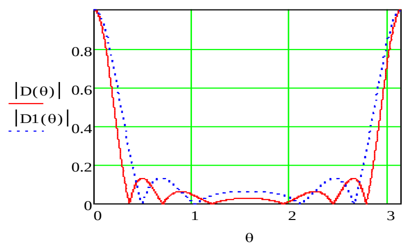


(c)



(d)

Fig. 6 – DC of horn device for frequencies: a) $f = 10000$ Hz; b) $f = 3000$ Hz; c) $f = 6000$ Hz, d) $f = 13000$ Hz

One of the approaches to study the features of the formation of the DC of the horn system, as well as to verify the reliability of the method used, was to calculate the spatial selectivity of the specified antenna.

Fig. 6 shows the radiation patterns of the disk antenna, according to the classical ones and obtained by the proposed method.

4. ANALYSIS AND DISCUSSION OF CALCULATION RESULTS

The results of the DC calculations are shown in Fig. 6. According to the obtained radiation patterns (Fig. 6, a-d), the spatial qualities of the horn are quite different in a given frequency range (DC is taken at fixed frequencies from the operating frequency range $f = (3000 - 13000$ Hz)). The DC is calculated based on formula (2) after being reduced to (9). Therefore, for the selected frequency range and for the calculated pressure distributions in the outlet cross-section of the horn, the DC (8) is written in accordance with the addition theorem (10).

$$D(\theta) = p_{aa}(\theta) =$$
$$= \left| \frac{r^2}{r^2 - r_1^2} \frac{2J_1(kr\sin(\theta))}{kr\sin(\theta)} - \frac{r_1}{r^2 - r_1^2} \frac{2J_1(kr_1\sin(\theta))}{kr_1\sin(\theta)} \right| - \quad (10)$$
$$- \left| \frac{r_2^2}{r^2 - r_1^2} \frac{2J_1(kr_2\sin(\theta))}{kr_2\sin(\theta)} - \frac{r_3^2}{r^2 - r_1^2} \frac{2J_1(kr_3\sin(\theta))}{kr_3\sin(\theta)} \right|.$$

Thus, for an uncompensated surface antenna, in accordance with the assumptions and simplifications inherent in the traditional approach [1] to antenna sound transparency, the representation of the DC in the form of an ellipsoid is useful only for the frequency range up to 6000 Hz (Fig. 6, a, b) for the used initial data.

4.1 Analysis and Discussion of AFR and PFR

Based on the obtained calculation and graphical data about AFR and PFR and the results of the analysis of the obtained materials, we can provide several of the following useful comments on the dynamics of acoustic processes in the horn. Thus, the acoustic field in the horn working space, according to the features of occurrence and distribution, belongs to oscillators operating in phase space and is described by a second-order differential equation (see Problem Statement), and the set of solution roots corresponds to fixed special points of the field in the horn environment, which determine the state of equilibrium of oscillatory systems and characterize the structure of the phase plane and the nature of oscillatory processes in the "diaphragm-horn mouth" system. Indeed, in the inner space, we observe a sequence of special points surrounded by a set of phase trajectories - separatrices. The change in the separatrices in the vicinity of the special points has an exponential character of a small monotonous slow increase or decrease in the velocity function. The special point corresponds to the "saddle" type, and the velocity at the point of such a stable node is zero. In total, for the given initial data in the horn space at lower frequencies, the set of phase trajectories forms three groups of special points of the "saddle" type, the frequency and size of which increase as they rich the outlet cross-section of the horn. This situation exists until the separatrix degenerates into a vertical line. So, formally, in the outlet cross-section of the horn we have a plane wave with an amplitude greater than the amplitude of the pressure waves in the throat of the horn.

4.2. Analysis of the Formation of Spatial Selectivity of the Horn

The results of the calculation of the radiation problem (Fig. 6) show that the computational model of the DC of such a horn has certain features. At the same time, it is of interest not only to clarify the features of the field formation process by the horn but also the degree of coincidence of the DC found by the proposed method of partial domains and the DC determined by the traditionally used approaches to the synthesis of circular interferential antennas.

In a simplified and traditional way, the horn DC is approximated by a rotational ellipsoid with the vertex in the geometric center of the horn's outlet cross-section. Such a radiation model is outdated and has a number of disadvantages associated with the impossibility of determining the side field and other elements of the DC.

That is, the proposed pressure distribution in the outlet section, obtained considering the special points of the horn, gives us three interfering sections of the outlet cross-section in the form of a nested ring and a disk with a single-phase center (Figs. 2-6). In this case, the possibility of determining such elements of the DC as additional maxima, minima of the directivity function, and the acuity of the directional action also disappears.

Thus, we have obtained the results of calculations of AFR, PFR, and DC of a conical horn, considering the influence of the field structure in the horn's II domain, its size, and frequency.

In general, the calculation of the DC in traditional approaches is reduced to the calculation of the DC of a disk circular acoustic antenna.

In addition, the diagrams show significant differences in the angular characteristics and the position of the angles and directional acuity determined by these methods in the middle and higher frequency ranges. And only in the lower frequency range (up to 6000 *Hz*) the horn directivity function acquires a successful representation of the DC as an ellipsoid. Here, in the region of the main maximum, the directivity function quickly decreases to a value of 0.2 (i.e., the side field levels are up to - (3-5) *dB* in the traverse directions).

As can be seen from the results, the horn is presented by a rather complex device, and this encourages the prospect of research.

5. CONCLUSIONS

The following conclusions can be made as a result of the work:

1. The application of the method of partial domains in the development of mathematical physics problems has been successfully extended to such a complex acoustic system as a horn.

2. The mechanism of forming the acoustic field with consideration of special points of the "saddle" type and

the extension of the results to the problems of determining the pressure, oscillatory velocity, impedance, and concentration factor are shown.

3. It is determined that in the wave problems of acoustics in the field of canalization and sound propagation, the method of partial domains is a rather convenient and visual tool for research. This is because, against the background of the orthogonality of the wave and trigonometric functions, the method successfully uses the boundary conditions and conjugation conditions of the partial domains of the object.

4. A solution to the wave problem of sound radiation by a source of small wave dimensions is performed and:

- the essence of the formation of the acoustic field in a wedge-shaped plane waveguide is revealed;
- the structure of the acoustic field containing special points of the "saddle" type, the consideration of which establishes the order of formation of plane wave fronts in the outlet cross-section of the horn, is determined.

5. Considering the pressure distribution in the horn outlet cross-section is essentially a change in the radiation conditions and is fragmented as a system of nested rings.

6. In this case, the analysis of the directivity function shows that:

- in the lower frequency range, the representation of the DC by the ellipse of rotation corresponds to the pressure distributions and representations of the results of the calculation model.
- in the range of higher frequencies, the DCs of the considered horns coincide with a small difference in the main maximum and the level of the side lobes.

7. The basis for extending the methodology of partial domains to the promising area of medical acoustics is expanded.

REFERENCES

1. Mendel Kleiner. *Electroacoustics* (Boca Raton: CRC Press - Taylor & Francis Group: 2013). ISBN: 9781439836187.
2. L. Cremer, M. Heckl, B.A.T. Petersson. *Structure-Borne Sound: Structural Vibrations and Sound Radiation at Audio Frequencies* (Berlin: Springer: 2005). ISBN: 9783540226963.
3. Leo L. Beranek, J. Mellow Tim. *Acoustics – Sound Fields and Transducers* (San Diego: Elsevier – Academic Press: 2012). ISBN: 9780123914217.
4. S.A Naida, M.S. Naida, *Electronics and Communications* **22** No 2, 56 (2017).
5. S.A. Nayda, V.S. Didkovs′kyy, M.S. Nayda, D.V. Parenyuk, Pat. 137653, Ukrayina, MPK(2006.01): A61B 5/12, opubl. 25.10.2019, byul. № 20/2019 [In Ukrainian].
6. B.S. Aronov, C. L. Bachand, *J. Acoust. Soc. Am.,* **140** No 3, 2162 (2016).
7. B. Aronov, *J. Acoust. Soc. Am.* **125** No 3, 803 (2009).
8. N.Y. Filipova, O.V. Korzhik, A.S. Chayka, S.A. Naida, M.O. Korzhik, A.S. Naida, *J. Nano- Electron. Phys.* **12** No 4, 04034 (2020).
9. V.T. Grinchenko, I.V Vovk, V.T. Matsypura. *Fundamentals of Acoustics* (Kyiv: Naukova Dumka: 2007).
10. V.T. Grinchenko, I.V. Vovk, V.T. Matsypura, *Acoustic Wave Problems* (New York: Begell House: 2018).
11. S.A. Naida, O.V. Korzhyk, I.O. Lastivka, O.V. Pavlenko, T.M. Zheliaskova, M.O. Korzhyk, A.S. Naida, N.S. Naida, O.S. Chaika, *J. Nano- Electron. Phys.* **14** No 1, 01035 (2022).

Використання методу часткових областей до визначення направлених властивостей конусного рупора кінцевої довжини для широкосмугового акустичного вушного ехо-спектрометру

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В роботі розглянуто і показано поширення методу часткових областей на постановку і розв`язок задачі формування просторової вибірковості випромінюючого акустичного рупора фіксованої довжини, що працює в ідеальному пружному середовищі, і який застосовується в оригінальному приладі для об'єктивної експрес-діагностики слуху людини – широкосмуговому вушному ехо-спектрометрі. Застосування вказаного методу забезпечує можливість уникнення неточностей та умовностей хвильового класичного підходу до постановки задач випромінювання, а також використання традиційних граничних умов (типу Неймана і Дирихле) і умов спряження на границях часткових областей канонічних форм, або максимально наближених до існуючих. Визначення функції направленості за тиском відбувається шляхом розв'язання в кожній області рівняння Гельмгольця в часткових областях, з подальшим визначенням максимального та мінімального тиску в точках поля зовнішньої області, як результат інтерференції акустичних хвиль, що були випромінені елементами ділянок поверхні устя рупора. Так формується кутова функція тиску, яка після нормування перетворюється на характеристику направленості. При цьому окремі розв`язки складових полів тисків, в обраних часткових областях визначаються з системи лінійних алгебраїчних рівнянь з невідомими коефіцієнтами, записаними для горла рупора, його порожнини, устя та околиці. Запропонований підхід видається актуальним та сучасним, бо дозволяє збільшити достовірність моделювання рупорів канонічних та ускладнених геометричних форм з використанням граничних умов та умов спряження обраних часткових областей. Розрахункові і експериментальні результати подано у вигляді діаграм направленості, амплітудно- частотних характеристик звукового тиску та фазо-частотних характеристик.

Ключові слова: Акустика, Широкосмуговий акустичний вушний ехо-спектрометр, Взаємодія полів, Зв'язаність, Режим випромінювання, Частинні області, Характеристика направленості, Частотна характеристика, Електроакустичний перетворювач.