The Possibilities Of Using Horn Combination For The Outer Ear Modelling

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Abstract

The electroacoustic model of outer ear's department of the auditory system presented in this work. The auricle presented as a horn that works on the reception of sound waves. A piece of short narrow rigid tube is imitating the outer ear canal.

The comparison of received results with the calculations with the help of the wave theory was completed with the purpose of rating the possibility of application the method of electroacoustic analogies to the calculation of the receiver.

The calculated frequency dependence of the gain on power of the external ear is proving the experimental data about the high frequency nature of the amplification of sound.

Keywords — *auditory system, outer ear, auricle, outer ear canal, horn combination, electroacoustic modelling, power gain.*

I. INTRODUCTION

The human's understanding of the process of sound perception is an urgent both medical and social problem. The same while solving several technical problems that connected with the testing of electroacoustic equipment, rating of acoustic rooms, protecting against noises, etc.

The mathematical modeling of the auditory system is one of the methods of predicting the main hearing characteristics. We should note that a considerable amount of scientific works about modeling the middle and inner ear is already devoted, however the problem for the case of outer ear has never been solved. A passage of sound through the external auditory canal was solved, while the role of the auricle has been considered as insignificant. In the end of the past century, it was traditionally taken the role of a sounds' funnel-gatherer. It was considered that the auditory sensitivity would not change if exclude the auricle from the system of conducting sounds, that is the concentration of sound energy by the human's auricle does not play a decisive role. The auricle's role was most likely considered as improve the localization of sounds [1]**Error! Reference source not found.**.

It is showed in the later works that the auricle and external auditory passage have their own resonant frequencies. So, the adult's external auditory passage has a resonance frequency of approximately 2500 Hz, and the auricle – in the range of 6 kHz. It provides the sound amplifying of each of these structures on their resonant frequency up to 10-12 dB [2].

The outer ear's functions were expanded to protective, amplification of high-frequency sounds, localization and determination of displacement of sound source in a vertical plane, because of experimental research data. Anyway, the question of the outer ear's modelling nowadays stays open.

The electroacoustic model of outer ear's department of the auditory system that consist of the combination horn, that imitates the ear canal, combined with a short narrow rigid tube, that plays the role of the external auditory passage, is presented in this work.

II. LITERATURE DATA ANALYSIS AND PROBLEM FORMULATION

The mathematical theory of different forms horns detailed in the works [3-5]. The solution of the finding the sound field of the inverted (receiving) speaker problem performed by L. Gutin [4]. The quantitative results of the frequency dependence of the gain for the parabolic, conical and exponential form horns are also presented in this particular work. However, the detailed mathematical theory, due to its complexity, is directly difficult to apply to describe the process of receiving sound waves with an external ear.

Let's look at the similar problems of the physiological processes modelling [6]. In the G. Fant's work [7] it is used electroacoustic horn schemes in the simulation of individual regions of the speech apparatus, they are developed by Lawrence [8] and based on the Morz's mathematical relations [3].

We'll try to use the electroacoustic horn scheme for the ear canal modelling following the fact that the main part of the middle and outer ear models are calculated by the method of electroacoustic analogies [9,10,11,12].

We'll also compare the results obtained by the wave method [4] and by the calculation of equivalent electroacoustic circuits, with the purpose of verification of the suitability of the approximate theory of the method of electroacoustic analogies to the solution of the inverse curve problem [7,8].

In case of conformity of these results, we will use the method of electroacoustic analogies for the ear canal modelling using a horn with a subsequent combination with a similar model of the external auditory passage [14].

III. PURPOSE AND OBJECTIVES OF THE STUDY STYLE

To analyse the possibility of application of an inverted horn to the acoustic modeling of an ear canal. To create an electroacoustic model of the external ear.

IV. CALCULATIONS OF THE FREQUENCY DEPENDENCE OF SOUND ACCEPTANCE BY EXTERNAL DEPARTMENT OF THE BEHAVIOR SYSTEM

A. *Theoretical studies of the receiving horns*

*1) **Wave method***:

The entire document should be in Times New Roman or Times font. Type 3 fonts must not be used. Other font types may be used if needed for special purposes. Theoretical studies of the horn as a receiver of sound [4] are based on the principle of reciprocity [15], which gives the ability to determine the acoustic characteristics of the receiver, proceeding from its properties as an emitter.

In this sense, it should be noted that the exact theory of the horn as an emitter does not exist. Usually the approximate Webster theory is used [16], in which it is assumed that the normal to the axis of the cross section of the horn are equipotential surfaces.

The Webster equation for an infinite horn in the harmonious process case:

$$\frac{\partial\varphi}{\partial x}+\frac{\partial(\ln S)}{\partial x}\cdot\frac{\partial\varphi}{\partial x}+k\varphi=0, \qquad (1)$$

where $\varphi=\varphi(x)$ - speed potential; $S=S(x)$ - variable section of a horn; $k=\frac{\omega}{c}$ - wave number (ω- circular frequency, c- sound speed in the environment);
x- coordinate along the horn's axis.

For a horn's group, which section varies according to the law $S=S_0x^m$ (S_0- area of the horn's entrance section; m- power factor, which determines a horn's configuration: $m=1$–parabolic horn; $m=2$ – conical horn; $m\to\infty$ – exponential horn; Ballantyne's solution [17]:

$$\varphi=S_0x^{-n}[I_n(kx)-iY(kx)]e^{i\omega t};\ \left(n=\frac{m-1}{2}\right) \qquad (2)$$

where I_n i Y_n - Bessel functions of the first and second order.

In the finite length horn, the sound wave is reflected from the section (so called «reflection from the open edge» [18]), and in the horn there is an overlay of the direct and reflected wave, which causes resonance phenomena. This strongly complicates the solution of the problem [4].

«Gain of a horn» K proposed by A. Kharkevich [19] is used to evaluate the efficiency of the horn as a sound receiver. This value is determined by the ratio of sound pressure to the output horn membrane, created by a pulsating source, which is located at the entrance to the horn, in the case of horn presence P_p and in case of his absence P_0:

$$K=\frac{P_p}{P_0} \qquad (3)$$

In the work [4] graphs of the frequency dependence of the gain for exponential and parabolic horns are provided.

These data can serve as a basis for comparing the results of calculations obtained by different methods.

*2) **Method of electroacoustic analogies***:

It is expedient to use the method of electroacoustic analogies for simplification [7],[8], if use of the low-frequency asymptotics for the solution of the simulated system of the auditory or speech apparatus (overall dimensions of the system are much smaller than the sound wave length) is possible. The use of electroacoustic scheme simplifies the combination of different parts of a complex system.

An electroacoustic scheme corresponding to an inverse horn that works on reception are developed by Laurent [8] based on the Morse's theoretical researches [3].

General expression for the square of a horn intersection $S(x)$, as a function of distance x along its axis, looks like [8]:

$$S(x)=\frac{S_0}{ch^2\varepsilon}\cdot ch^2\left(\frac{x}{h}+\varepsilon\right) \qquad (4)$$

where S_0 - area of the internal section of the horn; ε and h - constant values, that depends of a horn's form; $\varepsilon=0$ - catenoid horn; $\varepsilon\to\infty$ - exponential horn; $\varepsilon=\frac{x_0}{h}-j\frac{\pi}{2}, h\to\infty$ -conical horn.

The general electroacoustic scheme of the horn is shown in the Fig.1.

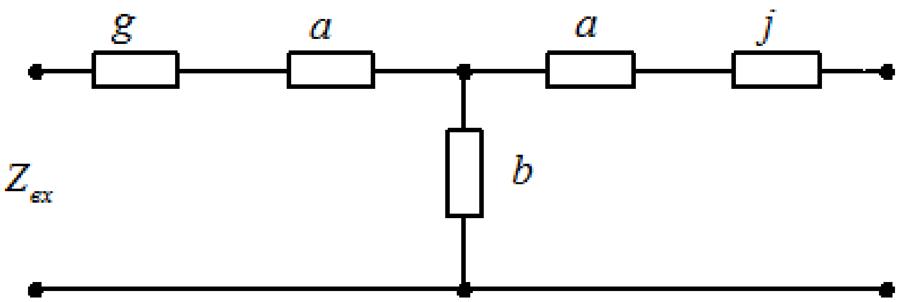

Fig. 1. Electroacoustic scheme of the horn

Values of the main elements of the scheme are based on the formulas:

$$\begin{cases} a = Z \cdot th\left(\dfrac{\gamma l}{2}\right); \\ b = \dfrac{z}{sh(\gamma l)}. \end{cases} \quad (5)$$

where Z - characteristic impedance:

$$Z = Z_0 \cdot \tau; \quad Z_0 = \frac{\rho c}{S_0}; \quad \tau = \frac{\gamma}{\gamma_0}\sqrt{1-\left(\frac{\omega_0}{\omega}\right)^2} \quad (6)$$

where ρ - medium density $\left[\dfrac{кг}{м^3}\right]$; γ - coefficient of propagation of the sound wave.

$$\gamma = \gamma_0 \cdot \tau; \quad \gamma_0 = \alpha + i\frac{\omega}{c}; \quad (7)$$

α - wave attenuation coefficient; ω_0 - critical frequency (loop frequency):

$\omega_0 = \dfrac{c}{h}$, where h - constant change of the horn's section.

Formulas for finding additional items depending on the type of speaker are presented in table 1.

$$\gamma_0 = ik, \quad (8)$$

where $k = \dfrac{\omega}{c}$ - wave number.

*1) **Exponential horn***

Let's present the changing of a horn intersection, according to [3]as:

$$S_l = S_0 \cdot e^{-h/l}, \quad (9)$$

where S_l - square of a horn intersection; l - horn length.

Then the parameter h will be equal to:

$$h = \frac{l}{\ln\dfrac{S_0}{S_l}}, \quad (10)$$

Based on this, we obtain the following formulas for finding the elements of the electroacoustic scheme for an exponential loop without loss:

$$\begin{cases} a = i\dfrac{\rho c}{S_0}\sqrt{1-\left(\dfrac{\omega_0}{\omega}\right)^2} \cdot tg\left[\dfrac{kl}{2} \cdot \sqrt{1-\left(\dfrac{\omega_0}{\omega}\right)^2}\right]; \\ b = \dfrac{\rho c}{S_0}\sqrt{1-\left(\dfrac{\omega_0}{\omega}\right)^2} \Big/ \left\{ i\sin\left[kl\sqrt{1-\left(\dfrac{\omega_0}{\omega}\right)^2}\right]\right\}. \end{cases} \quad (11)$$

Table I
Value of additional elements of the horn circuit

Horn type / Value of the scheme elements	Catenoid	Exponential	Conical
g	0	$\dfrac{z_0}{h\gamma_0}$	$\dfrac{z_0}{x_0\gamma_0}$
j	$-\dfrac{z_0}{h\gamma_0} cth \dfrac{l}{\gamma_0}$	$-\dfrac{z_0}{h\gamma_0}$	$\dfrac{z_0}{(x+l)\gamma_0}$

B. Calculation of the elements of an electroacoustic scheme for different types of horns

Let's consider the perfect case of a horn with rigid walls without losses. In this case, the coefficient γ_0 equals to

Value of the elements "g" and "j" are in accordance with table 1.

*2) **Conical horn***

For the conical horn, a constant change of section $h \to \infty$. Consequently, there is no locking frequency in the conical horn. This is true because a cone cut from a spherical volume limits the inner field. As the result, the value of elements "a" and "b" are based on formulas:

$$\begin{cases} a = i\dfrac{\rho c}{S_0}\cdot tgkl; \\ b = \dfrac{\rho c}{S_0} \Big/ (i\sin kl). \end{cases} \quad (12)$$

The elements "g" and "j" are based on formulas from the table 1. The value of the coordinate x_0 is founded for a certain horn size, while changing the flat cross of the horn with the corresponding spherical segment.

*3) **Catenoid horn***

For a catenoid horn, the change in cross-sectional square occurs according to the law:

$$S(l) = \frac{S_0}{ch^2\left(\dfrac{l}{h}\right)}, \quad (13)$$

As the result, the permanent change of section h is equal to:

$$h = \frac{l}{arcch\sqrt{\dfrac{S_0}{S_l}}}$$

The elements "a" and "b" of the equivalent electroacoustic scheme are determined by the formulas (11), and the elements "g" and "j" – according to the table 1. Moreover, in case of a catenoid horn, the element "g" turns out to be absent. The amplification gain graphs based on the power of an open exponential horn, obtained by the wave method [4], are shown in the Fig.2.

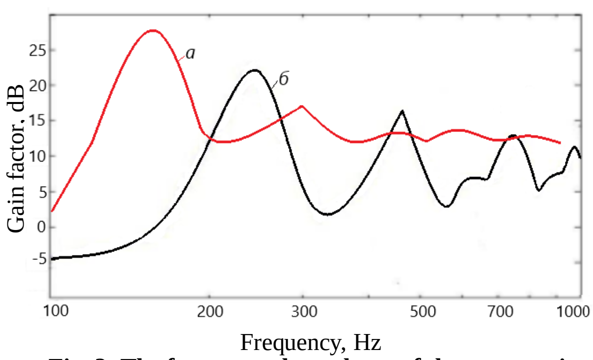

Fig. 2: The frequency dependence of the power gain factor of the receiving exponential horn: a – by the work results [[4]]; b – estimated data

C. Matching the results

In order to compare the results obtained by the wave method and the method of electroacoustic analogies, the data [4] are used. In particular, for the gain of the receiving exponential horn of the following sizes: square of the intersection 0.28 m^2; square of the outlet intersection 0.79 m^2; horn length 0.875m.

Theoretically, because of the large wave sizes of the horns, the comparison of the graphs shown in the image 2 is possible only up to 100Hz frequency. For higher frequencies, the application of the electroacoustic modeling technique is not fully correct. Nevertheless, despite the simplification of the calculations, the general nature of the coupling coefficient dependence frequency is maintained, although there is a resonance frequency shift.

The system «Ear canal-external auditory canal» has small sizes up to 20kHz frequency. Consequently, while applying to the calculation the method of electroacoustic analogies, we expect results that are more accurate.

*1) **The ear canal modelling with the help of receiving horns***

Schematic representation of the human's outer ear with the main dimensions, which are the basis for further calculations, are presented in the Fig 2.

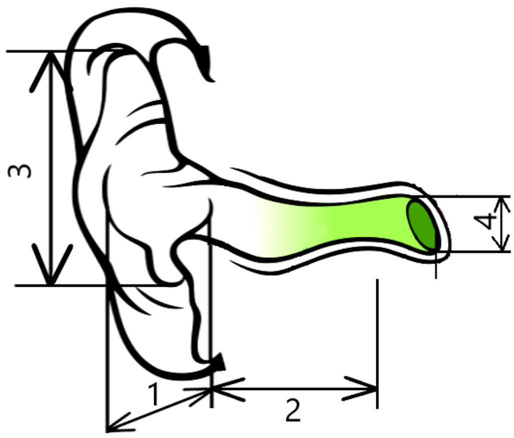

Fig. 3: Picture of an external ear

1- the length of cup-shaped entrainment of the ear canal $l_p = 0.02m$;
2- the length of the external auditory passage $l_P = 0.027m$;
3- input diameter of the ear canal deepening $D_0 = 0,026m$;
4- output diameter of the ear canal (equals to the auditory canal diameter) $D_l = 0,007m$

As a horn, we will consider the part of the ear canal, which corresponds to a cup-shaped entrainment.

We should note that since the conical horn is not a matching device for receiving a spherical wave with a narrow tube of the external auditory passage, in which a plane wave is spreading, we limit the calculations by the cases of exponential and catenoid horns.

Depending on the nature of the horn's load, it can be interpreted as open (acoustic load resistance $z_H = 0$) or closed ($z_H \to \infty$).

The Fig. 4,5 shows the graphs of the input acoustic resistance frequency dependence of the exponential and catenoid horns, calculated by the size of the entrainment of the ear canal. Acoustic resistance, normalized to its value at a frequency of 1000 Hz, is presented in dB.

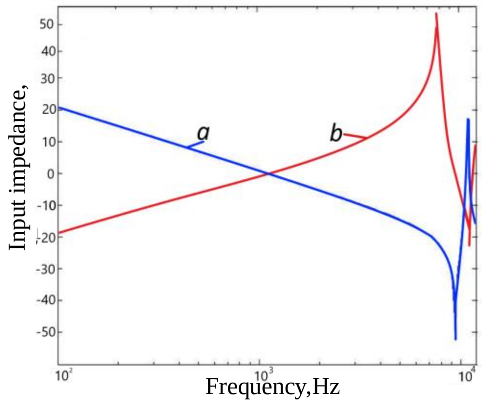

Fig. 4: Frequency dependence of the acoustic input resistance for the closed (a), and opened (b) exponential horn

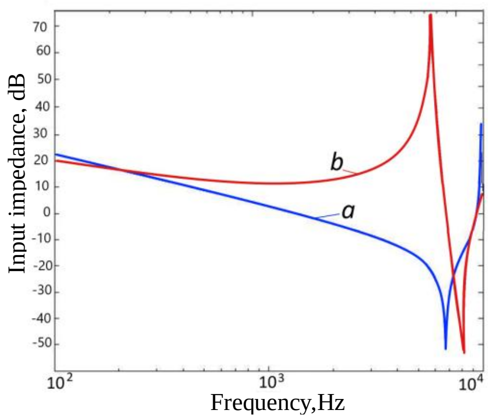

Fig. 5: Frequency dependence of the acoustic input resistance for the closed (a), and opened (b) catenoid horn

D. The ear canal system – external auditory canal

The external auditory canal modelling by the method of electroacoustic analogies is described in the paper [14]. The results obtained for a narrow rigid tube with the auditory canal size, are completely coincide with the theoretical calculations data [20].

The electroacoustic scheme of the combination of the receiver horn with a narrow tube is presented in the Fig. 6. The values of the elements A and B marked on the chart are determined by the formulas:

$$A = i\rho c S_e tg\frac{kl_{TP}}{2};\, B = \rho c S_e \Big/ i\sin kl_{TP}$$

where S_l external auditory canal square.

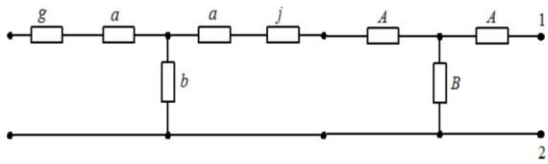

Fig. 6: The electroacoustic scheme of a horn, connected with a narrow tube

The results of the calculations of an input acoustic resistance of the external ear system using the catenoid horn are shown in the Fig 7.

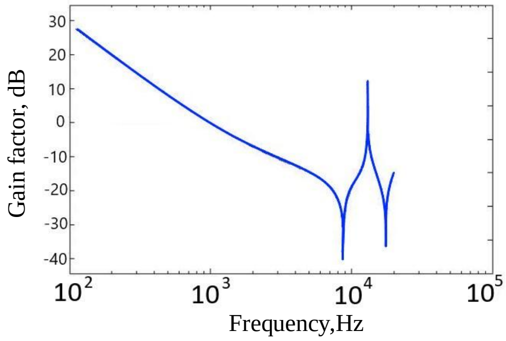

Fig. 7: Frequency dependence of the external ear acoustic input resistance for the ear canal modelling by the catenoid horn with an open external auditory passage

Fig. 8 shows the graphs of the external ear power gain by modeling the external ear with the catenoid horn (without a tympanic membrane). Gain factor counted by the formula (3) as well as for the horn.

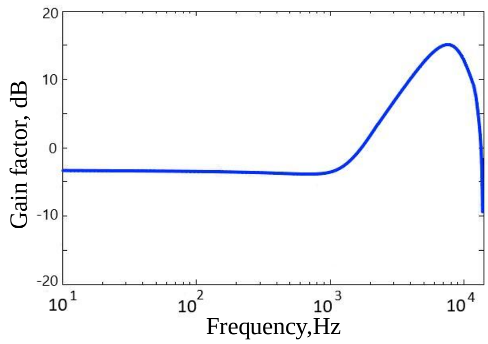

Fig. 8: Frequency dependence of the external ear power gain

E. Discussion of results

Analyzing the received graphs of the frequency dependence of the receiving horns input resistance (Fig. 3.4), we should note that the feature of a closed horn, as well as a closed narrow tube, is the transduction of the first resonant frequency to the antiresonance one.

For a closed exponential horn, the resonance frequency equals to 9.4 kHz, and for the catenoid is

6.7 kHz. The antiresonance frequencies for these horns are 10.5 kHz and 9.8 kHz.

For open horns, the resonance frequency is preceded by antiresonance. For an exponential horn, the resonance frequency is about 10.5 kHz, and the antiresonance is 9 kHz. For the catenoid horn, these values are lower and equals to 8.3 kHz and 6.7 kHz.

The values of the resonance and antiresonance frequencies practically change places when choosing the opposite extreme version of the load of the horn that indicates the correctness of the calculations.

The first frequency of the receiving horn resonance, loaded on the auditory canal, will occupy an intermediate value between the corresponding resonance frequencies of the considered extreme variants.

According to the experimental data provided in [2], the resonance frequency of the ear canal is about 5.5 kHz.

If during the experiment the microphone is installed at the entrance to the external auditory canal, then this situation corresponds to the model of the closed receiver horn.

For this catenoid horn, the resonance frequency is 6.7 kHz. The simulation of only the deepened part of the ear canal explains this difference in the resonance frequencies. Also, it explains by the possibility of inaccurate correspondence of the calculated horn and ear canal dimensions.

However, since the closed exponential horn has an even higher first resonance frequency, we believe that the two selected shapes of the horn catenoid horn is more suitable for the ear canal modeling.

The closed horn resonance and antiresonance frequencies are stored, when combining the horn's model with the electroacoustic scheme of the external auditory canal. This indicates that the loaded on the external auditory canal horn, is similar to the closed one. Relevant frequencies for the auditory canal [14] are most likely to shift to the higher frequencies. As a result, the resonance frequency of the system is observed in the area of 8-9 kHz, which improves the human perception of high-frequency sounds.

Finally, we will estimate the sound amplification factor with an external ear (Fig. 8). With sufficiently uniform involvement of the external ear in the frequency range (100-1000) Hz, where it practically does not participate in the amplification of the audio signal, at high frequencies there is a significant increase in sound energy (almost 15 dB).

The maximum gain in energy occurs at 6-7 kHz, where the spectrum of sizzling and whistling sounds is concentrated [6]. This indicates the need to preserve the ear canal for the eloquence of the speech sounds.

V. CONCLUSIONS

The work confirms the possibility of using an inverse horn working on the reception of the acoustic waves for modeling the human ear.

The problem is solved by the method of electroacoustic analogies, the application of which is appropriate due to small wave size of the external ear system.

The created electroacoustic scheme, which corresponds to the combination of the ear canal and external auditory canal, allows you to get the frequency dependence of the external ear gain.

From the gain factor analysis, we can see that the ear canal has the properties of a high frequency oscillations amplifier, and in conjunction with the auditory canal, the amplification region expands and occupies a frequency range in the range from 1 kHz to 20 kHz.

REFERENCES

[1] Gelfand S. Slukh: vvedenie v psiholigicheskuyu i phisiologicheskuyu acousticu. - M.:Meditsina, 1984.-350s.
[2] Al'tman Y. Rukovodstvo po audiologii /Y. Al'tman, G. Tavartkiladze. -M.:DMK Press, 2003.-360 s.
[3] Morz F. Kolebaniya i zvuk. -M.: Gostekhizdat, 1937. -465s.
[4] Goutin Y. Izbranniye trudy. –L.:Sudostroyeniye, 1977.-597s.
[5] Furduyev V. Electroacoustika.-M.: Gos. Izd-vo tekhn.-teor.lit., 1948.-256s.
[6] Luniova S., Didkovskiy V., Pedchenko O. Acoustica movorvorennia//Navchalniy posibnyk.- Lap Lambert Publishing, 2018.-135s.
[7] Fant G. Acousticheskaya teoriya recheobrazovaniya.-M.:Nauka, 1964.-284s.
[8] Laurent T. Matematisk behandling av kontinuerligt inhomogena ledningar medelst ekvivalenter samt exempel på metodens användning för olika praktiska problem", Tekniska meddelanden från Kungl, telegrafstyrelsen, pp. 113, 1940.
[9] Luniova S., Didkovskiy V., Kalinin S. Metod analisu zvukovykh poliv u vuz'kyh conichnih trubah z zhorstkymy stinkamy//Electronika i zvyazok, №6, 38-43, 2013.
[10] Marieev G.O. Sovriemenniye priedstavleniya o sriednem ukhe I ego matematicheskiye modeli// Saratovskiy nauchno-meditsinskiy jurnal- 8. № 1. S. 096-100, 2012.
[11] Purcell D.W. Estimating bone conduction transfer functions using otoacoustic emissions// Journal of the Acoustical Society of America, vol.144, no. 2, pp. 907-917, 2003.
[12] Frolov K.V. Infrazvuk, vibratsiya, chelovek. –M.: Machinostroyeniye, 1946.-304s.
[13] Nayda S.A. Formula serednyogo vukha liudyny v normi. Vidbyttya zvyky vid barabannoyi peretynky//Akustychniy visnyk.-T.5, №3, s. 46-51, 2002.
[14] Luniova S.A., Morozko T.V., Zamsha K.S. Mozhlyvosti modeliuvannya povitryanoho kanalu slukhovoi systemy// Microsystemy, electronica ta akustica, №4, s. 82-87, 2018.
[15] Reley (J.V.Stratt). Teoriya zvuka.- T.1. – V.-L.: Gos. Izd-vo tekhn.-teor.lit., 1940.-499 s.
[16] Webster A.G. Acoustical impedance, and theory of horns and of the phonograph//Peoc.Nat. Acad.Sci., 5, 1919.- p. 275-282. Reprinted in I.Audio Eng.Soc., 1977, v.25(1-2), pp. 24-28.
[17] Ballantine. S. Journal of the Franclin Institute, vol, 203, pp.85-101, 1927.
[18] Rzhevkin S.N. Kurs lektsiy po teorii zvuka.- M.: Izd-vo MGU, 1960.
[19] Kharkevich A.A. Electroacusticheskaya apparatura. –M.:Leningrad, 1933.-252 s.
[20] Flangan J. Analiz, sintez i vospriyatiye zvuka. –M.: Svyaz',1968.