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Modeling of sound propagation in the closed space and its interaction with obstacles

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1. Introduction

When the problems of noise reduction in the dwelling, industrial and other premises are being solved, the investigation on sound propagation in the closed space and its interaction with obstacles becomes indispensable. As essentially the sound propagation is the distribution of sound pressure, thus when the acoustic projecting of closed space (here the premises of various purposes are considered) is being implemented, it is often important to know and secure certain level of sound pressure in separate points. The values of this parameter in the analyzed object depend on a number of factors: geometry of the room, sound absorption of its walls, ceiling, floors, present things, nature of noise source, etc.

All this shows that the investigation on sound propagation in the closed space and its interaction with obstacles (for example, acoustic screens that limit closed space) is a complex task that needs theoretical modeling and experimental tests to be solved. Good choice or creation of theoretical model accelerates a lot the solution of the aforementioned task and guarantees the sufficiently accurate determination of the level of sound pressure in the closed space at any point. There are lots of bibliographical sources, which model the origin of acoustic field, while character of distribution in space and interaction with obstacles are described using the computational models of finite elements (FE), boundary elements (BE), finite differences (FD) and analytical models. When the acoustic tasks are being solved using the analytical method, the Kirchof-Helmholtz equation, the theory of geometrical diffraction, are used the most frequently. When the analytical acoustic models are being discussed, it is possible to state that they are more universal. However they describe the interaction of acoustic medium and structure approximately, more empirically [1]. The acoustic field modeled by them is diffusive, while the excitation source is point source. The method of finite differences is widely used to solve the problems of visualization of sound propagation in the rooms and reflection from the obstacles [2, 3]. When this method is used, the sound wave is expressed by the differential equations with partial derivatives. The main advantage of this method is relatively small need of computer resources, thus it is often used to model transient acoustic processes in the homogeneous field.

The method of boundary elements is also used to solve acoustic tasks [4, 5]. The environment is divided into direct (based on classical Helmholtz integral equation, where acoustic pressure and velocity of particles are the primary variables) and indirect (where primary variables are the differences of pressure and its direction's gradient beyond the boundary) [6, 7]. When this method is modeled, the discretization problem is encountered; in the area of high frequencies the number of elements has to be increased in order to receive accurate solution, and this increases significantly the usage of computer resources. When the interaction of partition with acoustic field is calculated, the plane of structure's center is used instead of its surface. In such a case when the tasks are solved by BE method, using the aforementioned indirect formulation, the thickness of the acoustic partition is not taken into account.

Another widely used method for formation of acoustic models is the method of finite elements. As well as in the case of finite differences, when this method is used, the wave's equation is being solved (taking into account boundary conditions) by dividing the space (in some cases, also the time) into elements. Then the wave's equation is expressed in the discreet set of linear equations for these elements. The method of finite elements could be also used to model the transfer of energy between separate surfaces, or energy exchange. The advantage of this method [8-10] is that it could relate directly the structural and acoustic mediums and under changing modeled environmental conditions evaluate their interaction, which is very important for formation of acoustic partition systems. This method is used to solve the three-dimensional tasks of acoustic medium, and the received results show completely the character of the acoustic field in the analyzed space. To note the disadvantages of this method, it shall be said that when the conditions of the modeled environment and excitation change, the model has to be made anew, and this usually needs a lot of time [11], while the solved tasks of free space are formed in the area of low frequencies. After the literature on the modeling on the basis of FEM had been reviewed, it became evident that this method is used to solve various acoustic tasks: investigation of acoustic properties of various materials, modeling of acoustic partition systems, investigation on sound propagation in various cavities, investigation on interaction between structural and acoustic mediums, etc. The main advantage of this method if compared to other ones, is that it could be used to model heterogeneous acoustic medium, to assess several excitation sources and to receive complete character of acoustic field in the analyzed space. The works [12] modeled two sources of different frequencies and sound pressures, which work separately and at the same time, as well as impulse (impact) excitation. While modeling the tasks of harmonic analysis and transient process were solved. The steady state acoustic fields received from separate excitation sources during harmonic analysis were summarized, according to the superposition principle, and in such a way the whole acoustic field was calculated that appears when several sources of different frequencies are acting at the same time. According to the received results, when the FE method formed by 2D model is used, it is possible to model the acoustic excitation that appears in the real conditions. However in order to model the sound propagation as adequately as possible in the closed space and its interaction with obstacles, besides the varying excitation conditions, the sound transmission through the obstacle should be taken into account, which is very important when the direct field of sound pressure is predominant if compared to the reflected field of sound pressure. Thus with regard to the aforementioned, the purpose of this work is

- to create the model of acoustic field that takes into account the sound propagation in the closed space and its interaction with obstacles in the real conditions, following FEM;
- to analyze the adequacy of this theoretical model for real fields and its application possibilities for designing of mobile and controlled systems of noise reduction.

2. Model of the sound propagation in the closed space on the basis of FEM

The interaction of structure and acoustic mediums in the formula of finite elements is described as follows:

$$\begin{bmatrix} [M_e] & [0] \\ \rho_0 [R_e]^T & [M_e^P] \end{bmatrix} \begin{Bmatrix} \{\ddot{u}_e\} \\ \{\ddot{P}_e\} \end{Bmatrix} + \begin{bmatrix} [C_e] & [0] \\ [0] & [C_e^P] \end{bmatrix} \begin{Bmatrix} \{\dot{u}_e\} \\ \{\dot{P}_e\} \end{Bmatrix} + \begin{bmatrix} [K_e] & -[R_e] \\ [0] & [K_e^P] \end{bmatrix} \begin{Bmatrix} \{u_e\} \\ \{P_e\} \end{Bmatrix} = \begin{Bmatrix} \{F_e\} \\ \{0\} \end{Bmatrix} \tag{1}$$

where $\left[M_e^P\right]$, $\left[M_e\right]$ are matrixes of the mass of acoustic medium and structure accordingly; $\left[C_e^P\right]$, $\left[C_e\right]$ are damping matrixes of acoustic medium and structure; $\left[K_e^P\right]$, $\left[K_e\right]$ are stiffness matrixes of acoustic medium and structure; $\rho_0\left[R_e\right]^T$ is relation matrix of acoustic medium and structure; $\{P_e\}$ is vector of pressure in the nodes and its derivatives $\{\dot{P}_e\}$, $\{\ddot{P}_e\}$ with regard to time; $\{\ddot{u}_e\}$ is vector of nodal displacement and its derivatives $\{\dot{u}_e\}$ $\{\ddot{u}_e\}$ with regard to time; $\{F_e\}$ is load vector; ρ_0 is density of air medium.

When the theoretical model was formed, the FEM software ANSYS 10 was used. The analyzed 2D model consisted of acoustic and structural mediums. In order to model them, the elements FLUID29 and PLANE42 were used. As the acoustic package FEM of the ANSYS 10 software does not take into account the loss of sound energy when the sound is transmitted through the obstacle, the methodology used for this model is specified in [13]. According to this methodology, when pressure of the incident sound wave is known, the loss of sound pressure is calculated when the wave passes from one medium to another, and the value of sound pressure is determined on the boundary of mediums – according to the scheme of the process shown in the Fig. 1, that would be the sound pressure on the junction of the second and third mediums. In such a way when the sound propagation in the closed space is modeled, firstly the system is excited by the sound source of certain size and frequency, and the field of sound pressure is determined in the closed space, as well as on the boundary between the incident wave and structural medium (boundary between the first and the second medium in the Fig. 1).

According to the present data, when the aforementioned methodology is used, the loss of sound pressure is calculated when the sound wave passes through the structural wave, as well as the values of sound pressure on the boundary of the second and third mediums (Fig. 1). These values are later used to excite and calculate sound pressure in the acoustic medium. Eventually the values of sound pressure calculated in the first stages are summarized using the principle of superposition, and acoustic field in the closed space with obstacle is calculated taking into account the loss of sound energy when the sound wave passes the obstacle. In order to computerize the calculations using the methodology [14], the ANSYS macro file was created in the programmable medium. This allowed making the calculations much faster.

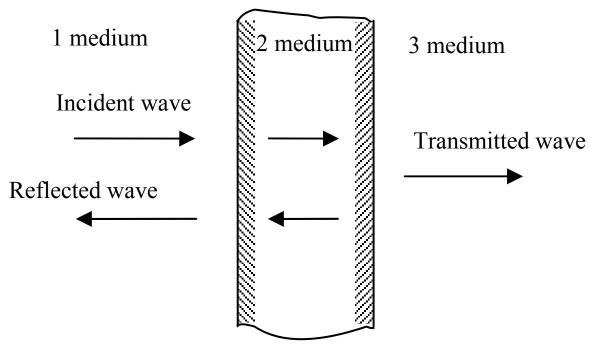

Fig. 1 The principal scheme of sound's transmission from the first medium to the third through the second medium

The noise sources in this work are modeled in the area of moderate frequencies (λ~l), i.e. in the area, to which the majority of industrial machines and equipment belongs and that is very topical in the machine acoustics. As the room of simple form (Testing laboratory of machine vibrations and acoustic noises of Technological Systems Diagnostics Institute) was used as the prototype of theoretical model, the method of point sources was used to model the noise sources. This method is simple and easily applicable. Two excitation sources were used, which frequencies were 1000 and 2000 Hz. The values of acoustic characteristics of walls, ceiling, floors and partition used in the model were taken from certain documentations of manufacturers: air density $\rho = 1.2$ kg/m^3; velocity of sound wave propagation $c = 335$ m/s; suppression coefficient of air sound $\mu = 0$; density of sound suppression's partition $\rho = 750$ kg/m^3; elasticity module of sound suppression's partition $E = 3.4 \cdot 10^9$ Pa; velocity of sound propagation in partition's material $c_p = 675$ m/s; coefficient of sound suppression's partition $\mu = 0.9$. The received results of the theoretical experiment are presented below.

According to the received results of theoretical experiment, when the interaction of propagated sound with obstacles is being modeled taking into account the loss of sound pressure while passing through the obstacle, the distribution character of sound pressure in the area behind the partition changes (Figs. 2 and 3). These figures show the excitation when two sources of different frequencies are acting at the same time.

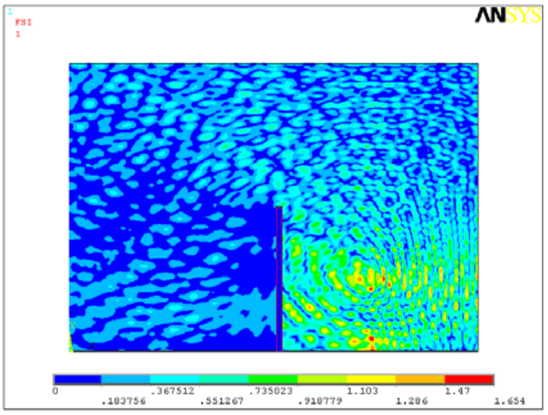

Fig. 2 Sound pressure in the closed space when two excitation sources of different frequency are used at the same time and taking into account energy losses during sound transmission through the obstacle

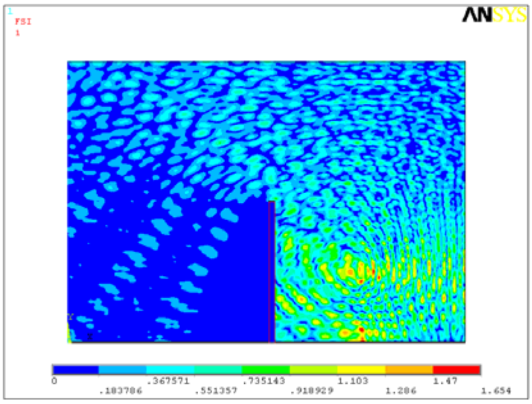

Fig. 3 Sound pressure in the closed space when two excitation sources of different frequency are used at the same time and not taking into account energy losses during sound transmission through the obstacle

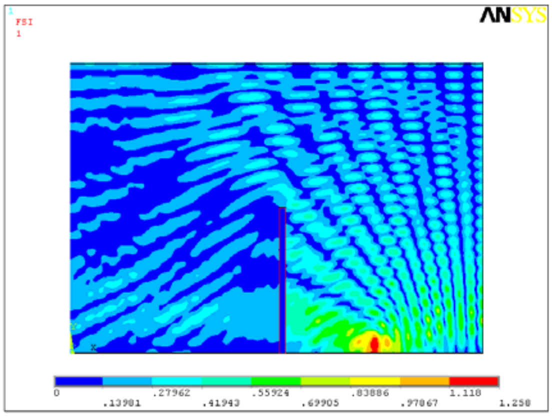

Fig. 4 Sound pressure in the closed space when 1000 Hz excitation is used and taking into account energy losses during sound transmission through the obstacle

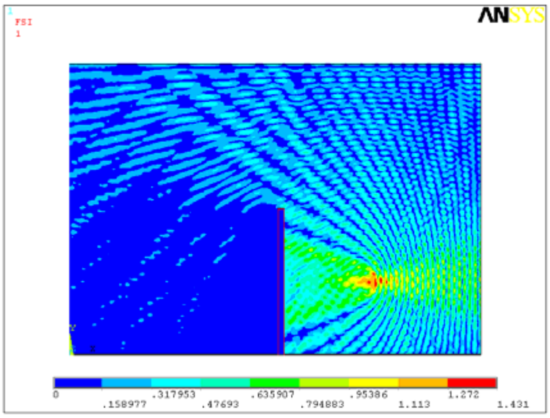

Fig. 5 Sound pressure in the closed space when 2000 Hz excitation is used and taking into account energy losses during sound transmission through the obstacle

When the cases of excitation sources of different frequencies are compared (Figs. 4 and 5), it is seen that the loss of sound pressure generated by the source of 2000 Hz frequency while passing through the obstacle is bigger than in case of 1000 Hz source. Fig. 6 shows the values of sound pressure in different measurement points (the position of these points is shown in Fig. 7).

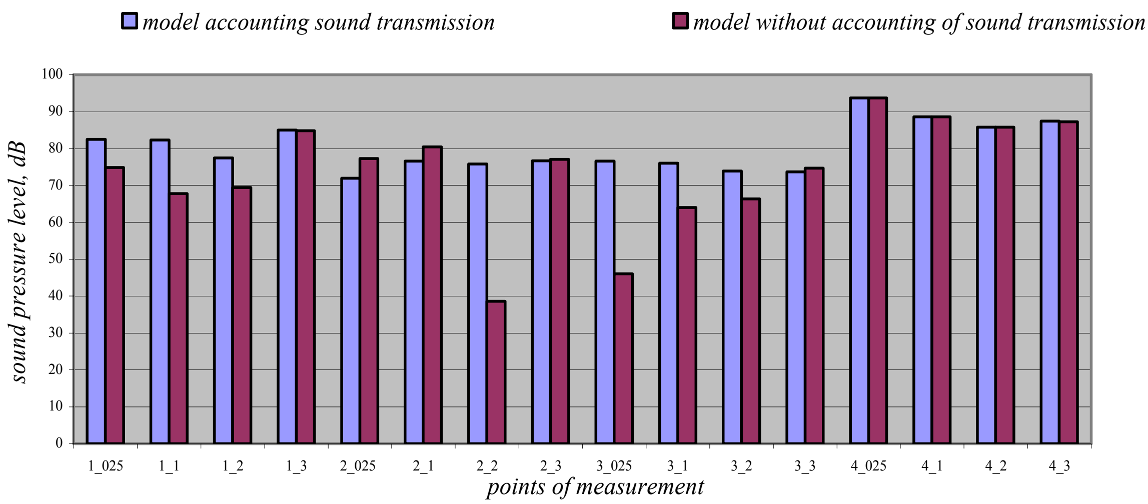

Fig. 6 Values of sound pressure in different measurement points using different theoretical models

3. Experimental test

In order to check the adequacy of the theoretical model, the experiment was done, and its results were compared with the theoretical ones. In order to imitate the experimental test, the initial data were selected accordingly: value of sound pressure generated by sound source, its frequency, absorption coefficients of room's planes and partition, etc. The acoustic partition (acoustic screen) was used in the experimental test. During the experiment the values of sound pressure were measured in front of and behind the acoustic partition in certain points. The principal scheme of experimental measurement of sound pressure is shown in the Fig. 7.

Marking of points shown in this scheme means the coordinates of certain point, for example, the point marked as 3_025, has *x* coordinate of 3 m, and *y* coordinate – 0.25 m, point 1_3 has *x* coordinate of 1 m, and *y* coordinate of 3 m, etc. The *x* coordinates of the first sound source shown in Fig. 7 are 5 m, *y* – 0.25 m; the *x* coordinate of the second sound source is 5 m, *y* – 1.2 m.

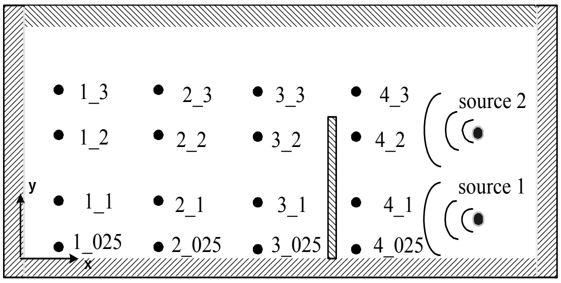

Fig. 7 Principal measurement scheme of sound pressure

When the analysis of sound propagation in testing laboratory and its interaction with obstacles was done, the aforementioned method on the basis of FEM was used together with harmonic analysis, during which the harmonic excitation at certain values of sound pressure in the analyzed frequencies was performed. The acoustic field in the testing laboratory was created using two loudspeakers. The values of sound pressure in different points of testing laboratory in front of and behind the partition were measured using the device Investigator 2260 and analyzer of vibrations and noise PULSE 3560 [15]. The received results of theoretical and experimental test are presented below.

According to the Fig. 8, the results of the theoretical model that takes into account losses of sound pressure during sound transmission through the obstacle coincide significantly better with the experimental results, if compared to the previous model [12], where it was considered that a part of sound energy radiated by the source could only be absorbed or reflected. When the values of sound-pressure level are compared separately in the height of one and two meters (Figs. 9 and 10), the area of so called parti-

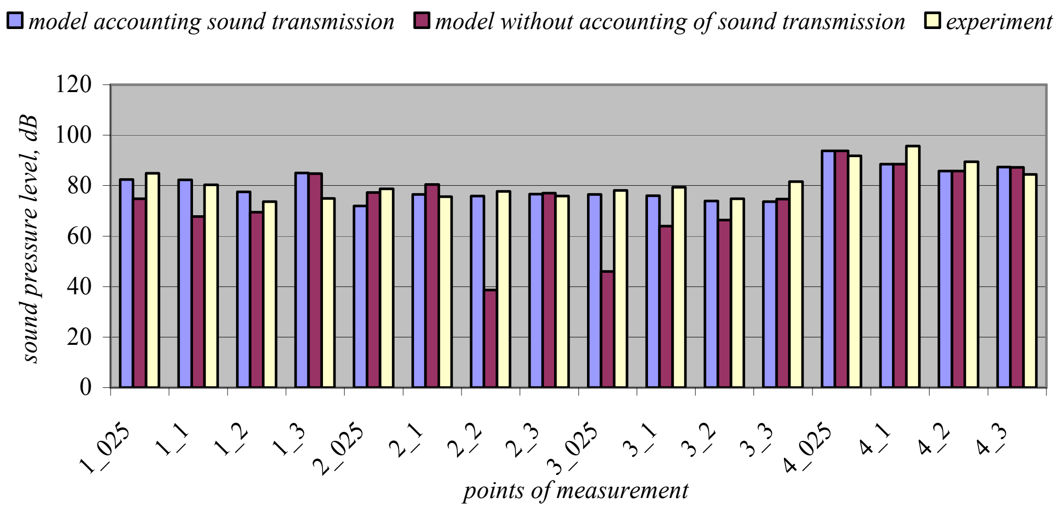

Fig. 8 Values of sound pressure in different points in the testing laboratory measured using the theoretical models on the basis of FEM and experimentally determined (arrangement of measurement points is shown in Fig. 7)

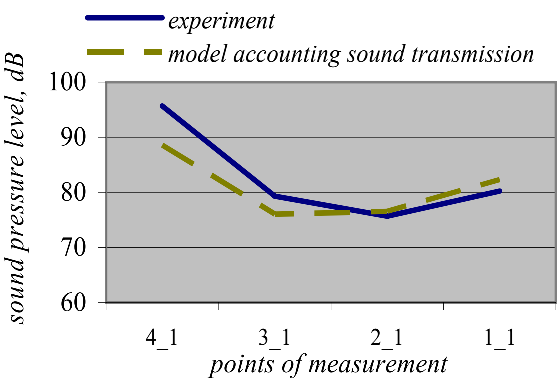

Fig. 9 Level of sound pressure was measured in the height of one meter in different points when excitation of 1000 and 2000 Hz is used at the same time

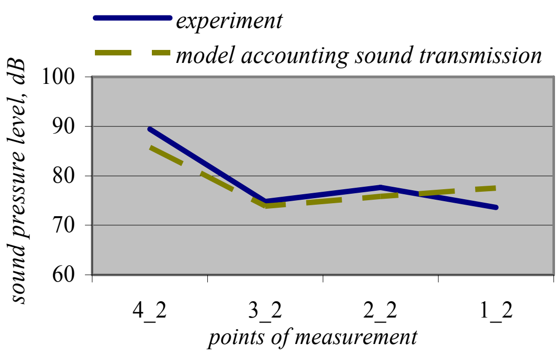

Fig. 10 Level of sound pressure was measured in the height of two meters at different points when excitation of 1000 and 2000 Hz is used at the same time

tion's "shadow" (place behind the partition) is clearly seen, where the values of sound pressure are significantly lower than these in front of the partition. The dependencies received during the experiment confirm this. Thus it is possible to state that the acoustic field created in the analyzed closed space is direct. When the values of sound pressure's level are compared at the measurement points 3_1 and 3_2, located immediately behind the partition at the height of one and two meters, it is seen that the level of sound pressure at point 3_1 is higher by several decibel than at point 3_2. This could be explained by the direction of sound emitted by the sources. That is, the point at the height of one meter, gets into the sound front emitted by the sources, and the waves that have passed through the obstacle and that has passed by it are summarized. The values of sound pressure's level of the points, which are furthest from the partition, which *x* coordinate is equal to one meter, at the heights of 0.25 m and 1 m are higher than of the points, which *x* coordinate is equal to 2 and 3 meters (Figs. 11 and 12).

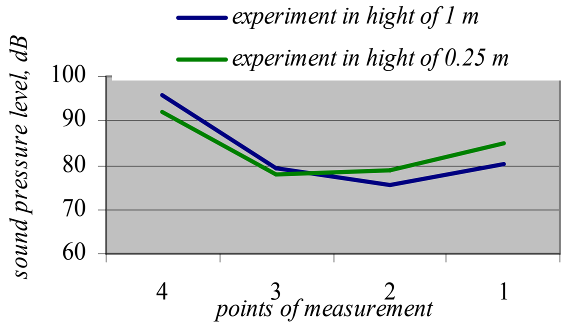

Fig. 11 Level of sound pressure measured at different heights at different points when excitation of 1000 and 2000 Hz is used at the same time

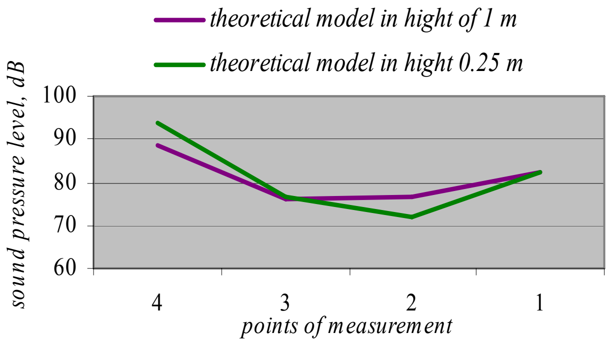

Fig. 12 Level of sound pressure calculated with the help of model at different heights at different points when excitation of 1000 and 2000 Hz is used at the same time

The increase of the values of sound pressure level at the aforementioned points could be explained by the fact that the closer they are to the surfaces reflecting the sound well (in this case these are the floors of testing laboratory and one of its walls), the reflected sound wave is summarized with the waves that have passed through the obstacle and that have passed by it. The data of experiment (Fig. 11) confirm these results received with the help of theoretical model (Fig. 12). The theoretical test has analyzed additionally the interaction of the sound propagated in the closed space with the obstacle, depending on its thickness. The received results are presented below.

According to Fig. 13, different thickness of partition affects the character of sound pressure in the area behind the partition. When thickness of the partition is 0.1 m (Fig. 13, a), the gradient of sound pressure acquires bigger values than in case when the thickness is 0.3 m (Fig. 13, b). It is noticed that in the case of thinner partition the gradient of sound pressure is the biggest in the directions of the wave that has passed through the obstacle and that has passed by it, while in the case of thicker partition sound pressure varies the most in the direction of the wave that has passed by the obstacle. The values of sound pressure level calculated with the help of the model at certain points (Fig. 14) show that they are significantly smaller in the case of thicker partition.

This shows that changes of geometrical parameters of the partition can change noticeably the character of

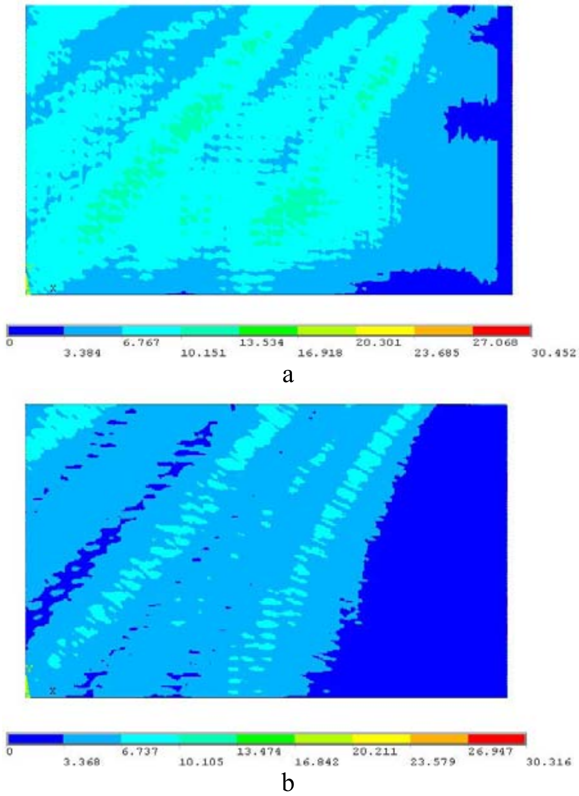

Fig. 13 Gradient of sound pressure in the area behind the partition: a – partition's thickness 0.1 m; b – partition's thickness 0.3 m

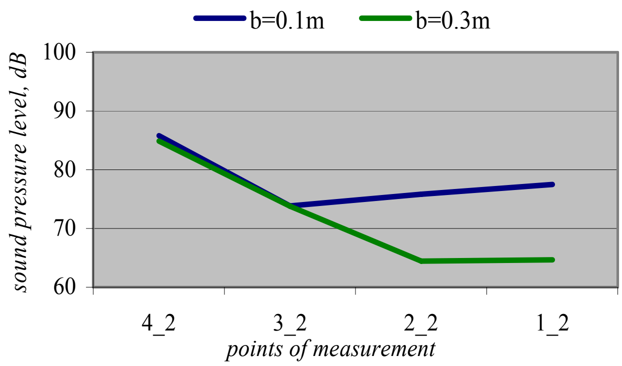

Fig. 14 Level of sound pressure calculated with the help of the model at the 2 m height, when different excitation sources of 1000 and 2000 Hz frequency are used at the same time at different thicknesses of the partition

acoustic fields and the values of sound pressure at certain points. These results confirm the statements specified in the bibliographical source [15].

4. Conclusions

The model of acoustic field that evaluates sound propagation in closed space and its interaction with obstacles in real conditions was created on the basis of FEM. This model differs from the previous one [12], because it additionally evaluates the sound transmission through the obstacle when several excitation sources of different frequency are used at the same time. The test of adequacy of the theoretical model showed that it reproduces real fields adequately and that it can be used to analyze the sound propagated in closed space and its interaction with obstacles, as well as to apply it for designing of mobile and controlled systems of noise reduction.

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GARSO SKLIDIMO UŽDAROJE ERDVĖJE BEI SĄVEIKOS SU KLIŪTIMIS MODELIAVIMAS

R e z i u m ė

Darbe nagrinėjamas uždaros erdvės akustinių laukų modeliavimas BEM pagrindu. Pateiktas sukurtas modelis, aprašantis garso sklidimą bei jo sąveiką su kliūtimis. Pateikti akustinio lauko teorinio modelio adekvatumo realiems laukams tyrimo rezultatai.

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MODELING OF SOUND PROPAGATION IN THE CLOSED SPACE AND ITS INTERACTION WITH OBSTACLES

S u m m a r y

On the basis of FEM the modeling of acoustic fields in closed space is analyze in the work. It analyzes the model that takes into account sound propagation in the closed space and its interaction with obstacles. The results of the adequacy of theoretical model of acoustic field to the real fields are presented.

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МОДЕЛИРОВАНИЕ РАСПРОСТРАНЕНИЯ ЗВУКА В ЗАКРЫТОМ ПРОСТРАНСТВЕ И ВЗАИМОДЕЙСТВИЕ ЕГО С ПРЕПЯТСТВИЕМ

Р е з ю м е

В работе на базе МКЭ рассматривается моделирование акустического поля в закрытом пространстве. Представлена разработанная модель распространения звука и его взаимодействие с препятствием. Представлены результаты адекватности теоретической модели поля реальному акустическому полю.

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