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OPTIMISATION OF ACOUSTICAL SHIELDS

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ABSTRACT

Excessive noise is still one of the harmful reality of our surrounding and consequently it is still in the focus of investigations for many specialists. Often it is not possible to reduce noise in the source as well as by active way and therefore it became necessary to use passive noise control means. This paper is devoted to investigation of acoustical shields which might be used at work places situated as inside buildings as at open places and on machines and to a possibility of optimization of shield parameters. A method for calculation of acoustical shields effectiveness and the procedure of analytical optimization are described in the paper. It is suggested that there are two most important actions should be done in order to noise reduction. These are - first of all, providing of required noise reduction levels, and the second - making this with the lowest expenses. It was derived that in that case, cost of a shield will depend on its material and square. The algorithm and software for interactive optimization, in other words, selection of the parameters of a shield, is obtained. Examples of numerical simulation are also presented.

INTRODUCTION

Noise exposed in the work area is one of the most unfavourable factors influences people at work. Being under excessive noise for a long period people become under such negative sensations as fear, anxiety, irritation and fatigue and moreover noise treatment might be a reason of different diseases like metabolism or cardio violations, wrong functions of kidneys or circulatory system. At the same time noise exposure might cause an accident situation or traumas. Problem of noise control is still actual taking into account continuing of enhancement of trauma accidents at operation areas and increase of professional diseases due to excessive surrounding noise influence what brings productivity reduction.

As it is shown in literature [1] there are many passive noise control means (sound proofed enclosures, cabs, mufflers, acoustical barriers as well as sound absorption systems) using for noise control at work area. Among these subjects it is suggested to consider acoustical shields as a very perspective means for noise reduction. Multifunctional elements of work station equipment (remote control panels, shelves divide work area, various protected elements, and the like) as well as specially designed acoustical shields might provide required noise reduction.

DESCRIPTION OF THE THEORETICAL MODEL

All ideas of modern acoustics is based at three main theories: wave, geometrical optics, and statistical. Wave theory allows to consider wave nature of sound as a strict physical task. Geometrical optics theory based on the light ray conception interprets geometrical optics features for acoustical problems. Statistical theory admitting certain idealisation of physical processes and not considering wave nature of sound is based on the method of energy summation of the signals. Many authors from Kirchhoff and Redfearn to Retinger and Maekawa devoted their investigations to acoustical shields. Nevertheless investigations shows that most of existing methods are not valid for diffraction angles bigger than 60 degrees. But in reality there are many work stations were noise source and receiver are situated very close to each other what means existence of big angles of diffraction (more than 60 degrees, and sometimes more than 100 or 120 degrees).

A new method for acoustical shields estimation is proposed by the authors. It is supposed to use the statistical theory of acoustics for the estimation taking into account random character of acoustical signal. Elaborated method allows to take into account features of shield construction and its location in a space, as well as acoustical features of nearby reflecting surfaces. Based on the Hyugense principal and Maekawa's assumptions [2] it is suggested that sound energy passes through and around a shield is generated by the set of secondary sources, when shield edges are presented as linear radiators (the length of a radiator is equal to the length of a shield side), and shield body and holes between a shield and nearby surfaces are presented as plane radiators with sizes of a shield and holes, respectively. Thus, energy in the specific point (at the receiver) are the sum of energy of different radiators (linear and plane, as well) which are presented, in their turn, as sets of noncoherent point radiators placed at the line or at the plane, respectively, with random phases what allows not to consider wave nature of sound [3]. Describing model takes into account sound diffracting around a shield in the zone of the deep acoustical shadow, propagation of wave energy through the shield body and sound energy reflected from a nearby surface. Acoustical shield effectiveness (ΔL) as an insertion loss it is suggested to estimate as a difference of sound pressure levels in the receiving point between sound came to the point without a shield and with a shield:

$$\Delta L = 10\lg\left(\frac{1}{(R+d)^2} + \frac{16\pi(1-\alpha')}{A'} + \frac{(1-\alpha_1)}{H^2+0.25(R+d)^2}\right) -$$

$$-10\lg\left(\frac{4\tau(1-\alpha)}{R^2}\arctan\left(\frac{ab}{2d\sqrt{4d^2+a^2+b^2}}\right) + \sum\frac{2\beta_i}{R^2 d_i} + \frac{2\pi(1-\alpha_1)}{H^2+0.25(R+d)^2} + \right. \tag{1}$$

$$\left. + \frac{4}{R'}\arctan\left(\frac{ah}{2d'(4(d')^2+a^2+h^2)}\right) + \frac{32\pi(1-\alpha'')}{A''}\right) + 8, \quad \text{dB}$$

where a, b are the width and the height of a shield, respectively; R, d are the distances from noise source and the receiver to the shield, respectively; H, h are the heights of a noise source location and a shield location, respectively; τ, α are the sound transmission and absorption coefficients of a shield; β_i is a diffraction coefficient at the i-edge of a shield; d_i, d' are the distances from the receiver to the i-edge of a shield and to the centre of a reflecting surface, respectively; α', α'' are the sound absorption of a building without shield installation and with it; α_1 is a sound absorption coefficient of a reflecting surface ($\alpha_1 = \alpha_{material}$ while h>0 and $\alpha = 0$ while h=0); A' and A" are equal squares of sound absorption of a building without shield and with it.

To test elaborated model a set of experimental investigations of acoustical shields was carried out. Analysis and comparing of theoretical calculations with results of experimental work shows rather good agreement.

EXAMINATION OF THE THEORETICAL MODEL AND SEARCH FOR AN OPTIMAL ACOUSTICAL SHIELD CONSTRUCTION

As it is shown in the formulae (1) when a shield is fixed its effectiveness depends on its geometrical parameters and its acoustical properties. Thus, certain level of noise reduction might be reached for acoustical shields of different dimensions what in its turn will definite the price of noise reduction means or in other words, economical effect of noise reduction. It is desirable to obtain required level of noise reduction with minimal expenses what raises optimisation task to be decided. Solution of the optimisation task cannot be find from experiments due to necessity of a huge amount of tests and, consequently, necessity of additional time and money. Presented formulae (1) allows significantly simplify shield optimisation due to a possibility of analytical solution obtaining.

In total, price of a shield depends on its geometry and material. Due to a limit of materials it is suggested at the first stage of optimisation to consider all characters of material as constants while geometrical parameters will be considered as the main variables. Such an approach brings a finite search for an optimal material at the second stage of optimisation.

Taking into account that the price of a shield is proportional to its square [1] it is suggested to consider shield square as a purpose function. Thus, the problem of minimisation of shield cost with providing required noise reduction ΔL might be presented as follows:

$$S := ab \rightarrow 0 \qquad (2)$$
$$\inf \varphi(a,b) := -\Delta L(a,b) + c,$$

where $\Delta L(a,b)$ is calculated by equation (1) and constant c is equal to noise reduction level at the frequency of 1000 Hz and might be varied from 3 to 14 dB.

For simplification it is proposed to consider acoustical shield situated at the nearby surface without a hole between a shield and a surface what means that there are only three ways for diffraction. Moreover it is supposed that noise source and receiver are symmetrical, respectively the centre of a shield.

Solution of a problem of optimisation is based on a method of infinite Lagrange multipliers. Lagrange function $\Phi = ab + \lambda[\Delta L - const]$ depends on three variables: shield width a, its height b, and on Lagrange multiplier λ. Extreme conditions for the mentioned function is also presented by three equations: first coincides with the link equation of the problem (2), and two others are derivatives by a and b of Lagrange function:

$$\varphi(a,b) :== \Delta L(a,b) + c = 0$$
$$\Phi'_a = b + \lambda \frac{\partial \Delta L}{\partial a} = 0 \qquad (3)$$
$$\Phi'_b = a + \lambda \frac{\partial \Delta L}{\partial b} = 0$$

After excluding of parameter λ two rest equations might be presented as follows:

$$\frac{\partial \Delta L}{\partial \ln a} - \frac{\partial \Delta L}{\partial \ln b} = 0. \qquad (4)$$

The system (3) has a numerical solution. The most difficult thing is to choose valid range for a and b variations. To determine the boundaries of such a range lets analyse function φ which is the left parameter in the link equation. While a and c are fixed φ becomes the function depending on only one argument - shield height b. Its graphic illustration is presented at the Fig. 1 where curves 1, 2, and 3 describe sound pressure levels for a=1m, 2m and 3 m, respectively.

As it is shown at the Fig. 1 investigated function is not monotonous and reaches its maximum at the point $b_*(a,c)$ which is determined solving the equation: $\frac{\partial \varphi}{\partial b} = 0$.

Value b_* is suggested to consider as the highest value of the range of b-variations because for any $b > b_*$ increase of shield height cause decrease of shield effectiveness what contradicts to physical nature of the problem.

Fig. 1 shows also that decrease of the width a causes displacement of the point of minimum of the function φ to the top. At the certain a_* the curve $\varphi(b)$ touch abscissas axis and for $a < a_*$ it lies higher than mentioned axis. The last idea means that when shield width lower than a_* for any (even big) b it is not possible to obtain required noise reduction. Thus, value of a_* which might be found by solving the following equations:

$$\frac{\partial \varphi}{\partial b} = 0$$
$$\varphi(b) = 0$$

is the lowest value of a-range when requirement $\varphi(a,b) = 0$ is fulfilled.

Carried out researches show that if $a>a_*$ and $0<b<b_*$ the function $\Delta L(a,b)$ has a minimum at the point $a=a_0$, and $b=b_0$. The magnitude of the function $\varphi(a,b,c)$ in that point depends on the certain c what is the value of required noise reduction level. Increase of c gives increase of $\varphi(a,b,c)$ and at certain point $c=c_*$ $\varphi(a,b,c)=0$. For any $c>c_*$ there is no acoustical shield which could provide required noise reduction. Thus, maximal noise reduction which might be obtain by acoustical shield is determined by solving the following system:

$$\frac{\partial \varphi}{\partial b} = 0$$
$$\frac{\partial \varphi}{\partial a} = 0$$
$$\varphi(a,b,c) = 0.$$

Therefore it is suppose that parameter $c<c_*$.

Taking into account all mentioned above ideas the following algorithm of system solution is suggested:

1. for fixed value of parameter $c<c_*$ the lowest boundary of a (shield width) is determined;
2. for fixed $a>a_*$ the respect shield height $0<b<b_*$ is determined solving the equation $\varphi(a,b)=0$;
3. the justification of the (4) equation is carried out, if condition of equation (4) cannot be satisfied parameter a should be changed and second step of the algorithm should be done again.

Graphic illustration of the algorithm is presented at the Fig. 2. At this figure the dependence of shield square as function of its width is described. Shield height might be determined from the equation $\varphi(a,b)=0$ which means reaching of required noise reduction level. As showed at the Fig. 2 shield square function is not monotonous and has well-recognisable minimum. The values of the width and the height of a shield which correspond to the point of minimum is determined from the equation (4).

CONCLUSIONS

1. A method for prediction of noise reduction by means of acoustical shields and valid for diffraction angles more than 60 degrees is presented. Method based on the statistical theory of acoustics using elements of wave and geometrical optics theories. The equation allows to take into account parameters of acoustical shield and conditions of its installation.

2. Based on obtained formulae optimisation of acoustical shields is carried out. As the result of optimisation some recommendations and

algorithm of search of acoustical shield of minimal square and consequently of minimal cost which provide required noise reduction are proposed. At the second stage discrete optimisation connected with shield material choosing is suggested.

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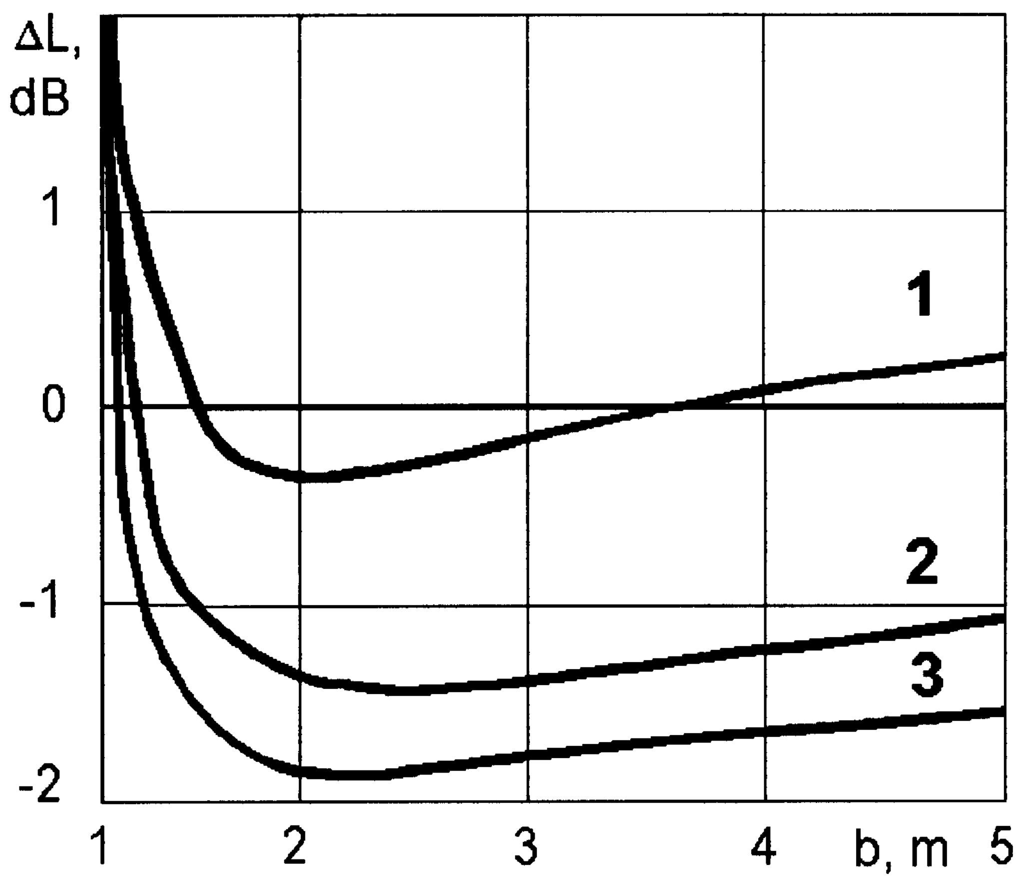

Fig. 1. Acoustical shield effectiveness for fixed shield width (a) and various shield height (b). 1 - for a=1m, 2- for a=2m, and 3 for a=3m.

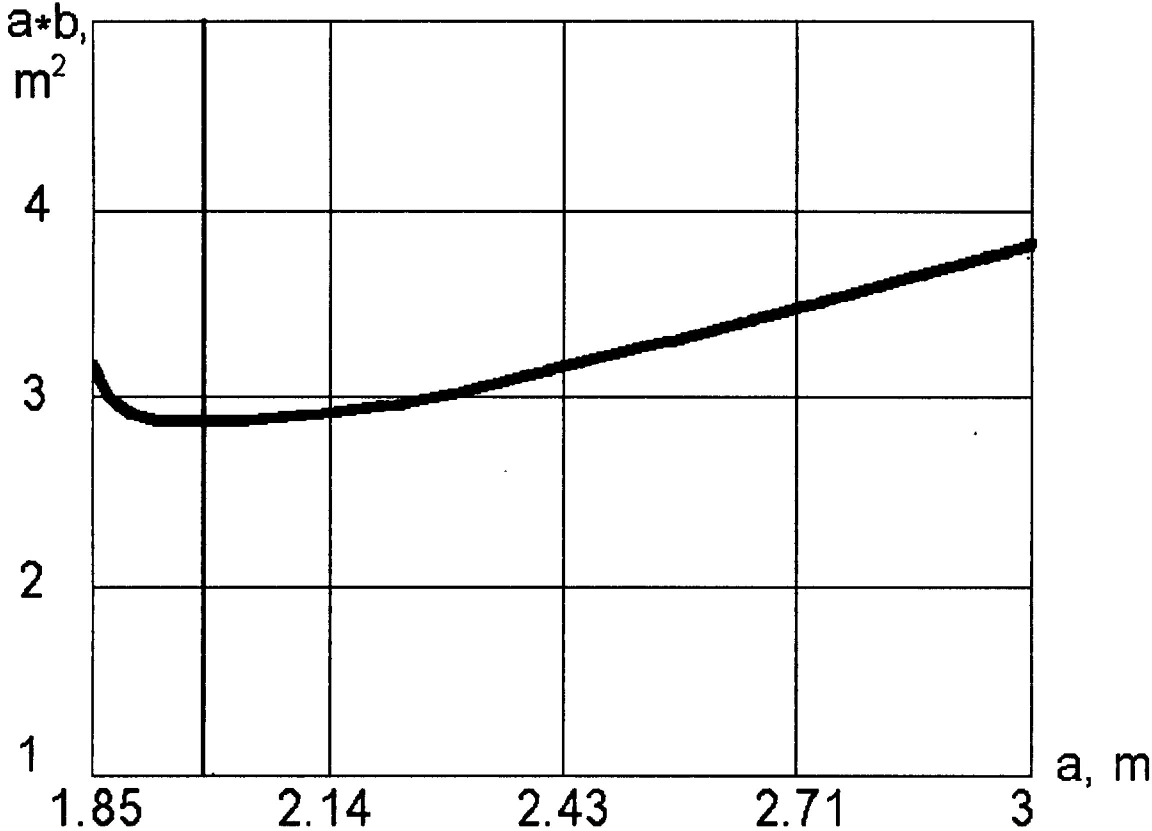

Fig. 2. Dependence of a barrier square on its width a.