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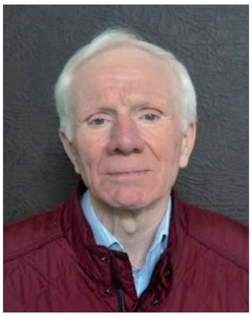

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THE EFFICIENCY CALCULATION METHOD FOR NOISE BARRIERS LOCATED ON BRIDGE STRUCTURES

ABSTRACT

The paper investigates the traffic flows noise reduction by means of noise barriers located on bridge structures (bridges, viaducts, overpasses etc.). The paper sets and solves the analytical problem of finding the acoustic efficiency of the sound-reflecting acoustically rigid barrier on an near-by territory that needs noise protection and is located below the linear noise source. The proposed mathematical design model takes into account the sound-reflecting acoustically rigid half-plane (the roadway of bridge structure) influence on the noise barriers acoustic efficiency. Based on this analytical study results, it is found that the acoustically rigid roadway influence on the barrier efficiency is rather negligible for points located above the structure roadway level in the acoustic shadow zone and the results of the barriers efficiency calculations using the well-known Maekawa's method and the method proposed in this paper are the same for this zone. In the acoustic shadow zone located below the structure roadway level, there is an area of the reduced barrier efficiency. This is not consistent with the fixed stereotype that with increasing the acoustic shadow angle the barrier efficiency only increases. For this sound field zone, there are significant differences between the calculation results obtained by the Maekawa's method and the method presented in this paper. The results discrepancy found in the calculations for this acoustic shadow zone is determined by the linear sound source shielding by the bridge structure roadway itself, which is taken into account in this calculation model. This is a new analytical result confirmed by the laboratory experimental studies of the noise barriers acoustic efficiency using the physical models.

KEYWORDS: bridge structure, noise shield, sound field, acoustic efficiency

МЕТОД РОЗРАХУНКУ АКУСТИЧНОЇ ЕФЕКТИВНОСТІ ШУМОЗАХИСНИХ ЕКРАНІВ НА МОСТОВИХ СПОРУДАХ

АНОТАЦІЯ

Стаття присвячена зниженню шуму транспортних потоків застосуванням шумозахисних екранів, встановлених на мостових спорудах (мостах, віадуках, шляхопроводах тощо). В статті поставлено та розв'язано аналітичну задачу з визначення акустичної ефективності звуковідбивного акустично жорсткого екрана на прилеглій території, що потребує шумозахисту і знаходиться нижче лінійного джерела шуму. Представлена розрахункова математична модель враховує вплив на

акустичну ефективність шумозахисного екрана звуковідбивної акустично жорсткої півплощини – полотна мостової споруди. За результатами даного аналітичного дослідження встановлено, що для точок в зоні акустичної тіні, розташованих вище рівня полотна споруди, вплив акустично жорсткого полотна на ефективність екрана є незначним і для цієї зони результати розрахунку ефективності екранів за відомим методом Маєкави та методом, викладеним у цій статті, збігаються. В зоні акустичної тіні, розташованої нижче рівня полотна споруди, відзначається наявність області пониженої ефективності екрана, що не узгоджується зі сталим стереотипом, що при збільшенні кута акустичної тіні, ефективність екрана тільки зростає. Для цієї зони звукового поля наявні суттєві розбіжності між результатами розрахунку, отриманих за методом Маєкави і методом, представленим у даній статті. Виявлена неузгодженість у результатах розрахунку в даній зоні акустичної тіні визначається впливом екранування лінійного джерела звуку самим полотном мостової споруди, врахованим у даній розрахунковій моделі. Це є новим аналітичним результатом, підтвердженим лабораторними експериментальними дослідженнями акустичної ефективності шумозахисних екранів на фізичних моделях.

КЛЮЧОВІ СЛОВА: мостова споруда, шумозахисний екран, звукове поле, акустична ефективність

INTRODUCTION

Each year the environmental issues become more acute in the world and attention is increasingly focused on their resolution. One of the most problematic is the noise reduction in the residential areas and in places of permanent people staying, because the excessive noise levels have the same degree of negative influence on human health as such factors as water and atmosphere pollutions.

The most widespread and intense sources of an excessive noise include industrial enterprises, construction sites, traffic flows etc. According to some reports [1, 2], just the traffic flows pollute up to 60-80% of the large cities territories with the excessive level noises, and in the villages located along the highways they are almost the only source of excessive noise.

It is also unfavorable that with every passing year the traffic volumes increase leads to the persistent noise levels rise. One of the most effective acoustic and construction means for the traffic noise reduction in near-by territories is the noise-protecting barriers use. The noise-protecting barriers use is one of the most effective acoustic and construction means for the traffic noise reduction in near-by territories and the only noise protecting means for the bridge structures.

The study of the influences of the barrier structural parameters, as well as of the relative locations of the sound source, barrier and noise protected zone has begun since the 50s of the last century and continues to nowadays, as is evidenced by numerous publications [3-10]. Most publications devoted to the noise barriers efficiency calculations are based either on the experimental studies carried out by Maekawa and his students from the late 1960s to the early 1970s or on the approximate numerical methods [3, 11]. However, for screens arranged on the bridge structures there are significant discrepancies between the calculations results obtained when using those methods and the field measurements results.

In this regard, the qualitative assessments of the noise barriers efficiency depending on their design parameters and arrangement location, as well as their acoustic efficiency enhancement remain extremely important and actual.

Thus, the work purpose was to develop a refined computational model for calculating the acoustic efficiency of noise barriers, installed on bridge structures, with an aim of determining the traffic flow noise reduction in adjacent areas located below a linear noise source.

PROBLEM STATEMENT

One of the unsolved problems is the acoustic efficiency determination for the noise barriers installed on bridge structures.

The acoustic field determination by mathematical means is based on the Helmholtz equation solution for an area around the “barrier-linear sound source-half-plane” system. It is reasonable to apply the finite regions method for the solution finding. Based on this method, the region, where the equation solution should be found, is divided into a number of canonical domains with boundary conditions, which in the equation can be solved, and then the separate regions should be "sewn" along the corresponding boundaries according to the force and kinematic components.

Thus, the problem arises to define the acoustic field created by the linear sound source in a form of an infinitely long cylinder with a radius much smaller than the wavelength. This sound source operates at a zero vibration mode (is pulsating) with a circular frequency w and is at a distance g above an acoustically rigid half-plane. The acoustically rigid barrier having a height h is located at the arbitrary angle α to the horizontal at a distance b from the linear sound source. Behind the barrier there is an acoustically rigid plane with an arbitrary inclination angle β (Figure 1).

ANALYTICAL SOLUTION

The Helmholtz equation for the oscillation speed potential Φ in the polar coordinate system on the plane has the form:

$$\frac{\partial^2\Phi}{\partial t^2} - c^2\left[\frac{1}{r}\left(\frac{\partial}{\partial r}r\frac{\partial\Phi}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2\Phi}{\partial\theta^2}\right] = 0 \;. \qquad (1)$$

Let's split the space around the barrier into three parts (Figure 1). Partial region I has the appearance of the area outside a circle of radius h with the following boundary conditions:

$$\frac{\partial\Phi}{\partial\theta} = 0 \text{ for } \begin{bmatrix} \theta = 0, r > h \\ \theta = \pi + \beta, r > h \end{bmatrix} . \qquad (2)$$

The partial solution can be represented in the following form [12]:

$$\varphi_b(r,\theta) = \left[A_b\,\mathrm{H}_b^{(1)}(kr) + B_b\,\mathrm{H}_b^{(2)}(kr)\right]\times$$
$$\times\left[C_b\cos(b\theta) + D_b\sin(b\theta)\right], \qquad (3)$$

or

$$\varphi_b(r,\theta) = \left[A_b\,\mathrm{J}_b(kr) + B_b\,\mathrm{N}_b(kr)\right]\times$$
$$\times\left[C_b\cos(b\theta) + D_b\sin(b\theta)\right] , \qquad (4)$$

where and henceforth, $\mathrm{H}_b^{(1)}$, $\mathrm{H}_b^{(2)}$, J_b and N_b are the symbols of cylindrical functions, namely, Hankel functions of the 1st and 2nd kinds, and Bessel and Neumann functions, respectively; and $k=\omega/c$ is a wave number.

Using partial solutions of the type (3) with the Sommerfeld condition being taken into account and using the boundary conditions, we obtain:

$$\Phi_1 = \sum_{m=0}^{\infty} A_m \cdot \frac{\mathrm{H}_{\delta_1 m}^{(1)}(kr)}{\mathrm{H}_{\delta_1 m}^{(1)}{}'(kh)}\cos(\delta_1 m\theta) \;, \qquad (5)$$

where $\delta_1 = \dfrac{\pi}{\pi+\beta}$.

Similarly, for partial regions II and III we can write:

$$\Phi_{II} = \sum_{n=0}^{\infty} B_n \cdot \frac{\mathrm{J}_{\delta_2 n}(kr)}{\mathrm{J}_{\delta_2 n}{}'(kh)}\cos(\delta_2 n\theta) \;, \qquad (6)$$

where $\delta_2 = \dfrac{\pi}{\alpha}$,

$$\Phi_{III} = \sum_{q=0}^{\infty} C_q \cdot \frac{\mathrm{J}_{\delta_3 q}(kr)}{\mathrm{J}_{\delta_3 q}{}'(kh)}\cos(\delta_3 q(\theta-\alpha)) \;, \qquad (7)$$

where $\delta_3 = \dfrac{\pi}{\pi+\beta-\alpha}$.

The diffraction of an infinite cylindrical sound source of small wave dimensions located in region I on a wedge with acoustically rigid surfaces and an opening angle $\pi+\beta$, that is, when $h<r_S$, is described by the following expression [13]:

$$\Phi_0 = \frac{\delta_1 i}{2}\begin{cases} \sum_{m=0}^{\infty}\varepsilon_m\,\mathrm{H}_{\delta_1 m}^{(1)}(kr_S)\,\mathrm{J}_{\delta_1 m}(kr)\cos(\delta_1 m\theta_S)\cos(\delta_1 m\theta), & r \ge r_S \\ \sum_{m=0}^{\infty}\varepsilon_m\,\mathrm{H}_{\delta_1 m}^{(1)}(kr)\,\mathrm{J}_{\delta_1 m}(kr_S)\cos(\delta_1 m\theta_S)\cos(\delta_1 m\theta), & r < r_S, \end{cases} \qquad (8)$$

where $\varepsilon_m = \begin{cases} 1, & m=0 \\ 2, & m>0 \end{cases}$.

Then the field in region I can be written in the following form:

$$\Phi_I = \Phi_0 + \Phi_1 \;,$$

or based on expressions (5) and (8) the following formula is obtained:

$$\Phi_I = \sum_{m=0}^{\infty} A_m \cdot \frac{\mathrm{H}_{\delta_1 m}^{(1)}(kr)}{\mathrm{H}_{\delta_1 m}^{(1)}{}'(kh)}\cos(\delta_1 m\theta) +$$
$$+\frac{\delta_1 i}{2}\begin{cases} \sum_{m=0}^{\infty}\varepsilon_m\,\mathrm{H}_{\delta_1 m}^{(1)}(kr_S)\,\mathrm{J}_{\delta_1 m}(kr)\cos(\delta_1 m\theta_S)\cos(\delta_1 m\theta), & r \ge r_S \\ \sum_{m=0}^{\infty}\varepsilon_m\,\mathrm{H}_{\delta_1 m}^{(1)}(kr)\,\mathrm{J}_{\delta_1 m}(kr_S)\cos(\delta_1 m\theta_S)\cos(\delta_1 m\theta), & r < r_S \;, \end{cases} \qquad (9)$$

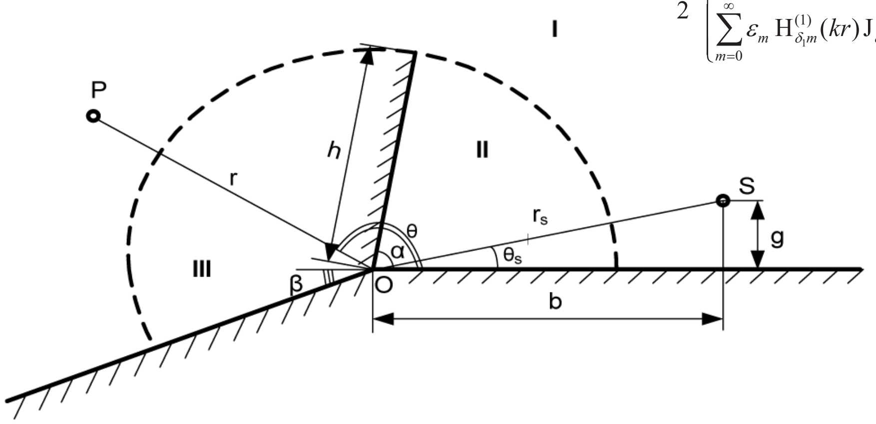

Figure 1 – Computational geometric model of a sound-reflecting barrier installed on a bridge structure.
S - linear sound source; P - reference point

where Φ_I is the oscillation speed potential in region I with an allowance for the sound source field.

The conditions for connecting the fields at the borders can be written as follows:

$$\Phi_I = \Phi_{II} + \Phi_{III},$$
$$r = h,$$
$$\theta \in \left[0,(\pi+\beta)\right] \;, \qquad (10)$$

$$\frac{\partial \Phi_I}{\partial r} = \begin{cases} \dfrac{\partial \Phi_{II}}{\partial r}, & r = h, \quad \theta \in [0, \alpha] \\ \dfrac{\partial \Phi_{III}}{\partial r}, & r = h, \quad \theta \in [\alpha, (\pi + \beta)] \end{cases} . \tag{11}$$

If the values (5) - (7) are inserted into the system of equations (10) and (11), the following expressions are obtained:

$$\frac{\delta_1 i}{2} \sum_{m=0}^{\infty} \varepsilon_m \mathrm{H}^{(1)}_{\delta_1 m}(kr_S) \mathrm{J}_{\delta_1 m}(kh) \cos(\delta_1 m \theta_S) \cos(\delta_1 m \theta) +$$
$$+ \sum_{m=0}^{\infty} A_m \cdot \frac{\mathrm{H}^{(1)}_{\delta_1 m}(kh)}{\mathrm{H}^{(1)\prime}_{\delta_1 m}(kh)} \cos(\delta_1 m \theta) =$$
$$= \sum_{n=0}^{\infty} B_n \cdot \frac{\mathrm{J}_{\delta_2 n}(kh)}{\mathrm{J}_{\delta_2 n}{}'(kh)} \cos(\delta_2 n \theta) +$$
$$+ \sum_{q=0}^{\infty} C_q \cdot \frac{\mathrm{J}_{\delta_3 q}(kh)}{\mathrm{J}_{\delta_3 q}{}'(kh)} \cos\left(\delta_3 q \left(\theta - \frac{\pi}{2}\right)\right); \tag{12}$$

$$\frac{\delta_1 i}{2} \sum_{m=0}^{\infty} \varepsilon_m \mathrm{H}^{(1)}_{\delta_1 m}(kr_S) \left(\mathrm{J}_{\delta_1 m}(kh)\right)' \cos(\delta_1 m \theta_S) \cos(\delta_1 m \theta) +$$
$$+ \sum_{m=0}^{\infty} A_m \cos(\delta_1 m \theta) = \begin{cases} \sum\limits_{n=0}^{N} B_n \cos(\delta_2 n \theta), & \theta \in [0, \alpha] \\ \sum\limits_{q=0}^{Q} C_q \cos\left(\delta_3 q \left(\theta - \dfrac{\pi}{2}\right)\right), & \theta \in (\alpha, (\pi + \beta)] \end{cases} . \tag{13}$$

After the functional relationships algebraization procedure with taking into account the orthogonality of the corresponding functions sets, the following equations system in the unknown coefficients A, B and C form is obtained:

$$\begin{cases} \sum\limits_{m=0}^{\infty} A_m \dfrac{\mathrm{H}^{(1)}_{\delta_1 m}(kh)}{\mathrm{H}^{(1)\prime}_{\delta_1 m}(kh)} I_{m\mu} - \sum\limits_{n=0}^{\infty} B_n \dfrac{\mathrm{J}_{\delta_2 n}(kh)}{\mathrm{J}_{\delta_2 n}{}'(kh)} I_{n\mu} - \sum\limits_{q=0}^{\infty} C_q \dfrac{\mathrm{J}_{\delta_3 q}(kh)}{\mathrm{J}_{\delta_3 q}{}'(kh)} I_{q\mu} = \\ = -\dfrac{\delta_1 i}{2} \sum\limits_{m=0}^{\infty} \varepsilon_m \mathrm{H}^{(1)}_{\delta_1 m}(kr_S) \mathrm{J}_{\delta_1 m}(kh) \cos(\delta_1 m \theta_S) I_{m\mu} \\ \sum\limits_{m=0}^{\infty} A_m I_{m\eta} - \sum\limits_{n=0}^{\infty} B_n I_{n\eta} - 0 = -\dfrac{\delta_1 i}{2} \sum\limits_{m=0}^{\infty} \varepsilon_m \mathrm{H}^{(1)}_{\delta_1 m}(kr_S) \mathrm{J}_{\delta_1 m}(kh) \cos(\delta_1 m \theta_S) I_{m\eta} \\ \sum\limits_{m=0}^{\infty} A_m I_{m\varsigma} - 0 - \sum\limits_{q=0}^{\infty} C_q I_{q\varsigma} = -\dfrac{\delta_1 i}{2} \sum\limits_{m=0}^{\infty} \varepsilon_m \mathrm{H}^{(1)}_{\delta_1 m}(kr_S) \mathrm{J}_{\delta_1 m}(kh) \cos(\delta_1 m \theta_S) I_{m\varsigma} \end{cases} \tag{14}$$

where

$$I_{m\mu} = \int_0^{\pi+\beta} \cos(\delta_1 m \theta) \cos(\delta_1 \mu \theta) d\theta = \begin{cases} (\pi + \beta), & \mu = m = 0 \\ (\pi + \beta)/2, & \mu = m \neq 0 \\ 0, & \mu \neq m \end{cases} ,$$

$$I_{n\mu} = \int_0^{\alpha} \cos(\delta_2 n \theta) \cos(\delta_1 \mu \theta) d\theta ,$$

$$I_{q\mu} = \int_{\alpha}^{\pi+\beta} \cos(\delta_3 q (\theta - \alpha)) \cos(\delta_1 \mu \theta) d\theta ,$$

$$I_{n\eta} = \int_0^{\alpha} \cos(\delta_2 n \theta) \cos(\delta_2 \eta \theta) d\theta = \begin{cases} \alpha, & \eta = n = 0 \\ \alpha / 2, & \eta = n \neq 0 \\ 0, & \eta \neq n \end{cases} ,$$

$$I_{m\eta} = \int_0^{\alpha} \cos(\delta_1 m \theta) \cos(\delta_2 \eta \theta) d\theta ,$$

$$I_{m\varsigma} = \int_{\alpha}^{\pi+\beta} \cos(\delta_1 m \theta) \cos(\delta_3 \varsigma (\theta - \alpha)) d\theta ,$$

$$I_{q\varsigma} = \int_{\alpha}^{\pi+\beta} \cos(\delta_3 q (\theta - \alpha)) \cos(\delta_3 \varsigma (\theta - \alpha)) d\theta =$$
$$= \begin{cases} \pi + \beta - \alpha, & \varsigma = q = 0 \\ (\pi + \beta - \alpha)/2, & \varsigma = q \neq 0 \\ 0, & \varsigma \neq q \end{cases}$$

The algebraic equations infinite system (14) is solved by a reduction method.

CALCULATIONS RESULTS ANALYSIS

The sound field determined by the expressions (6), (7) and (9) and obtained based on the equations system (14) solution will be analyzed without considering the earth influence for the assessment of the efficiency (ΔL, dB) of the noise barrier located on the bridge structure. The noise barrier efficiency is determined as the sound pressure levels difference in the acoustic shadow zone points:

$$\Delta L = L_1 - L_2 = 20 \lg \frac{|p_1|}{|p_2|} , \tag{15}$$

where L_1 and L_2 are the sound pressure levels, dB, in the acoustic shadow points without and with a barrier, respectively; p_1 and p_2 are the sound pressures, Pa, without and with a barrier, respectively, determined by the following expression:

$$p = \rho_0 \frac{\partial \Phi}{\partial t} , \tag{16}$$

where ρ_0 is the environment density.

In Figure 2, for the field of a linear sound source located on the bridge, the sound pressure levels dependence on the angle (θ) of the reference point location, without any barrier and with a vertical acoustically rigid barrier (the reference point radius vector rotates counterclockwise and at zero degree is in the bridge roadway plane) is presented.

The linear source sound field without a screen is,

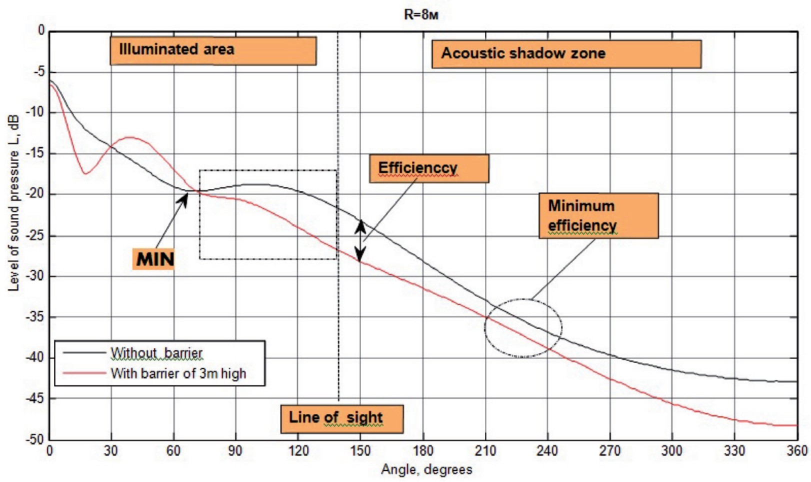

Figure 2 – Sound pressure levels around the "barrier - half-plane - linear sound source" system without and with a barrier

on the whole, almost uniformly decreasing with the reference point angle increase (the distance from the source increases). However, between the sound source and half-plane edge (the bridge roadway edge) there is an area, where the decay uniformity is disturbed and the minimum sound pressure zone is observed ("MIN"), from which the sound pressure level increases towards the sound source (which is natural) and towards the half-plane edge. This fact is caused by the interference of the direct sound from the source and the sound reflected from the half-plane edge. For points below the bridge roadway, the bridge structure roadway becomes a barrier itself and the sound pressure level drops rapidly.

The sound field of this linear source with the barrier is much more complicated. In the illuminated zone area, between the noise source and the barrier, a sound field explicit interference pattern with periodic changes of the sound pressure minima and maxima is observed and the pattern configuration depends mainly on the frequency and distance between the sound source and barrier.

As can be seen from Figure 2, the barrier acoustic performance is observed even in the illuminated area (highlighted by a dotted rectangle). When the reference point moves into the acoustic shadow zone, the barrier efficiency continues to increase and reaches its maximum ("Efficiency"). With the further increase of the reference point angle (below the bridge roadway), the minimum acoustic efficiency area ("Minimum efficiency") is observed, after which (with the angle increase) the efficiency gradually increases again.

The whole space around the "barrier - half-plane - linear sound source" system can be divided into the following characteristic zones (Figure 3):

I is a half-space bounded by the line of sight, barrier and the bridge roadway (illuminated zone). In this zone there are the interference phenomena due to the sound reflection from the bridge roadway and acoustically rigid noise barrier;

II is the half-space in the acoustic shadow zone, limited by the line of sight, barrier and maximum barrier efficiency line. With the reference point angle increasing in this zone the barrier efficiency monotonously increases to its maximum value. The maximum acoustic efficiency line is above the bridge roadway level and is inclined at an angle to the horizon. Its exact direction and location depends on many factors (barrier inclination angle and its distance to the sound source, sound frequency, etc.). The barrier height dependence is negligible;

III is the half-space between the directions of maximum and minimum barrier efficiency. In this area, the barrier efficiency monotonously decreases (with the reference point angle increase) to a minimum value. The minimum efficiency line direction is also practically independent of the barrier height;

IV - is the half-space limited by the minimum barrier efficiency line and the reverse side of the bridge deck surfacing. In this zone the noise barrier efficiency gradually increases again.

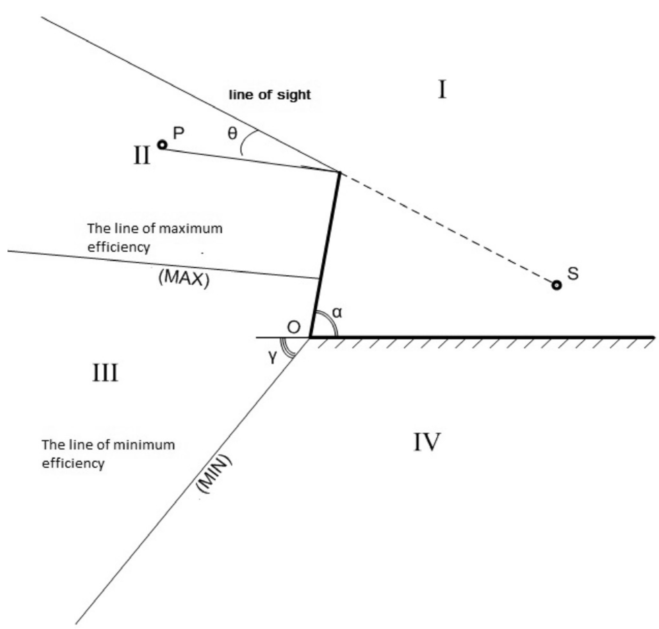

Figure 3 – The characteristic of the sound field around the "barrier - half-plane - linear sound source" system: α – barrier inclination angle; θ – acoustic shadow angle; γ – minimal barrier efficiency line angle

CONCLUSIONS

The article presents a mathematical model for calculating the acoustic efficiency of noise barriers installed on bridge structures. The barriers efficiency characteristics obtained by this method not in all acoustic shadow zones agree with the traditional notion that the screen performance monotonically increases with the increase of the Fresnel number.

The generally accepted Maekawa's design model [3] is based on the fact that the sound source is located in a free space and the only obstacle to the sound propagation is the noise barrier. For such problem formulation, the barrier efficiency uniform dependence on the Fresnel number is quite natural.

The design model discussed in this paper is slightly different from the Maekawa's model, because, in addition to the barrier, it takes into account the presence of an acoustically rigid half-plane, such as the bridge deck surfacing.

The analytical study found out that the results of calculating the barriers acoustic efficiency determined by these two calculation models agree only in the acoustic shadow zone located above the bridge structure roadway. Significant differences were found for the acoustic shadow points below the bridge structure roadway level. The barrier efficiency at these points (if a Fresnel number significantly increases) is actually much lower than the values that could be obtained by the Maekawa's method.

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