21. Shono, A., Kotani, T. (2019). Clinical implication of monitoring regional ventilation using electrical impedance tomography. Journal of Intensive Care, 7 (1). doi: https://doi.org/10.1186/s40560-019-0358-4
22. Ward, L. C. (2018). Bioelectrical impedance analysis for body composition assessment: reflections on accuracy, clinical utility, and standardisation. European Journal of Clinical Nutrition, 73 (2), 194–199. doi: https://doi.org/10.1038/s41430-018-0335-3
23. Shchelykalina, S. P., Nikolaev, D. V., Kolesnikov, V. A., Korostylev, K. A., Starunova, O. A. (2020). Data Views Technology of Bioimpedance Vector Analysis of Human Body Composition. 17th International Conference on Electrical Bioimpedance, 77–83. doi: https://doi.org/10.1007/978-981-13-3498-6_12
24. Nikolaev, D. V., Schelykalina, S. P. (2016). Lektsii po bioimpedansnomu analizu sostava tela cheloveka. Moscow: RIO TSNIIOIZ MZ RF, 152.
25. Martirosov, E. G., Nikolaev, D. V., Rudnev, S. G. (2006). Tekhnologii i metody opredeleniya sostava tela cheloveka. Moscow: Nauka, 248.
26. Nikolaev, D. V., Smirnov, A. V., Bobrinskaya, I. G., Rudnev, S. G. (2009). Bioimpedansniy analiz sostava tela cheloveka. Moscow: Nauka, 392.

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ESTIMATING THE INFLUENCE OF DOUBLE-SIDED ROUNDED SCREENS ON THE ACOUSTIC FIELD AROUND A LINEAR SOUND SOURCE

Vitalii Didkovskyi
Doctor of Technical Sciences, Professor*

Vitaly Zaets
Corresponding author
PhD, Associate Professor*
E-mail: zaetsv@i.ua

Svetlana Kotenko
PhD, Junior Researcher
Department of Building Physics and Energy Efficiency
State Enterprise «State Research Institute of Building Constructions»
Preobrazhenska str., 5/2, Kyiv, Ukraine, 03037

Volodymyr Denysenko
PhD, Associate Professor**

Yuriy Didenko
PhD, Associate Professor**

*Department of Acoustic and Multimedia Electronic Systems
National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute»
Peremohy ave., 37, Kyiv, Ukraine, 03056

**Department of Higher and Applied Mathematics
Kyiv National University of Trade and Economics
Kyoto str., 19, Kyiv, Ukraine, 02156

This paper reports a study into the acoustic field of transport flow around noise protection screens located on both sides of the sound source.

Most research on noise protection involving noise protection screens relates to the assessment of the effectiveness of screens located on one side of the noise source. The influence of the second screen on the effectiveness of the first one has been investigated only experimentally. Therefore, it is a relevant task to assess the mutual impact of the two screens between which the linear sound source is located.

A problem was stated in such a way that has made it possible to derive an analytical solution and find a sound field around a linear sound source. In this case, the sound source was limited on both sides by acoustically rigid screens with finite thickness. The screens' cross-sections were shaped as part of a ring with arbitrary angles and the same radius.

The problem was solved by the method of partial domains. This method has made it possible to obtain an infinite system of algebraic equations that were solved by the method of reduction. Such an approach to solving a problem allows a given solution to be applied for different cases of the mutual location of screens, source, and territory protected from noise.

The study results help estimate a field between the screens, the dependence of increasing sound pressure on the road on the geometric size of the screen and the width of the road. In addition, the solution resulted in the ability to assess the impact of one screen on the efficiency of another in the frequency range of up to 1,000 Hz. It has been shown that the mutual impact of screens could reduce the screen efficiency by 2 times.

The study reported here could make it possible to more accurately calculate the levels of the sound field from traffic flows when using noise protection screens, which is often performed in practice when designing new and reconstructing existing highways

Keywords: rounded noise protection screen, method of partial domains, two-sided noise protection screens, noise reduction

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1. Introduction

Noise is one of the undesirable environmental factors. The largest sources of noise are transporting highways [1, 2]. Noise protection screens are one of the most effective means of reducing transport noise.

The levels of the sound field behind a screen are influenced by a large number of parameters, primarily the geometric dimensions of the screens and the mutual location of the screen sound source, as well as the noise-protected area [3].

Also important is the design of the noise protection screen, its soundproofing [4] and sound absorption properties [5]. In particular, many studies addressed the arrangement of Helmholtz resonators as an effective absorber of low-frequency sound [6, 7]. A great impact on the noise reduction by a screen is exerted by heterogeneous atmospheric conditions [8]: wind direction and strength, air temperature gradient, etc.

The factors also include the presence of another screen on the other side of the sound source. The existence of screens on both sides of the road is due to the need to reduce noise levels on both sides of the transport highway. This is a typical case when the highway or railway passes through the settlement. As a result of the reflection of sound from one screen, the reflected sound wave begins to spread in the direction of the second screen, and, therefore, the sound levels increase while the sound field changes its structure.

Thus, it is a relevant task to study analytically the effect of two-sided screens on the acoustic field around a linear sound source.

2. Literature review and problem statement

Systemic studies into the effectiveness of noise protection screens started in the second half of the 20th century. Paper [9] reports the results from experimental studies of the field around single screens and gives empirical formulas to determine the effectiveness of screens for point and linear sound sources. Later, article [10] proposed a formula for determining the effectiveness of the screen, which made it possible to find the effectiveness of screens in a wide range of frequencies with sufficient accuracy at that time. However, those studies did not take into consideration the presence of roads and other reflective surfaces. Later, work [11] analyzed the propagation of a sound wave between two parallel screens with the ground surface between them using a laser. Sound levels on the "illuminated" side of the screen were predicted.

Subsequently, paper [12] proposed a model of the sound field around rigid parallel screens. The model was based on finding a sound field from imaginary sound sources. Article [13] compared the results of finding a field by the method of imaginary sources and a numerical method of boundary regions. Thus, spatial and spectral characteristics of reducing the levels of sound behind the screen were obtained, which indicated the nature of the change in sound pressure behind the screen. However, that approach is limited in its application because a radiation theory of sound propagation is known to have limitations in the low-frequency domain. The method of boundary regions is a numerical method with a non-predefined accuracy.

In addition, experimental studies into the influence of two-sided screens on the acoustic field around sound sources were also carried out. Study [14] showed that the effect of the second screen on the effectiveness of the first one is negligible. The authors of work [15] also made the same statement. However, other studies [16] at a similar distance between screens of 50 m revealed a decrease in the efficiency of one of the screens by 2.8 dB. Paper [17] also reported the results of full-scale studies that found a decrease in screen efficiency by up to 4.4 dB. Therefore, the assessment of the impact of one screen on the effectiveness of another one was not actually resolved.

Article [18] proposes to apply the method of partial domains for finding analytically the acoustic field in areas of complex shape. The authors of [19] even partially managed to model the field around screens on both sides of the road. In work [20], the preceding model was improved by accounting for the presence of dense infrastructure behind the screens. However, the methods for evaluating the sound field that were given in those works have not been practical applied and the reported results cannot be compared with data by other researchers.

Thus, stating and analytically solving the problem could make it possible to determine not only qualitative but also quantitative characteristics of the mutual impact of screens in a wide range of frequencies.

3. The aim and objectives of the study

The purpose of this study is to assess the impact of screens on both sides of the sound source on the acoustic field. This could improve forecasting sound levels when designing noise protection screens.

To accomplish the aim, the following tasks have been set:

– to state and solve a mathematical problem to determine a sound field from a linear sound source with two rounded screens;

– to identify the influence of the second screen on the efficiency of the first one, and to define significant factors influencing the change in screen efficiency.

4. The study materials and methods

To determine an acoustic field from the sound source around two screens, it was necessary to solve the Helmholtz equation considering the corresponding boundary conditions. To this end, such a configuration of the sound source of the screens and the surface of the earth was proposed that made it possible to split the entire area into several canonical parts. In each part of the field, we managed to notate a solution to the Helmholtz equation in a general form, which makes it possible to conjugate these areas at their common boundaries.

The areas are conjugated on the basis of sound pressure and fluctuation velocity corresponding to the speed potential (Φ) and the first derivative from the potential of the speed for a coordinate.

The solution to the problem employs the property of orthogonal functions, which makes it possible to move from a system of functional infinite series to an infinite system of algebraic equations to be solved by the method of reduction. To obtain sufficient accuracy of the results, it is necessary to process several hundred equations, which is why the system was solved and the sound fields were constructed in the MATLAB (USA) programming environment.

5. Results of studying an acoustic field around a linear sound source with two screens

5. 1. Problem statement and solution

Noise protection screens' cross-sections can take the shape of a rectangle (vertical or inclined) and more complex forms, including a sector of the ring. Screens can be located both on one side and on both sides of the road.

The surface of the road along which vehicles move is most often made of asphalt or concrete coating, so it can be considered an acoustically rigid material. The surface behind the screen is also typically horizontal and acoustically rigid.

In addition, traffic in our study is considered as a continuous source of sound whose characteristics do not change along the entire length.

All these conditions and approximations result in the problem whose geometry is shown in Fig. 1.

Fig. 1 shows how all the airspace around the screen was divided into three regions. The regions were split so that one can record a solution to the Helmholtz equation and meet the boundary conditions for them.

The above-described physical model is reduced to the following problem. There is a half-space, which is limited by an acoustically rigid surface. In this half-space, there are two noise protection screens of the same thickness *d*. The screens are formed by sectors of two infinitely long cylindrical surfaces with a radius *D* having a common axis, which is located on the surface of an acoustically rigid half-plane. One end of the screens is also located in an acoustically rigid plane, the other one is at angles α_1 and α_2. The screens are acoustically rigid.

The sound source, *S*, is in the form of an infinitely long cylinder of an infinitely small radius, operating at zero oscillation mode and emitting a harmonious sound wave of frequency *f*. This source is at a distance r_S from the axis of cylindrical surfaces and at angle α_S to an acoustically rigid plane.

It is required to find an acoustic field at any point *P*, which is at any distance *r* from the axis of cylindrical surfaces and at any angle   to the horizontal plane.

Given the geometry of the problem, we shall place the polar coordinate system at point O, which coincides with the axes of cylindrical surfaces.

As is known from [21], in the polar coordinate system, the Helmholtz equation for the velocity potential Φ takes the following form:

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

A numerical solution is represented in the following form:

$$\varphi_b(r,\theta)=\left[A_bH_b^{(1)}(kr)+B_bH_b^{(2)}(kr)\right]\times$$
$$\times\left[C_b\cos(b\theta)+D_b\sin(b\theta)\right] \tag{2}$$

or

$$\varphi_b(r,\theta)=\left[A_bJ_b(kr)+B_bN_b(kr)\right]\times$$
$$\times\left[C_b\cos(b\theta)+D_b\sin(b\theta)\right], \tag{3}$$

where, hereafter, $H_b^{(1)}$, $H_b^{(2)}$, J_b and N_b are the designations of cylindrical functions, namely, Hankel function of the 1st and 2nd kind, Bessel function, and Neiman function, respectively; $k=\omega/c$ is the wavenumber. Moreover, using any solution is arbitrary and depends on the boundary conditions and the geometry of the problem.

Region I.

Region I takes the form of an area outside a circle with a radius of $D+d$ under the following boundary conditions:

$$\frac{\partial\varphi}{\partial\theta}=0 \text{ at } \begin{cases}\theta=0, r>D+d,\\ \theta=\pi, r>D+d.\end{cases} \tag{4}$$

For this region, we shall apply a solution to the Helmholtz equation in form (2). In this solution, the function $H_b^{(1)}$ describes waves propagating from the coordinate origin; the function $H_b^{(2)}$ – waves coming from infinity.

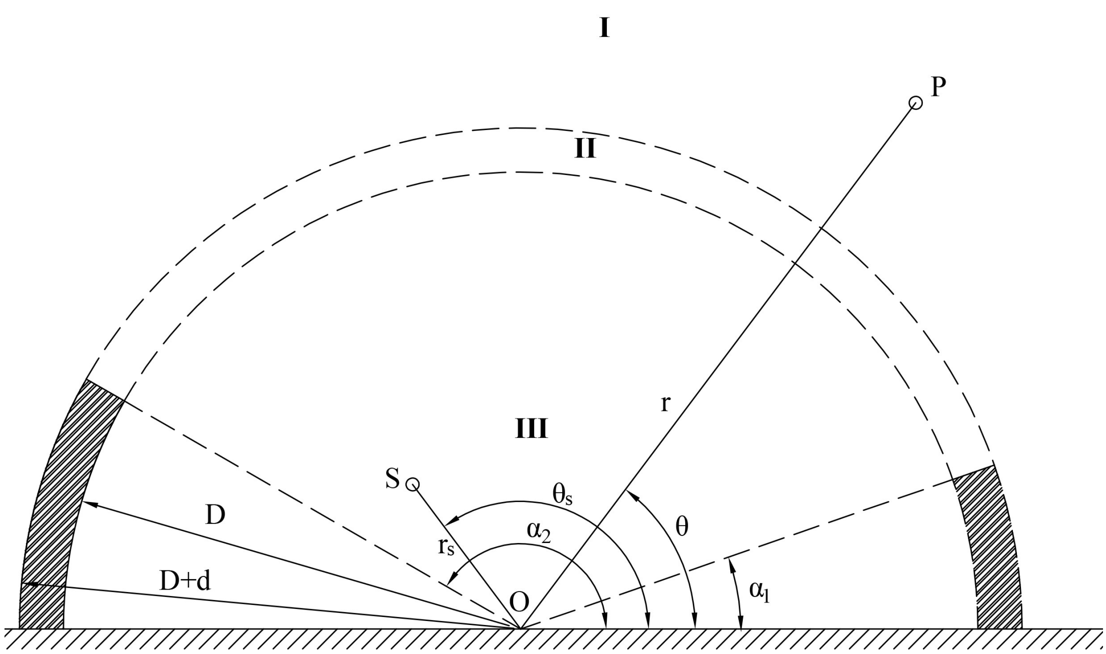


Fig. 1. Estimation geometric model of double-sided rounded noise protection screens

Given the radiation condition by Sommerfeld at infinity, one can reject the function $H_b^{(2)}(kr)$ in equation (2) as, according to the geometry of region I, there are no waves coming from infinity.

Then, to meet the conditions at the border θ=0 and θ=π.

$$\begin{bmatrix} -C_b\sin(b\theta)+ \\ +D_b\cos(b\theta)=0\big|_{\theta=0} \\ -C_b\sin(b\theta)+ \\ +D_b\cos(b\theta)=0\big|_{\theta=\pi} \end{bmatrix} \Rightarrow \begin{bmatrix} D_b=0 \\ C_b\sin(\pi b)=0 \end{bmatrix} \Rightarrow$$

$$\Rightarrow \left[\begin{array}{l} \begin{cases} D_b=0 \\ C_b=0 \end{cases} \\ \begin{cases} D_b=0 \\ \sin(\pi b)=0 \end{cases} \end{array}\right. \Rightarrow \left[\begin{array}{l} \text{a trivial case,} \\ \begin{cases} D_b=0, \\ b=n,\ n=0,\pm1,\pm2... \end{cases} \end{array}\right.$$

Record:

$$\varphi_n(r,\theta)=\tilde{A}_n^{(1)}\cdot H_{\pi n}^{(1)}(kr)\cdot\cos(\pi n\cdot\theta),\quad n=0,\pm1,\pm2... \tag{5}$$

The full solution to the equation consists of the full sum of partial solutions.

In addition, since multipliers $\tilde{A}_n^{(1)}$ are unknown, it is possible to divide each term of the amount by $H_{\pi n}^{(1)\prime}\left[k(D+d)\right]$; that would simplify the expressions when the conjugate conditions are met:

$$\Phi_1=\sum_{n=0}^{\infty}A_n^{(1)}\frac{H_{\pi n}^{(1)}(kr)}{H_{\pi n}^{(1)\prime}\left[k(D+d)\right]}\cos(n\theta). \tag{6}$$

Region II.

Region II is a sector of the ring with radii D and $D+d$ under the following boundary conditions:

$$\frac{\partial\varphi}{\partial\theta}=0 \text{ at } \begin{bmatrix} \theta=\alpha_1,\ D+d\ge r>D, \\ \theta=\alpha_2,\ D+d\ge r>D. \end{bmatrix} \tag{7}$$

The screen boundaries at $\theta=\alpha_1$ and $\theta=\alpha_2$ are acoustically rigid.

We shall use solutions (3) to the Helmholtz equation. Then, to meet the conditions at the boundary $\theta=\alpha_1$ and $\theta=\alpha_2$.

$$\begin{bmatrix} -C_b\sin(b\theta)+D_b\cos(b\theta)=0\big|_{\theta=\alpha_1} \\ -C_b\sin(b\theta)+D_b\cos(b\theta)=0\big|_{\theta=\alpha_2} \end{bmatrix} \Rightarrow$$

$$\Rightarrow \begin{bmatrix} D_b=0 \\ C_b\sin\left[(\alpha_2-\alpha_1)b\right]=0 \end{bmatrix} \Rightarrow$$

$$\Rightarrow \left[\begin{array}{l} \begin{cases} D_b=0 \\ C_b=0 \end{cases} \\ \begin{cases} D_b=0 \\ \sin\left[(\alpha_2-\alpha_1)b\right]=0 \end{cases} \end{array}\right. \Rightarrow$$

$$\Rightarrow \left[\begin{array}{l} \text{a trivial case,} \\ \begin{cases} D_b=0, \\ b=\dfrac{\pi n}{\alpha_2-\alpha_1},\ n=0,\pm1,\pm2... \end{cases} \end{array}\right.$$

Record:

$$\varphi_n(r,\theta)=A_n^{(2)}\cdot J_{\frac{\pi n}{\alpha_2-\alpha_1}}(kr)\times$$
$$\times\cos\left(\frac{\pi n}{\alpha_2-\alpha_1}\cdot\theta\right)+...+ \qquad n=0,\pm1,\pm2...$$
$$+A_n^{(3)}\cdot N_{\frac{\pi n}{\alpha_2-\alpha_1}}(kr)\cdot\cos\left(\frac{\pi n}{\alpha_2-\alpha_1}\cdot\theta\right),$$

Following the transformations similar to the solution for the first region, one can write down the velocity potential Φ_{II} for region II in the following form:

$$\Phi_{II}=\sum_{n=0}^{\infty}\left[A_n^{(2)}\cdot\frac{J_{\delta_1 n}(kr)}{J_{\delta_1 n}(kD)}+A_n^{(3)}\frac{N_{\delta_1 n}(kr)}{N_{\delta_1 n}(kD)}\right]\cos(\delta_1 n\theta), \tag{8}$$

where

$$\delta_1=\frac{\pi}{\alpha_2-\alpha_1}.$$

Region III.

Region III is a half-circle of radius D under the following boundary conditions:

$$\frac{\partial\Phi}{\partial r}=0 \text{ at } \begin{bmatrix} \theta=0,\ r\le D, \\ \theta=\pi,\ r\le D. \end{bmatrix} \tag{9}$$

Since region III hosts the origin of coordinates, we shall also use solution (3) to the Helmholtz equation (1).

Given that the Neumann function (N) at the coordinate origin tends to minus infinity, and the Bessel function (J) – to unity, the term $B_bN_b(kr)$ in solution (3) is discarded because the field at the coordinate origin is finite. Then, having conducted similar mathematical computations, we obtain:

$$\Phi_3=\sum_{n=0}^{\infty}A_n^{(4)}\cdot\frac{J_{\pi n}(kr)}{J'_{\pi n}(kD)}\cos(\pi n\theta). \tag{10}$$

Diffraction field from the sound source.

For ambiguity, we shall assume that the sound source is in region III, that is, $r_S<D$.

The diffraction of an infinite cylindrical sound source of small wave dimensions on a wedge with acoustically rigid surfaces and an opening angle π is described by the following expression from [22]:

$$\Phi_0=\frac{i}{2}\begin{cases} \sum\limits_{n=0}^{\infty}\varepsilon_n H_n^{(1)}(kr_s)J_n(kr)\times \\ \times\cos(n\theta_s)\cos(n\theta), & r<r_s, \\ \sum\limits_{n=0}^{\infty}\varepsilon_n J_n(kr_s)H_n^{(1)}(kr)\times \\ \times\cos(n\theta_s)\cos(n\theta), & r\ge r_s, \end{cases} \tag{11}$$

where Φ_0 is the potential of fluctuation velocity emitted by the source;

$$\varepsilon_n=\begin{cases} 1,\ n=0, \\ 2,\ n>0. \end{cases}$$

Then the field in region III is determined as follows:

$$\Phi_{III} = \Phi_3 + \Phi_0. \qquad (12)$$

We shall write down the conditions for field conjugation at the boundaries:

Since the Helmholtz equation is a differential equation of the 2nd order, the conjugation of regions must be performed based on the velocity potential – which corresponds to the sound pressure, and based on the first derivative from the velocity potential – corresponding to the fluctuation velocity of the particles of the medium.

For pressure:

$$\Phi_I = \Phi_{II}, \quad r = D + d, \quad \theta \in [\alpha_1, \alpha_2], \qquad (13)$$

$$\Phi_{II} = \Phi_{III}, \quad r = D, \quad \theta \in [\alpha_1, \alpha_2]. \qquad (14)$$

For velocity:

$$\frac{\partial \Phi_I}{\partial r} = \begin{cases} \dfrac{\partial \Phi_{II}}{\partial r}, & r = D + d, \quad \theta \in [\alpha_1, \alpha_2], \\ 0, & r = D + d, \quad \theta \in [0, \alpha_1] \cup [\alpha_2, \pi], \end{cases} \qquad (15)$$

$$\frac{\partial \Phi_{II}}{\partial r} = \begin{cases} \dfrac{\partial \Phi_{II}}{\partial r}, & r = D, \quad \theta \in [\alpha_1, \alpha_2], \\ 0, & r = D, \quad \theta \in [0, \alpha_1] \cup [\alpha_2, \pi]. \end{cases} \qquad (16)$$

Substituting expressions (6), (8), (10) to (12) in conjugation conditions (13) to (16) and using the properties of orthogonal functions, as described in [4, 23], one can derive an infinite system of algebraic equations relative to unknown $A_n^{(1)} - A_n^{(4)}$, which is solved by the method of reduction.

5. 2. Assessment of the impact of the second screen on the efficiency of the first one

5. 2. 1. General provisions

The evaluation of the results was to build a field of efficiency of noise protection screens and analyze numerical values of efficiency. Screen performance, similarly to [3–5], means the difference in the sound pressure levels of the field without the screen and with the screen:

$$dL = 20\lg\left(\frac{p_{with}}{p_{out}}\right), \qquad (17)$$

where p_{with} is the sound pressure when using screens, determined from the velocity potentials Φ_I–Φ_{III} (6), (8), (12), in the appropriate region; p_{out} is the sound pressure in the absence of screens, determined from the velocity potential Φ_0 of the sound source (11).

In this case, the sound pressure without a screen and with the screen was derived for 25 frequencies (23), which are evenly distributed in the octave band. This approach has made it possible to model the noise signal and eliminate a pronounced interference pattern, which is characteristic only of tonal signals [4, 24]:

$$\bar{p} = \sqrt{\sum_{i=1}^{25} \left[p(f_i) \right]^2}, \qquad (18)$$

where $p(f_i)$ is the field of sound pressure at the i-th frequency within the one-octave band, Pa;

$\bar{p}$ is the average sound pressure in the octave frequency band, Pa.

Fig. 2, *a* shows the default sound field around two-sided screens; Fig. 2, *b* depicts a field of efficiency. Negative values indicate that the sound pressure has increased.

As one can see in Fig. 2, *a*, the sound pressure between screens almost does not vary with a distance, indicating that the reflected sound from the screens is at significant levels. Increasing the sound levels on the road due to the influence of two screens for a frequency of 125 Hz (Fig. 2, *b*) is in the range from 5 dB to 10 dB.

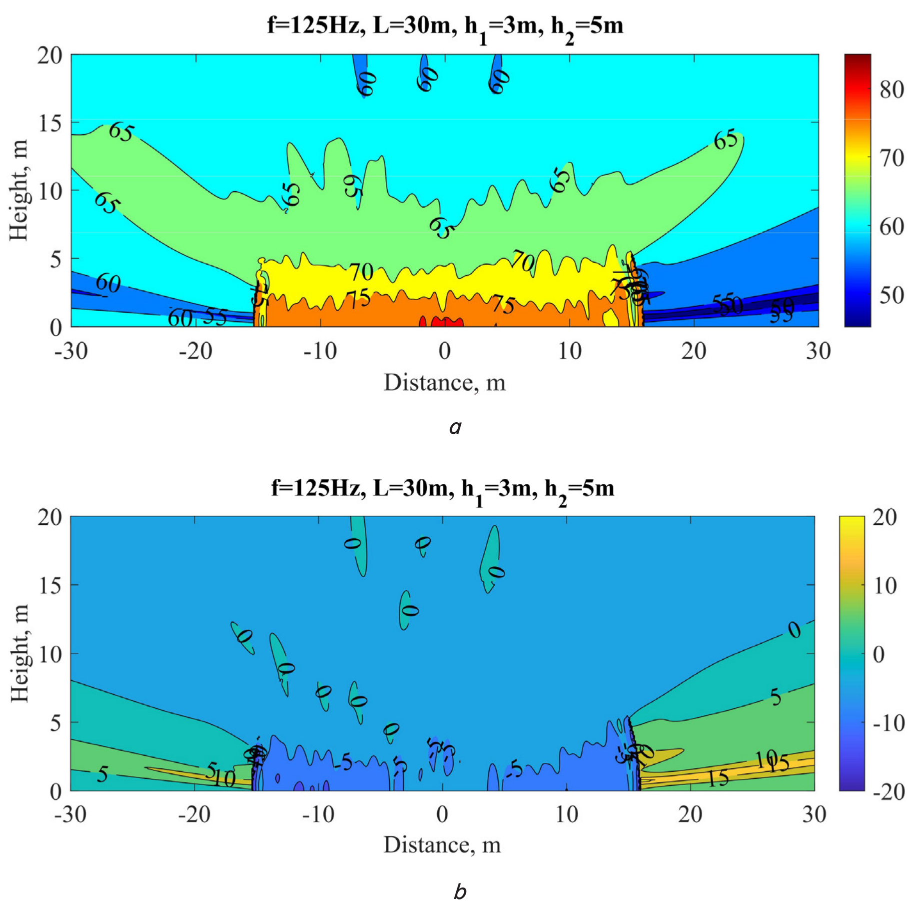


Fig. 2. Sound fields around a linear sound source with two screens (frequency, 125 Hz; distance between screens, L= 30 m; screen height to the left, h_1=3 m; screen height to the right, h_1=5 m): *a* – sound pressure level field; *b* – efficiency field

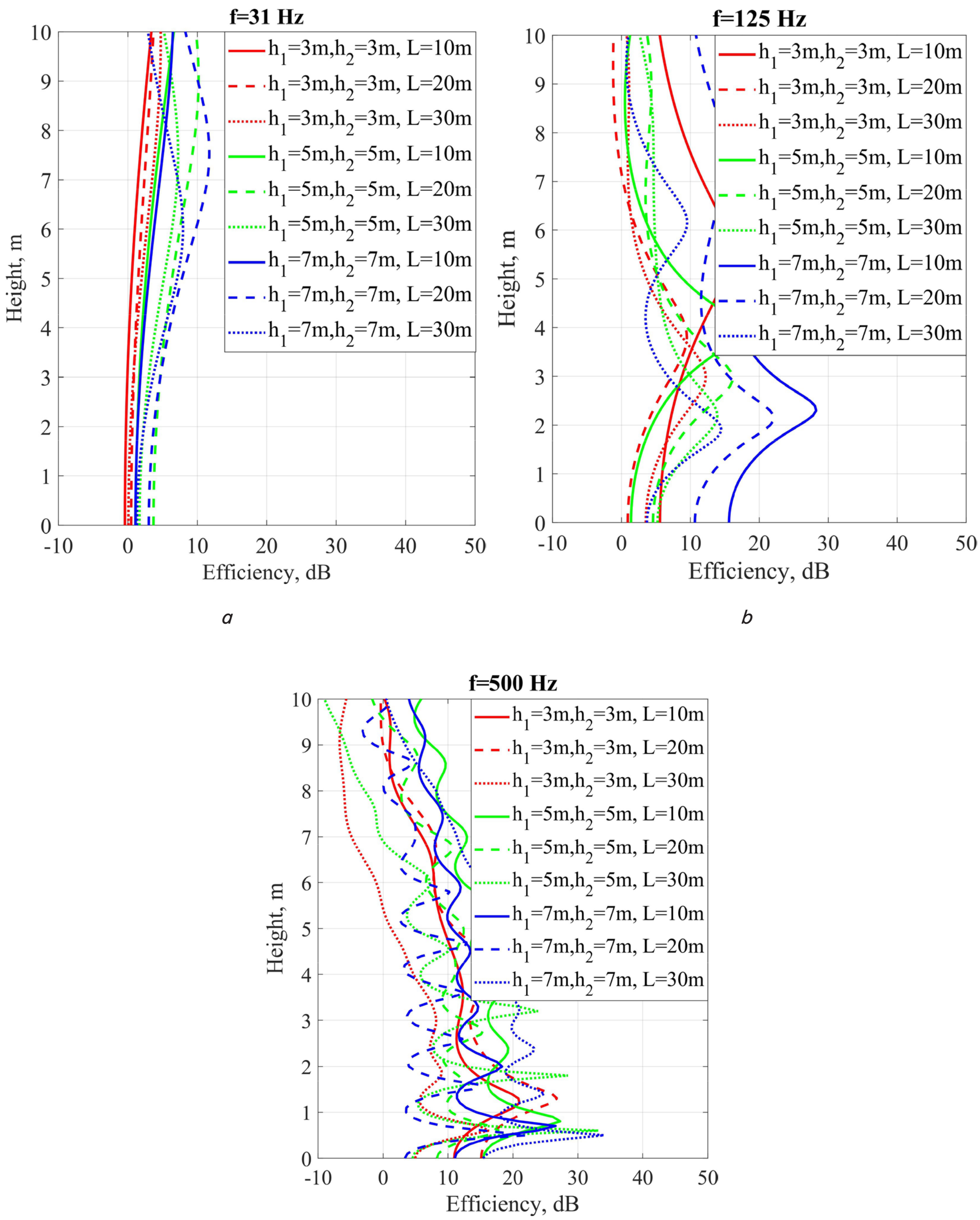
5. 2. 2. The efficiency of noise protection screens

To analyze the sound field around noise protection screens, sound fields for three-octave bands of frequencies of mean geometric frequencies f – 31.5 Hz, 125 Hz, and 500 Hz were calculated. In this case, the distance between the screens L was 10 m, 20 m, and 30 m; the height of screens h_1 and h_2 was 3 m, 5 m, and 7 m (Fig. 3). The screen thickness d in all cases was 0.1 m.

Fig. 3, *a–c* shows the effectiveness value of noise protection screens at a distance of 30 m from the sound source for octave frequency bands of a mean geometric frequency of 31.5 Hz, 125 Hz, and 500 Hz, respectively.

Fig. 3, *a* shows that the efficiency of screens at a frequency of 31 Hz is quite insignificant; near the surface of the earth, it is in the range from 0 dB to 4 dB.

The lower boundary of the range corresponds to the screens with a height of 3 m, and the upper part of the range –7 m. One can also see that near the surface of the earth, the greatest efficiency of screens is observed at a distance between screens equal to 20 m. For distances of both 10 m and 30 m between screens, their efficiency is lower.



a *b* *c*

Fig. 3. Efficiency of noise protection screens at a distance of 30 m from the sound source at different screen heights and the distance between screens: *a* – f=31 Hz; *b* – f=125 Hz; c – f=500 Hz

With an increase in frequency to 125 Hz (Fig. 3, *b*), the impact of the height of the screens and the distances between them becomes more significant. Thus, the efficiency of screens with a height of 3 m is in the range from 2 dB to 7 dB near the earth surface and increases to 11–16 dB for screens with a height of 7 m.

With a further increase in the frequency to 500 Hz, fluctuations in the efficiency of the screen in the range of 5–25 dB are observed, and it is quite difficult to trace any pattern.

In general, it can be argued that the presence of a second screen leads to a decrease in the efficiency of the first screen and, in general, the efficiency of the screens is limited to the magnitude of 20–25 dB.

5. 2. 3. How one screen impacts the performance of another one

Article [26] reported stating and solving the problem of finding a sound field on a one-way rounded noise protection screen. The results of solving that problem were compared to the results of finding a sound field in the presence of two screens. The difference in the efficiency of one-way and two-sided screens is shown in Fig. 4. Calculation results are given for points at a distance of 30 m, horizontally from the noise source. Negative values indicate a decrease in screen performance as a result of having another screen.

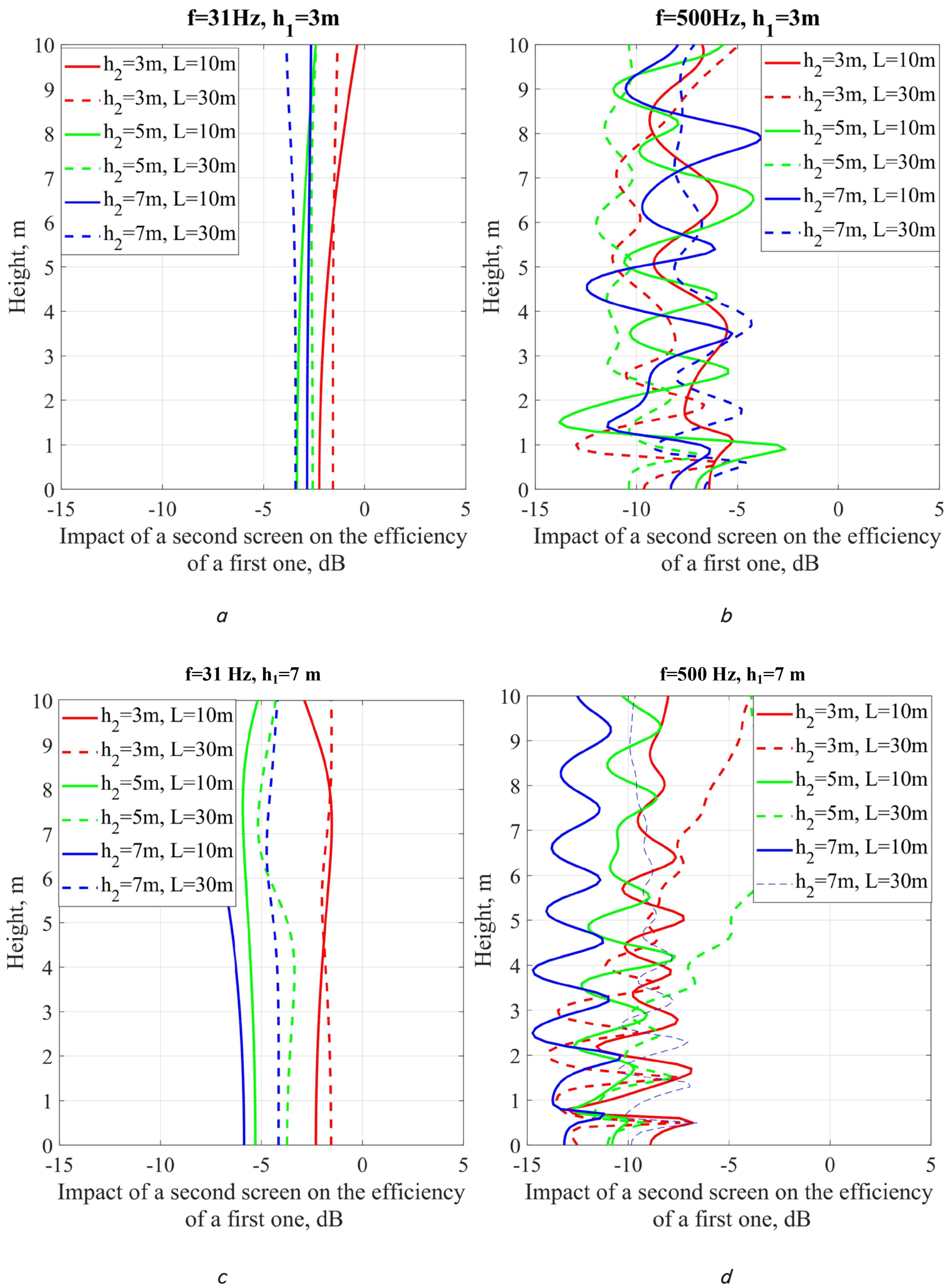


Fig. 4. Influence of a second screen on the efficiency of a first one (calculation points at a distance of 30 m from the sound source): *a* – f=31 Hz, h_1=3 m; *b* – f=500 Hz, h_1=3 m; *c* – f=31 Hz, h_1=7 m; *d* – f=500 Hz, h_1=7 m

Fig. 4, *a* shows that the reduction in screen efficiency with a height of 3 m at a frequency of 31 Hz is in the range of 2–4 dB and almost does not depend on the height of the other screen and the distance between them.

When the screen height increases to 7 m (Fig. 4, *c*), the impact of the second screen becomes more significant. Thus, at a height of the second screen of 3 m, the decrease in the efficiency of the first one is 2–3 dB and almost does not depend on the distance between the screens. With an increase in the height of the second screen to 7 m, the decrease in the efficiency of the first screen is 4–7 dB, the lower limit corresponds to the distance of 10 m between the screens, and the upper – 30 m between the screens.

When the frequency increases to 500 Hz, the impact of the second screen becomes more noticeable in general. For a 3-m screen, having a different screen reduces performance by 5 to 11 dB and is almost independent of the distance between screens. If the height of the first screen increases to 7 m, then the impact of the second screen increases and is in the range from 7 to 15 dB. Moreover, the lower limit corresponds to the height of the second screen of 3 m, the upper limit – for the height of the second screen of 7 m.

6. Discussion of results of studying the impact of two-sided screens on the acoustic field

Applying the method of partial domains has made it possible to state and solve the problem of finding a field around a linear sound source, which is limited by an acoustically rigid half-plane and two acoustically rigid rounded noise protection screens of different heights. As shown by studies reported in [25], in the far-field, the results obtained for rounded screens may well be comparable to the results for straight vertical screens.

Therefore, it can be argued that a second screen makes a significant change in the nature of the sound field around the sound source, and leads to a decrease in the efficiency of screens.

It has been shown that the presence of a second screen at low frequencies leads to a decrease in screen efficiency by up to 6 dB (Fig. 4, *c*), which is more than half of the entire screen efficiency (Fig. 3, *a*).

At higher frequencies, the efficiency decrease is even greater and reaches the value of 15 dB (Fig. 4, *d*) for a frequency of 500 Hz, compared to the remaining screen efficiency (Fig. 3, *c*). That is, the loss of efficiency is also about 50 %.

It is clear that the resulting values are the maximum values in the assessment of loss of efficiency since, in the model, all surfaces were acoustically rigid and the absorption of sound pressure levels in the atmosphere was not taken into consideration. In a real situation with impedance earth surfaces and surfaces of noise protection screens, the impact of the second screen on the efficiency of the first one should be less.

Within the framework of our work, the effect of sound absorption properties of screens on their acoustic efficiency was not assessed but, in further studies, this must be done. In addition, it is advisable to carry out full-scale measurements or laboratory tests involving the model.

A given model could only be used for sound-reflecting noise protection screens in the low- and medium-frequency range with frequencies up to 1,000 Hz.

It should also be noted that the field between screens has also undergone significant changes compared to the field with one screen [24]. As shown in Fig. 2, *b*, the sound pressure levels increased by an average of more than 5 dB, which also requires further research taking into consideration the more appropriate sound absorption properties of screens.

7. Conclusions

1. Owing to the application of the method of partial domains, it was possible to state and solve the problem of finding a field around a linear sound source with screens on both sides. Giving the screens a rounded shape has made it possible to reduce the number of regions and, accordingly, unknowns that must be derived when solving the problem compared to the problem for vertical screens [19]. In addition, such a problem statement makes it possible to set the real width of the screen, change the height of the screens independently of each other, and the distance between them, which allows expanding the practical scope of solutions.

2. Based on the calculation results, the influence of a second screen on the effectiveness of a first screen was revealed. It has been shown that the decrease in screen efficiency could reach 50 % and depends on both the sound frequency and the distance between the screens, as well as their height. It is shown that the greater the distance between the screens, the lower their mutual effect, especially at low frequencies.

References

1. Maraş, E. E., Uslu, G., Uslu, A. (2016). Effects of Noise Barriers on Reducing Highway Traffic Noise. International Refereed Journal of Engineering and Science, 5 (2), 01–11. Available at: http://www.irjes.com/Papers/vol5-issue2/A520111.pdf
2. Mozhaiv, O., Kuchuk, H., Shvets, D., Tretiak, V., Tretiak, M., Ostropilets, V. et. al. (2019). Minimization of power losses by traction-transportation vehicles at motion over a bearing surface that undergoes deformation. Eastern-European Journal of Enterprise Technologies, 1 (1), 69–74. doi: https://doi.org/10.15587/1729-4061.2019.156721
3. Echevarria Sanchez, G. M., Van Renterghem, T., Thomas, P., Botteldooren, D. (2016). The effect of street canyon design on traffic noise exposure along roads. Building and Environment, 97, 96–110. doi: https://doi.org/10.1016/j.buildenv.2015.11.033
4. Zaets, V., Kotenko, S. (2017). Investigation of the efficiency of a noise protection screen with an opening at its base. Eastern-European Journal of Enterprise Technologies, 5 (5 (89)), 4–11. doi: https://doi.org/10.15587/1729-4061.2017.112350
5. Didkovskyi, V., Zaets, V., Kotenko, S. (2020). Improvement of the efficiency of noise protective screens due to sound absorption. Technology Audit and Production Reserves, 3 (1 (53)), 11–15. doi: https://doi.org/10.15587/2706-5448.2020.206018
6. Wang, Z. B., Choy, Y. S. (2019). Tunable parallel barriers using Helmholtz resonator. Journal of Sound and Vibration, 443, 109–123. doi: https://doi.org/10.1016/j.jsv.2018.11.013

7. Didkovskiy, V., Naida, S., Zaets, V. (2019). Experimental study into the Helmholtz resonators' resonance properties over a broad frequency band. Eastern-European Journal of Enterprise Technologies, 1 (5 (97)), 34–39. doi: https://doi.org/10.15587/1729-4061.2019.155417
8. Heimann, D. (2010). On the Efficiency of Noise Barriers Near Sloped Terrain – A Numerical Study. Acta Acustica United with Acustica, 96 (6), 1003–1011. doi: https://doi.org/10.3813/aaa.918363
9. Maekawa, Z. (1968). Noise reduction by screens. Applied Acoustics, 1 (3), 157–173. doi: https://doi.org/10.1016/0003-682x(68)90020-0
10. Kurze, U. J. (1974). Noise reduction by barriers. The Journal of the Acoustical Society of America, 55 (3), 504–518. doi: https://doi.org/10.1121/1.1914528
11. Hutchins, D. A., Pitcarn, D. (1983). A laser study of multiple reflections within parallel noise barriers. The Journal of the Acoustical Society of America, 73 (6), 2216–2218. doi: https://doi.org/10.1121/1.389548
12. Muradali, A., Fyfe, K. R. (1998). A study of 2D and 3D barrier insertion loss using improved diffraction-based methods. Applied Acoustics, 53 (1-3), 49–75. doi: https://doi.org/10.1016/s0003-682x(97)00040-6
13. Salomons, E. M., Geerlings, A. C., Duhamel, D. (1997). Comparison of a ray model and a Fourier-boundary element method for traffic noise situations with multiple diffractions and reflections. Acta Acustica united with Acustica, 83 (1), 35–47. Available at: https://www.ingentaconnect.com/content/dav/aaua/1997/00000083/00000001/art00009
14. Halliwell, R. E. (1982). Field performance of parallel barriers. Canadian Acoustics, 10 (3), 9–18. Available at: https://jcaa.caa-aca.ca/index.php/jcaa/article/view/486/155
15. Nelson, P. M., Abbott, P. G., Salvidge, A. C. (1977). Acoustic performance of the M6 noise barriers (No. LR-731 Lab. Rpt.).
16. Fleming, G. G., Rickley, E. J. (1992). Parallel barrier effectiveness under free-flowing traffic conditions (No. FHWA-RD-92-068; DOT-VNTSC-FHWA-92-1; HW227/H2002/4E7B1112). United States. Federal Highway Administration. Available at: https://rosap.ntl.bts.gov/view/dot/8967
17. Watts, G. R. (1996). Acoustic performance of parallel traffic noise barriers. Applied Acoustics, 47 (2), 95–119. doi: https://doi.org/10.1016/0003-682x(95)00031-4
18. Mobarakeh, P. S., Grinchenko, V. T. (2015). Construction Method of Analytical Solutions to the Mathematical Physics Boundary Problems for Non-Canonical Domains. Reports on Mathematical Physics, 75 (3), 417–434. doi: https://doi.org/10.1016/s0034-4877(15)30014-8
19. Vovk, I. V., Matsypura, V. T. (2010). Noise-protective properties of the barriers located along the both sides of traffic artery. Akustychnyi visnyk, 13 (4), 3–14. Available at: http://dspace.nbuv.gov.ua/handle/123456789/79836
20. Vovk, I. V., Grinchenko, V. T., Matsypura, V. T. (2012). Soundproof properties of the barriers located along the city street. Akustychnyi visnyk, 15 (2), 3–16. Available at: http://dspace.nbuv.gov.ua/handle/123456789/116171
21. Abramovits, M., Stigan, I. (Eds.) (1979). Spravochnik po spetsial'nym funktsiyam. Moscow: Nauka, 832.
22. Shenderov, E. L. (1972). Volnovye zadachi gidroakustiki. Leningrad: Sudostroenie, 347.
23. Hrinchenko, V. T., Vovk, I. V., Matsypura, V. T. (2007). Osnovy akustyky. Kyiv: Naukova dumka, 640.
24. Didkovskyi, V., Zaets, V., Kotenko, S. (2021). Revealing the effect of rounded noise protection screens with finite sound insulation on an acoustic field around linear sound sources. Eastern-European Journal of Enterprise Technologies, 1 (5 (109)), 16–22. doi: https://doi.org/10.15587/1729-4061.2021.224327
25. Zaets, V. (2021). Influence estimation of the inclination angle of the top of the noise protection barrier on its efficiency. Technology Audit and Production Reserves, 1 (1 (57)), 12–16. doi: https://doi.org/10.15587/2706-5448.2021.225474