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SIMPLE METHODS FOR DETERMINATION OF THE ACOUSTICAL PROPERTIES OF GROUND SURFACES

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The interactions between the sound wave and the ground surface belong to the most important phenomena determining the outdoor noise propagation. In the present study, the exact theory of noise propagation and two simple models of the ground effect are analysed. The paper presents a method of determination of the effective flow resistivity, based on the two-channel measurement of the sound level (the exact theory). For the simplified model of the ground effect, the adjustable parameters are given as a function of the effective flow resistivity. Similarly for the ground effect model given by ISO 9613, the dependence of the ground factor (as a function of the effective flow resistivity) is presented. Additionally, for a few selected types of ground surfaces, the values of the model parameters were determined.

Keywords: ground effect, noise propagation.

1. Introduction

Noise propagation in open space depends on many phenomena. Close to the source, geometrical spreading and ground effect have a major influence on noise propagation. Further from the source, air absorption, refraction and the atmospheric turbulence must be taken into account [1]. In many real situations simplified models of noise propagation are preferred [2–4]. These models have many advantages important for the noise mapping applications: short computation times, a limited number of input parameters (detailed input data are not available in real situations). Simplified models of noise propagations can be used when the calculations of the sound level in the frequency bands are not required and a total sound level (dBA) is sufficient. In most cases simple models can be used for noise sources with the maximum acoustic energy from the intermediate frequency range.

The most common problem with estimating the noise propagation is determination of the parameter (or parameters) characterizing the ground surface. In the exact theory, the acoustic properties of a ground surface are characterized by the acoustic impedance Z depending on the sound frequency f and the effective flow resistivity σ. In the present study, a simple method for determination of σ is proposed. It is based on the two-channel measurement of the sound level at two different distances from the source and/or at two different heights above the ground surface.

In this paper two simplified models of the ground effect are analysed. The expressions of the model free parameters as functions of effective flow resistivity are given. Additionally, the methods of the parameters determination for these models are presented.

2. Noise produced by a stationary source above the ground surface

Let us consider the non-directional point source at the height H_s above a flat ground surface. The A-weighted, squared sound pressure in the n-th frequency band can be written as follows (for H_s and $H_o \ll d$):

$$p_{An}^2 = \frac{W_{An}\rho c}{4\pi d^2} \cdot Gr_n, \tag{1}$$

where W_{An} is the sound power in the n-th frequency band, ρc is the air specific impedance and d is the distance between the source and the receiver. The ground factor Gr_n, describing the interactions between the sound wave and the ground surface, depends on the frequency, the ground impedance in the n-th frequency band Z_n, the height of the source H_s and the receiver H_o (Fig. 1):

$$Gr_n \to Gr_n(d, H_s, H_o, Z_n). \tag{2}$$

The function Gr_n can be presented in the exact (Sec. 3.1) or simplified form (Sec. 3.2).

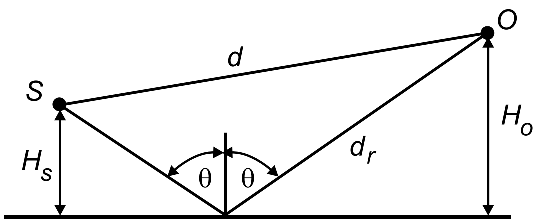

Fig. 1. Source – receiver geometry in the horizontal plane.

3. Determination of the acoustical properties of ground surfaces

3.1. The exact theory

The ground impedance depends upon the affective flow resistivity σ [5]:

$$Z_n = 1 + 9.08\,(f/\sigma)^{-0.75} + i \cdot 11.9\,(f/\sigma)^{-0.73}\,. \tag{3}$$

Other models of the ground impedance have also been proposed [6].

The exact formula of the ground factor Gr_n is defined by [7],

$$Gr_n = 1 + |Q_n|^2 \left(\frac{d}{d_r}\right)^2 + 2\,|Q_n|\,\frac{d}{d_r}\cos\left[\frac{2\pi f_n}{c}(d-d_r)+\varphi_n\right], \tag{4}$$

where d and d_r denote the path lengths of the direct and the reflected wave (Fig. 1), and $Q = Q\exp(i\varphi)$ is the complex, spherical wave reflection coefficient given by:

$$Q = R_p + (1-R_p)\,F(\mu). \tag{5}$$

In the above equation,

$$R_p = \frac{\cos\theta - \rho c/Z}{\cos\theta + \rho c/Z} \tag{6}$$

is the plane wave reflection coefficient, θ is the reflection angle from the ground surface and the function

$$F(\mu) = 1 + i\sqrt{\pi}\mu\exp\left(-\mu^2\right)\operatorname{erfc}(-i\mu), \tag{7}$$

where

$$\mu = \sqrt{i\frac{\pi f d_r}{c}}\left(\cos\theta + \frac{\rho c}{Z}\right). \tag{8}$$

Equation (1) can be rewritten in the following form:

$$p_A^2 = \frac{W_A\rho c}{4\pi d^2}\cdot Gr_A, \tag{9}$$

where W_A denotes the total A-weighted sound power. The function Gr_A is given by

$$Gr_A = \sum_n q_n \cdot Gr_n(d, H_s, H_o, Z_n), \tag{10}$$

where

$$q_n = \frac{W_{nA}}{W_A} \tag{11}$$

is the relative sound power spectrum of the point source.

Using the definition of the sound level,

$$L_{pA} = 10\cdot\log\left(\frac{p_A^2}{p_o^2}\right), \qquad p_o = 2\cdot 10^{-5}\ \text{Pa}, \tag{12}$$

and Eq. (9), we get

$$L_{pA} = L_{WA} + 10\cdot\log\left(\frac{s_o}{4\pi d^2}\right) + F_g, \tag{13}$$

where the function

$$F_g = 10\cdot\log(Gr_A) = 10\cdot\log\left(\sum_n q_n\cdot Gr_n(d, H_s, H_o, \sigma)\right) \tag{14}$$

corresponds to the exact ground factor in decibels. The quantity (Eq. (13))

$$L_{WA} = 10 \cdot \log \left(\frac{W_A \rho c}{p_o^2 s_o} \right), \quad s_o = 1 \text{ m}^2 \tag{15}$$

is the A-weighted sound power level of the point source.

When the effective flow resistivity σ is known, the relationships (13) and (15) allow the sound level to be determined at the distance d from the point source (in Ref. [1] the classification of σ for the full range of ground surfaces can be found).

The method of determination of σ is presented below. It is based on the two-channel measurement of the sound level L_{pA}.

Let us write the sound level for the first channel (at the distance d_1, at the height $H_o^{(1)}$):

$$L_{pA}^{(1)} = L_{WA} + 10 \cdot \log \left(\frac{s_o}{4\pi d_1^2} \right) + 10 \cdot \log \left(\sum_n q_n \cdot Gr_n^{(1)} \left(d_1, H_s, H_o^{(1)}, \sigma \right) \right), \tag{16}$$

and for the second channel (at the distance d_2, at the height $H_o^{(2)}$):

$$L_{pA}^{(2)} = L_{WA} + 10 \cdot \log \left(\frac{s_o}{4\pi d_2^2} \right) + 10 \cdot \log \left(\sum_n q_n \cdot Gr_n^{(2)} \left(d_2, H_s, H_o^{(2)}, \sigma \right) \right). \tag{17}$$

Subtracting Eqs. (16) and (17) we obtain:

$$L_{pA}^{(1)} - L_{pA}^{(2)} - 10 \cdot \log \left(\frac{d_2^2}{d_1^2} \right) = 10 \cdot \log \left(\frac{\sum\limits_n q_n \cdot Gr_n^{(1)} \left(d_1, H_s, H_o^{(1)}, \sigma \right)}{\sum\limits_n q_n \cdot Gr_n^{(2)} \left(d_2, H_s, H_o^{(2)}, \sigma \right)} \right). \tag{18}$$

We get the correct value of the effective flow resistivity σ when the left, L, and right, $R(\sigma)$, sides of the above equation are equal. If there is no σ which makes $L = R(\sigma)$ then we take $\widetilde{\sigma}$ which meets the condition:

$$\text{error} = |L - P(\widetilde{\sigma})| = \text{minimum}. \tag{19}$$

Equation (18) can be rewritten in the following form:

$$L_{pA}^{(1)} - L_{pA}^{(2)} - 10 \cdot \log \left(\frac{d_2^2}{d_1^2} \right) = 10 \cdot \log \left(\sum_n 10^{0.1 \cdot \delta L_{pAn}^{(2)}} \frac{Gr_n^{(1)} \left(d_1, H_s, H_o^{(1)}, \sigma \right)}{Gr_n^{(2)} \left(d_2, H_s, H_o^{(2)}, \sigma \right)} \right), \tag{20}$$

where

$$\delta L_{pAn}^{(2)} = L_{pAn}^{(2)} - L_{pA}^{(2)} \tag{21}$$

is the mentioned A-weighted sound power spectrum ($L_{pAn}^{(2)}$ is the A-weighted sound level in the n-th frequency band and $L_{pA}^{(2)}$ is the total A-weighted sound level), registered in the second channel (at the distance d_2, at the height $H_o^{(2)}$). Thus a two-channel measurement of sound level L_{pA} is required to determine the effective flow resistivity, provided that measurement of the sound level spectrum L_{pAn} is made in one channel. In Ref. [8] a very similar method is proposed.

To illustrate this method, measurements of the sound level above a grass-covered ground were performed ($H_s = 0.6$ m, $d_1 = 4$ m, $H_o^{(1)} = 1.3$ m, $d_2 = 11.0$ m and $H_o^{(2)} = 1.5$ m). In the measurements, the following equipment was used:

- the noise source Brüel&Kjær 4224,
- two-channel sound level-meter type B&K 2144 (with two microphones type B&K 4165).

Figure 2 presents the numerical solution of Eq. (20). As it can be seen, the smallest error (Eq. (19)) was obtained for $\sigma = 85$ kPa·s/m^2 (the error is ≈ 0.25 dB).

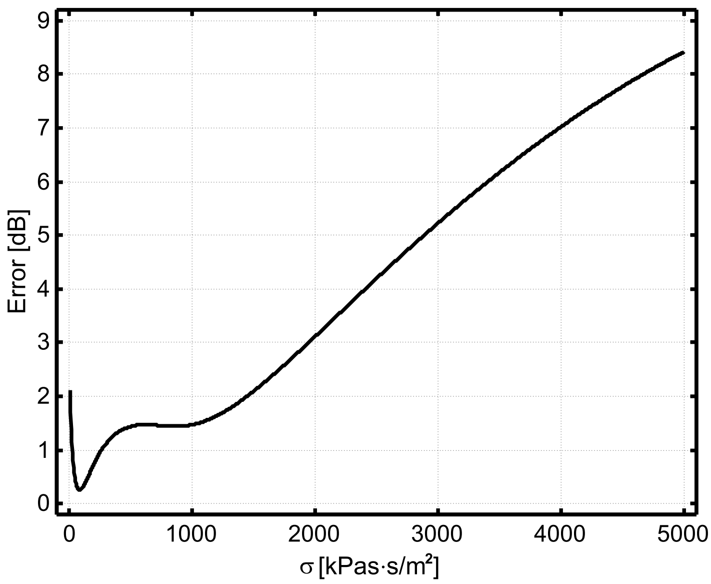

Fig. 2. The numerical solution of Eq. (20) ($H_s = 0.6$ m, $d_1 = 4$ m, $H_o^{(1)} = 1.3$ m, $d_2 = 11.0$ m and $H_o^{(2)} = 1.5$ m).

3.2. *The simplified model*

In Ref. [9] the exact ground factor (Eq. (10)) was approximated by a simple function:

$$\widetilde{Gr}_A \cong \frac{\beta}{1 + \gamma \left(\dfrac{d}{H_s + H_o} \right)^2}, \tag{22}$$

where β and γ are the model's free parameters. β describes the acoustic wave reflection close to the source ($d \to 0, \widetilde{Gr}_A \to \beta$) and γ characterizes the acoustic properties of the ground surface.

In the present study, the adjustable parameters were calculated by the least square analysis for $0.5 < H_s < 2$ m, $1.2 < H_o < 10$ m, $10 \leq d \leq 1000$ m, and for $20 < \sigma < 5000$. The A-weighted spectrum of a "typical roadway, with any railway traffic and many industrial sources of outdoor noise", was used as reference [10].

On the basis of the values of β and γ deduced for different heights of the source, H_s, and the observation point, H_o, and various ground surfaces, the regression line was fitted using the following formulas:

$$\beta = A \exp(B \cdot \sigma) + C \exp(D \cdot \sigma), \tag{23}$$

and

$$\gamma = E \cdot \exp(F \cdot \sigma), \tag{24}$$

where A, B, C, D, E and F are the regression coefficients. The regression curves are presented in Fig. 3 and Fig. 4, and the values of the regression coefficients are given in Table 1. Using dependences (23) and (24), the values of β and γ were calculated for a few selected types of ground surfaces (Table 2).

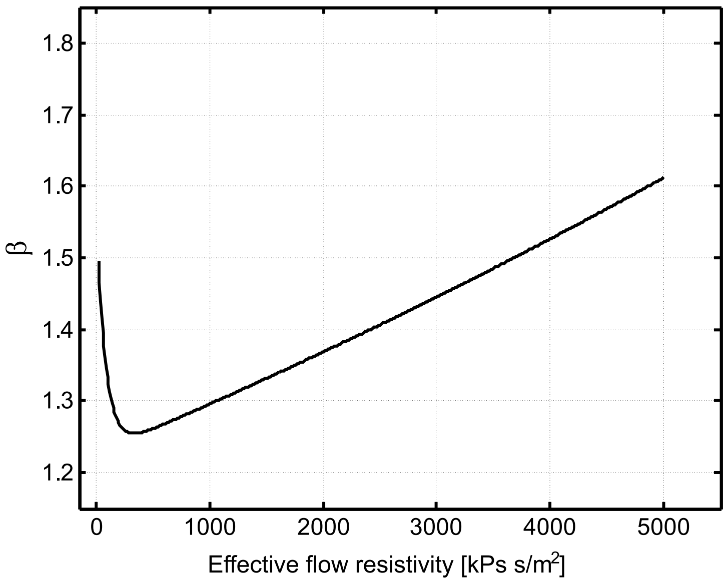

Fig. 3. Changes in the β parameter as a function of the effective flow resistivity σ.

Using the simplified form of the ground effect (Eq. (22)), the sound level is

$$L_{pA} = \widetilde{L}_{WA} + 10 \log \left(\frac{s_o}{4\pi d^2} \right) - 10 \log \left(1 + \gamma \left(\frac{d}{H_S + H_o} \right)^2 \right), \tag{25}$$

where

$$\widetilde{L}_{WA} = 10 \log \left(\frac{\beta W_A \rho c}{p_o^2 s_o} \right) \tag{26}$$

is the effective (modified by the reflection (β parameter) from the ground close to the source) sound power level of the noise source.

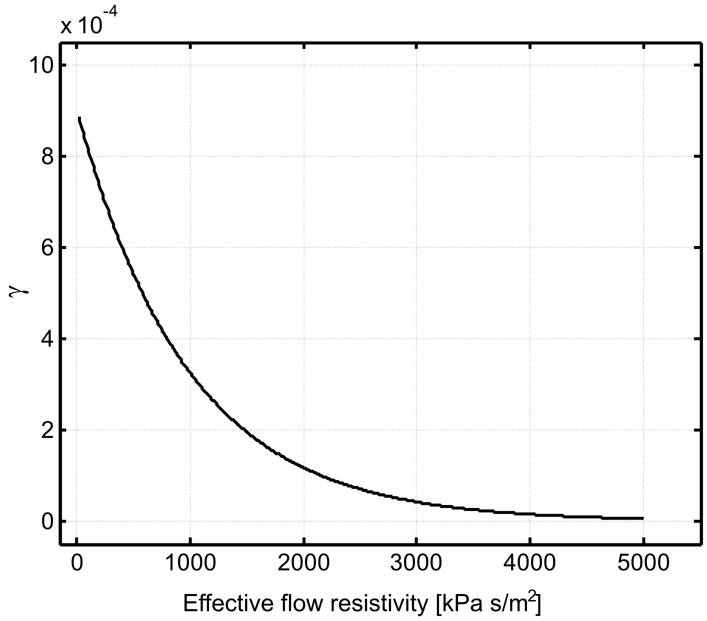

Fig. 4. Changes in the γ parameter as a function of the effective flow resistivity σ.

Table 1. The regression and correlation coefficients of the simplified model of the ground effect.

The regression coefficients		The correlation coefficients
A	$3.6 \cdot 10^{-1}$	0.54
B	$-1.2 \cdot 10^{-2}$	
C	1.22	
D	$5.5 \cdot 10^{-5}$	
E	$9.04 \cdot 10^{-4}$	0.3
F	$-10.2 \cdot 10^{-4}$	

As shown in Ref. [9], the coefficient γ can be calculated from:

$$\gamma = \frac{(m-1)}{\left(\left(\frac{d_2}{H_s + H_o^2}\right)^2 - m\left(\frac{d_1}{H_s + H_o^2}\right)^2\right)}, \tag{27}$$

where m is given by

$$m = \left(\frac{d_1}{d_2}\right)^2 \cdot 10^{0.1 \cdot \left(L_{pA}^{(1)} - L_{pA}^{(2)}\right)}. \tag{28}$$

$L_{pA}^{(1)}$ in Eq. (28) is the sound level at the distance d_1 and the height $H_o^{(1)}$. $L_{pA}^{(2)}$ is the sound level at the distance d_2, and the height $H_o^{(2)}$.

Table 2. The values of the free model's parameters β and γ (Eq. (22)) and ground factor G (ISO 9613) for various ground surface.

Description of surface	Effective flow resistivity σ [kPa·s/m^2]	β	γ	G
0.1 m new fallen snow, over older snow	20	1.5	$8.9\cdot10^{-4}$	$65.2\cdot10^{-2}$
Sugar snow	35	1.4	$8.7\cdot10^{-4}$	$59.3\cdot10^{-2}$
Floor of evergreen forest	50	1.4	$8.6\cdot10^{-4}$	$54.4\cdot10^{-2}$
Airport grass or old pasture	$100 \div 300$	1.3	$8.2\cdot10^{-4}$ $\div$ $8.9\cdot10^{-4}$	$43.1\cdot10^{-2}$ $\div$ $25.1\cdot10^{-2}$
Roadside dirt, ill-defined, small rocks up to 0.01m mesh	500	1.3	$5.4\cdot10^{-4}$	$18.8\cdot10^{-2}$
Sandy silt, hard-packed by vehicles	1000	1.3	$3.3\cdot10^{-4}$	$13\cdot10^{-2}$
Thick layer of clean limestone chips (0.01 to 0.025 m mesh)	2000	1.4	$1.2\cdot10^{-4}$	$9.6\cdot10^{-2}$
Old dirt roadway, small stones with interstices filled by dust	3000	1.4	$4.2\cdot10^{-5}$	$8.4\cdot10^{-2}$
Earth, exposed and rain-packed	5000	1.6	$5.5\cdot10^{-6}$	$7.4\cdot10^{-2}$

4. The ISO 9613-2 method

The procedure of noise attenuation outdoors, described by ISO 9613 [11], is recommended by the European Union as an interim computation method for strategic noise mapping of industrial noise [12].

The ISO 9613 takes into account the following phenomena: geometrical divergence, atmospheric absorption, screening by obstacles and the ground effect. The acoustic properties of the ground surface are described by the ground factor G, but ISO 9613 specifies only three categories of surfaces: hard ground (e.g. paving, water, ice, concrete and all other ground surfaces having a low porosity, $G = 0$), porous ground (e.g. ground covered by grass, trees or other vegetation and all other ground surfaces suitable for the growth of vegetation, such as farming land, $G = 1$), and mixed ground (G takes on the values from 0 to 1).

Unfortunately, in daily practice it is very difficult to find the correct value of the ground factor G for a specific ground surface. In Ref. [13], the following dependence of G as a function of effective flow resistivity σ is proposed (Fig. 5):

$$
\begin{aligned}
&G = 1, && \sigma \le 300,\\
&G = \left(\frac{300}{\sigma}\right)^{0.57}, && \sigma > 300.
\end{aligned}
\tag{29}
$$

In the present study, calculations of the ground factor G (ISO 9613) have been performed. The ground attenuations in the octave bands at a specific distance were calculated using the exact model (Eq. (14)) and ISO 9613 (Eq. (9) and Table 3 in [11]). The

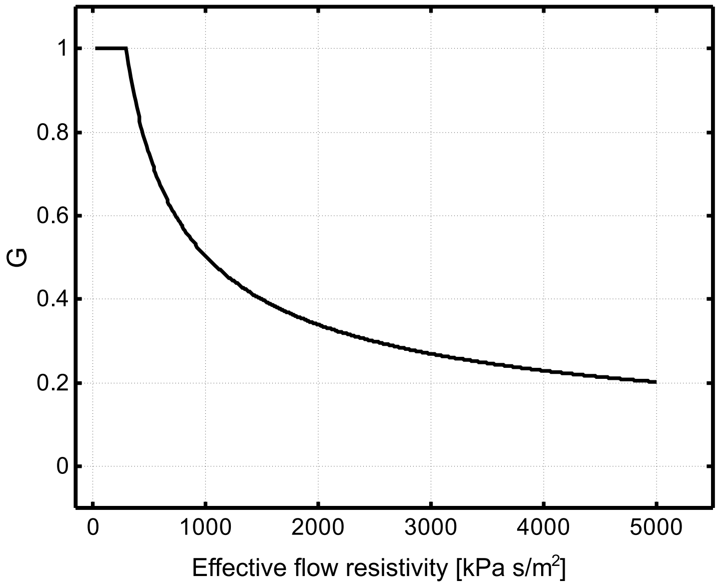

Fig. 5. Changes in the ground factor G calculated using Eq. (29).

correct value of the ground factor G was that for which the difference between the total sound level L_{pA} obtained by means of the exact model and ISO 9613 was minimal. A hypothetical comparison of the ground attenuations calculated using both models is presented in Fig. 6.

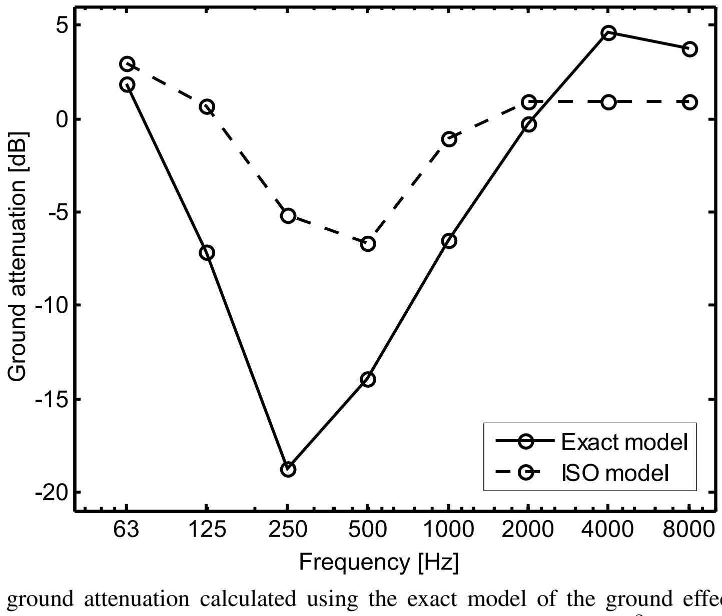

Fig. 6. The ground attenuation calculated using the exact model of the ground effect and ISO 9613 ($d = 40$ m, $H_s = 0.5$ m, $H_o = 1.2$ m, $\sigma = 25$ kPa s/m^2).

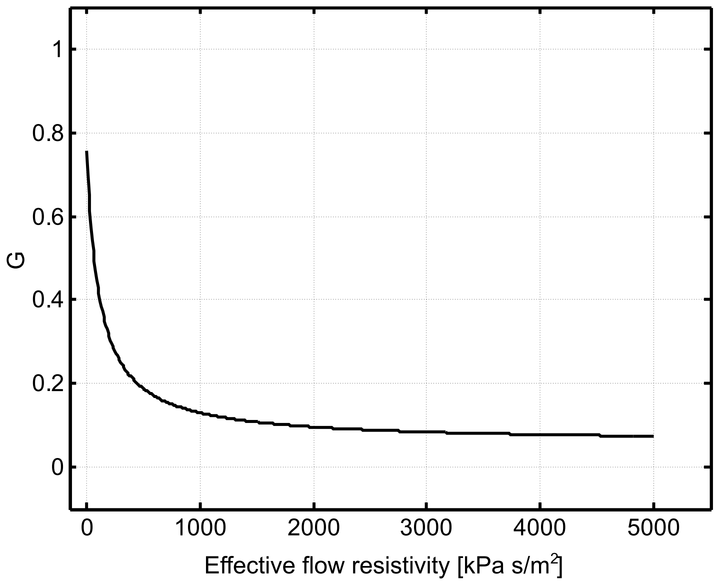

Fig. 7. Changes in the ground factor G as a function of the effective flow resistivity σ (Eq. (30), Table 3).

Table 3. The regression and correlation coefficients (Eq. (30)).

The regression coefficients		The correlation coefficients
G_1	$5.9 \cdot 10^{-2}$	0.55
G_2	86.4	
G_3	114.3	

The calculations were performed for $H_s = 0.5, 1.0, 2.0$ m, $H_o = 1.2, 4, 6, 8, 10$ m and $d = 40$, 80 and 120 m. In this way 540 values of G were obtained. On the basis of these values, the regression line was fitted using the following formula:

$$G = \frac{G_1\sigma + G_2}{\sigma + G_3}, \tag{30}$$

where G_1, G_2 and G_3 are the regression coefficients. The values of G_1, G_2 and G_3 are presented in Table 3. Using the obtained dependence, the ground factors G for various ground surfaces were calculated (Table 2).

5. Conclusions

In the present study, the ground effect on the noise propagation estimation has been analysed. Based on the exact formula of the ground effect, the method of effective flow resistivity σ determination has been derived. To determine σ, the measurements of sound level L_{pA} at two different distances and at different heights above the ground surface are required. Knowledge of the effective flow resistivity allows to predict the noise level at any distance from the source, using the exact model of the ground effect (other phenomena are neglected).

Additionally, for the simplified model of the ground effect, the expressions of the adjustable parameters as functions of the effective flow resistivity are given, along with the method of determination of the parameters.

Similarly, for the ground effect model given by ISO 9613, the dependence of the ground factor on the effective flow resistivity has been also determined.

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