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THE EFFECT OF SOUND ABSORPTION BY THE AIR ON NOISE PROPAGATION

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In this paper, the relationship between the sound level (measured in dB(*A*)) and the distance was derived on the assumption that air absorption is the only essential factor affecting noise propagation. It was shown that at a great distance from the source "rapid sound level drop", exceeding 6 dB(*A*), occurs when the distance is doubled.

1. Introduction

In the environment of man noise is in most cases generated by the sources which can be treated as directional point sources (e.g. single means of transportation, transformer stations, construction machinery [8]). From the acoustic point of view, it is possible to shape the environment only when the explicit relations among the quantities describing the effect of noise on man are known, i.e. those among the indices of noise evaluation and quantities related to the process of noise generation and propagation, including the length of the propagation path.

In general, the annoyance of noise with time invariable spectrum is evaluated by means of sound level expressed in dB(*A*). The continuons weight function $W(f)$ corresponding to the correction curve *A* is given in the Appendix.

When the source is directionless, full information on the noise generation process is contained in the power spectral density. In Section 2.1, the function $P(f)$ that can be applied to a broad class of real sources is proposed. Table 2 gives the parameters of this function for different car types.

The sound propagation in the air is the effect of superposition of a few elementary phenomena: (classical and molecular) absorption, refraction and interaction of waves with the ground surface. When the source is close to the ground surface and the observation point is at least a few metres over the surface, which corresponds e.g. to the case "vehicle-apartment a few storeys over the ground" (Fig. 1), only the air absorption plays a significant role. Under this assumption, the noise propagation process can be described by only two quantities: a parameter related to the absorption (Section 2.2) and the distance between the observation point and the source. The latter quantity is of particular significance, e.g. because increasing the distance between a transportation route and buildings is one of the most effective methods of protecting the acoustic climate in the environment of man.

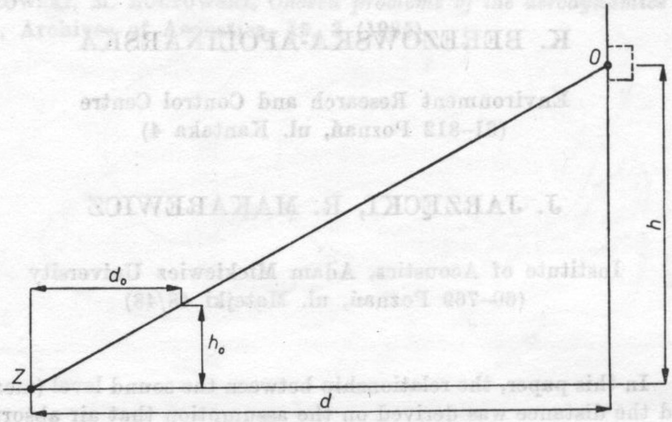

Fig. 1. Mutual position of source (Z) and the observation point (0) high over the ground surface

In Section 3, an explicit relationship between the sound level [$dB(A)$] and the distance is derived. Analysis of this dependence (Section 4) shows the usefulness of introducing the "critical distance" R which when exceeded leads to a rapid level drop (Fig. 2). Table 4 gives the values of R for a chosen car type, with varying atmospheric conditions (temperature, humidity).

2. Sound propagation in the air

When the sound source (Z) is much closer to the ground surface than the observation point (0) (Fig. 1), the effects of interaction between the acoustic wave and the ground surface — the "ground effects" [4] — can be neglected. ATTENBOROUGH showed [2] that when the height (h) of the observation point is a few meters over the ground surface, the failure to consider these effects leads to error of about 1 $dB(A)$. When the above assumption is satisfied, only the direct wave reaches the observation point.

This wave undergoes refraction. It is assumed that the atmospheric conditions, i.e. the wind speed and temperature changes with height, permit this phenomenon to be neglected. PIERCY and EMBLETON [7] emphasized that refraction plays a significant role only when the source and the observation point are at the ground surface.

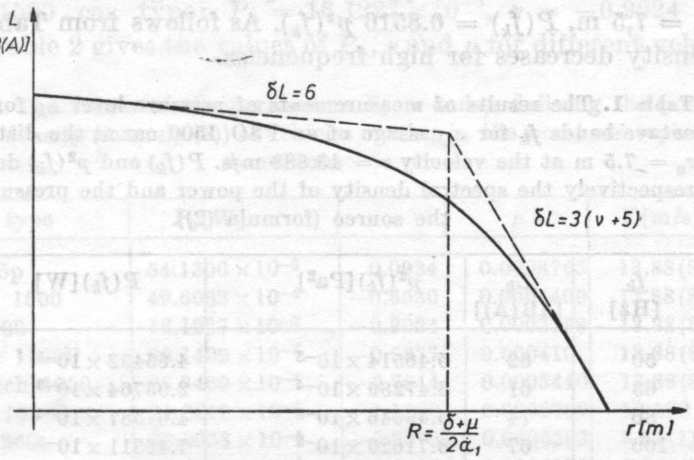

Fig. 2. Sound level drop δL for a double distance for $r \ll R$ and $r \gg R$, where R is the "critical distance" (formula (12))

It will be assumed further on that absorption by the air is the main factor affecting the sound propagation. When $p^2(f)$ is the spectral density of the acoustic pressure, then, for a source at the ground surface,

$$p^2(f) = \frac{P(f)\exp\{-2\alpha(f)\}\varrho c}{2\pi r}, \tag{1}$$

where $r = \sqrt{h^2+d^2}$ is the distance from the observation point (Fig. 1), $\varrho_0 c = 415$ [Pas/m] is the acoustic resistance of the air, $\alpha(f)$ is the absorption coefficient and $P(f)$ is the power spectral density of the source.

2.1. *Power spectral density of the source*

Let's assume that at the distance $r = \sqrt{h_0^2+d_0^2}$ (Fig. 1), the level of the acoustic pressure was measured in the successive frequency bands, $L_1, \ldots, L_k, \ldots, L_n$, with the centre frequencies $f_1, \ldots, f_k, \ldots, f_n$. From the definition of the pressure level, $L_k = 10 \log p_k^2/p_0^2$, $p_0 = 2\times10^{-5}$ Pa, it is possible to determine the values of $p_1^2, \ldots, p_k^2, \ldots, p_n^2$. When Δf_k is the width of the kth frequency band, then $p_k^2 = p^2(f_k)\Delta f_k$, where $p^2(f_k)$ is the pressure spectral density for the centre frequency of the band, f_k. According to formula (1), this quantity can be related to the power spectral density of the source in the following way

$$P(f_k) = \frac{2\pi r_0^2 p^2(f_k)}{\varrho_0 c}. \tag{2}$$

(This formula has been derived under the assumption that $2\alpha(f)r_0 \ll 1$, i.e. the absorption at the distance r_0 does not play a significant role). E.g. for the distance $r_0 = 7{,}5$ m, $P(f_k) = 0.8516\ p^2(f_k)$. As follows from Table 1 the power spectral density decreases for high frequencies.

Table 1. The results of measurements of pressure level L_k for 1/3 octave bands f_k for a passage of an FSO 1500 car at the distance $r_0 = 7.5$ m at the velocity $v = 13.888$ m/s. $P(f_k)$ and $p^2(f_k)$ denote respectively the spectral density of the power and the pressure of the source (formula (2))

f_k [Hz]	L_k [dB(A)]	$p^2(f_k)$ [Pa^2]	$P(f_k)$ [W]
50	62	5.46514×10^{-5}	4.65432×10^{-5}
63	61	3.47289×10^{-4}	2.95764×10^{-3}
80	74	5.49046×10^{-5}	4.67587×10^{-4}
100	67	8.71629×10^{-5}	7.42311×10^{-5}
125	90	1.37931×10^{-2}	1.17467×10^{-2}
160	88	6.82116×10^{-3}	5.80914×10^{-3}
200	69	1.90720×10^{-5}	5.88242×10^{-5}
250	72	1.09302×10^{-4}	9.30864×10^{-5}
315	73	1.09329×10^{-4}	9.31089×10^{-5}
400	75	1.37490×10^{-4}	1.17091×10^{-4}
500	71	4.34112×10^{-5}	3.69705×10^{-5}
630	74	6.92934×10^{-5}	5.90128×10^{-5}
800	71	2.75174×10^{-5}	2.34349×10^{-5}
1000	70	1.73913×10^{-5}	1.48110×10^{-5}
1250	70	1.37931×10^{-5}	1.17467×10^{-5}
1600	68	6.82116×10^{-6}	5.80914×10^{-6}
2000	68	5.48658×10^{-6}	4.67257×10^{-6}
2500	68	4.35142×10^{-6}	3.70583×10^{-6}
3150	68	3.45730×10^{-6}	2.94436×10^{-6}
4000	67	2.17907×10^{-6}	1.85557×10^{-6}
5000	68	2.17571×10^{-6}	1.85299×10^{-6}
6300	66	1.09822×10^{-6}	9.35290×10^{-7}
8000	65	6.91208×10^{-7}	5.88658×10^{-7}
10000	60	1.73913×10^{-7}	1.48110×10^{-7}

Let us assume that

$$P(f) = P_0 f^{\nu} \exp(-\mu f). \tag{3}$$

The values of P_0, r and ν can be determined by regression analysis. Having found the logarithm of expression (3), we obtain

$$\ln P = \ln P_0 + \nu \ln f - \mu f,$$

which in the notation $y = \ln P$, $a = \ln P_0$ and $\ln f = x_1$, gives the linear dependence

$$y = a + \nu x_1 - \mu x_2. \tag{4}$$

From the measured and calculated set of values $\{x_1(k) = \ln f_k, x_2(k) = f_k, y(k) = \ln P(f_k)\}$ (see Table 1), the following coefficients were obtained for an FSO 1500 car type: $P_0 = 16.1227 \times 10^{-3}$, $\nu = -0.9024$ and $\mu = 0.0003188$. Table 2 gives the values of P_0, ν and μ for different vehicle types.

Table 2. The values of the parameters P_0, ν and μ defining the power spectral density (formula (3)) of vehicles moving in the worst atmospheric conditions

Vehicle type	P_0 [W]	ν	μ	V [m/s]
Fiat 125p	54.1300×10^{-6}	0.0934	0.0008765	13.88 (8)
Polonez 1500	49.6063×10^{-4}	−0.6530	0.0004409	13.88 (8)
FSO 1500	16.1227×10^{-3}	−0.9024	0.0003188	13.88 (8)
Zastava 1100P	38.1409×10^{-4}	−0.5677	0.000410	13.88 (8)
Moskvitch 1500	28.3469×10^{-4}	−0.7014	0.0003440	13.88 (8)
Żuk A 151 C	91.2619×10^{-3}	−1.1700	0.0002789	12.500
Ikarus 260	63.6958×10^{-4}	−0.5072	0.0006393	8.61 (1)
Jelcz 080	77.1012×10^{-4}	−0.6407	0.0006170	6.94 (4)
Star 38	43.1774×10^{-4}	−0.6199	0.0005105	10.55 (5)
Star 244 RS	27.0045×10^{-5}	−0.0381	0.0008744	10.27 (7)
Star 244	23.1085×10^{-5}	−0.0649	0.0007720	9.72 (2)
Star C 200	68.6694×10^{-5}	−0.0807	0.0008275	9.72 (2)
Tarpan F 237 R	32.8785×10^{-4}	−0.4994	0.0007091	9.72 (2)
Fiat 126p	37.2276×10^{-2}	−1.5213	−0.0002175	10.27 (7)

Expression (1), defining the pressure spectral density, includes besides the power spectral density of the source, $P(f)$, also the absorption coefficient $\alpha(f)$, which will now be considered.

2.2. *Absorption coefficient*

The energy of sound propagating in the air is absorbed due to heat conduction, viscosity and molecular relaxation in the medium where the acoustic wave propagates. This absorption is described by exponential function $\exp\{-2\alpha(f)r\}$ (formula (1)), where r is the length of the propagation path and α is the absorption coefficient. This coefficient is quite a complex function of frequency f, because each of the relaxation processes is described by a dependence of the form $Af^2/(B+f^2)$, where the parameters A and B depend on the temperature T and the humidity H of the medium.

In paper [1], numerical values of the absorption coefficient were given for the different frequencies, humidities and air temperatures. It was shown that over the frequency range 100–1000 Hz the coefficient a can be apparoximated by the formula [3]

$$a = a_1 f. \tag{5}$$

Table 3 gives the values of the parameter a and of the correlation coefficient K for the temperatures $T = 0, 5, 10, 15$ and 20°C and the humidities $H = 20, 40, 60$ and 80%. In all cases $K > 0.930$ which proves a good agreement between formula (5) and the real values of a.

Standard [11], recommended by the US Federal Aviation Administration, also gives the linear dependence (5) but the values of the parameter a_1 are slightly different.

These results were to some extent confirmed by SUTHERLAND and BASS [10]. They showed that for limited frequency bands the absorption coefficient may be assumed to be $a \sim f^k$, where the exponent falls within the interval (0, 2). In the present case it was assumed that $k = 1$.

The approximation expressed by formula (5) is surprising because each of the relaxation processes and the phenomena of energy transport, responsible for classical absorption, are described by nonlinear functions of frequency. Good approximation of the real values of the coefficient $a(f)$ by the linear dependence (5) is explained by the fact that over the frequency range 10–1000 Hz the energy absorption is caused above all by the relaxation of oxygen molecules. A significant fact is that the above range is small when compared with the whole range where this relaxation occurs (we may follow the principle that each nonlinear function, in an appropriately narrow range of variability of its argument, can be replaced by a linear function).

Considering formulae (1), (3) and (5), the pressure spectral density $p^2(f)$, at the distance r from the source, can thus be expressed in the following way:

$$p^2(f) \frac{P_0 \varrho_0 c}{2\pi r^2} f^\nu \exp\{-[\mu + 2a_1 r]f\}, \tag{6}$$

where $\varrho_0 c = 415$ [Pas/m], while P_0, ν and μ are the parameters descibing power spectral density (formula (3), Table 2).

3. Sound level

The principal aim of this investigation is to determine the dependence between the sound level L and the distance r, on the assumption that the conditions specified at the beginning of Section 2 are satisfied. As follows from the definition of the sound level (formula (A2)) at first it is necessary to determine the dependence of the (frequencyweighted) pressure on the distance. This dependence is defined by formulae (6) and (A5):

$$p_A^2 = \frac{P_0 \varrho_0 c}{2\pi r^2} \int_0^\infty W(f) f^\nu \exp\{-[\mu 2 a_1 r] f\} df.$$

Substitution of the explicit weight function $W(f)$ (formula (A4)) gives

$$p_A^2 = \frac{P_0 W_0 \varrho_0 c}{2\pi r^2} \int_0^\infty f^{\nu+2} \exp\{-[\mu+\delta+2a_1 r]\} df,$$

where $W_0 = 1.467 \times 10^{-6}$ and $\delta = 6.141 \times 10^{-4}$ (see the Appendix). Integration [5] gives

$$p_A^2 = \frac{P_0 W_0 \varrho_0 c}{2\pi r^2} \frac{\Gamma(\nu+3)}{[\mu+\delta+2a_1 r]^{\nu+3}}, \tag{7}$$

where $\Gamma(\nu+3)$ is EULER's gamma function. From the definition of the sound level expressed in $dB(A)$ (formula ($A2$)), it follows thus that

$$L(r) = L_0 - 20 \log r - \Delta L(r), \quad [\mathrm{dB}(A)], \tag{8}$$

where

$$L_0 = 10 \log \left\{ \frac{P_0 W_0 \varrho_0 c \Gamma(\nu+3)}{2\pi p_0^2 [\mu+\delta]^{\nu+3}} \right\}$$

and

$$\Delta L(r) = 10(\nu+3) \log \left\{ 1 + \frac{2a_1 r}{\delta+\mu} \right\} \tag{9}$$

is a sound level drop caused by absorption. (It can readily be noticed that for $a_1 = 0$ also $\Delta L = 0$).

4. Discussion of the results

Formula (9) implies that when observation point is close to the source, so that the inequality $r \ll (\delta+\mu)(2a_1)$ is satified, then ΔL is a negligibly small quantity ($\Delta L \ll 1$ dB(A)). In this case formula (8) becomes

$$L(r) = L_0 - 20 \log r, \tag{10}$$

which means the drop $\delta L = 6$ dB(A) when the distance is doubled.

When the distance between the observation point and the source is great, $r \gg (\delta+\mu)/(2a_1)$, then the level drop δL for a double distance is much greater, for (formula (9))

$$\Delta L(r) \approx 10(\nu+3) \log \left(\frac{2a_1 r}{\delta+\mu} \right)$$

and (formula (8))

$$L(r) = L_0+10(\nu+3)\log\left(\frac{2a_1}{\delta+\mu}\right)-10(\nu+5)\log r. \tag{11}$$

As follows from this dependence for a double distance $\delta L = 3(\nu+5)$, which for $\nu - 1.5$ (Table 2) gives the drop $\delta L > 10\,\mathrm{dB}(A)$.

This result is a little surpising. However, it should be borne in mind that formula (11) is valid for the distances r exceeding greatly the "critical distance" R, where

$$R = \frac{\delta+\mu}{2a_1}. \tag{12}$$

Substitution of $\delta = 6.141\times10^{-4}$ (see the Appendix), the parameter μ characterizing the power of the source (Table 2) and the quantities a_1 (Table 3) into this eguation gives the "critical distances" R for the sources of different type.

Table 3. The parameter a_1 (formula (4)) and the correlation coefficient K for the different temperatures T and humidities H

H [%] \ T[°C]		0	5	10	15	20
20	a_1	1.182×10^{-6}	1.769×10^{-6}	2.373×10^{-6}	2.744×10^{-6}	2.727×10^{-6}
	K	0.9308	0.9753	0.0012	0.9836	0.9687
40	a_1	1.960×10^{-6}	2.280×10^{-6}	2.373×10^{-6}	1.936×10^{-6}	2.727×10^{-6}
	K	0.9913	0.9753	0.9912	0.9531	0.9507
60	a_1	2.056×10^{-6}	1.956×10^{-6}	2.229×10^{-6}	1.358×10^{-6}	1.129×10^{-6}
	K	0.9792	0.9611	0.9645	0.9501	0.9571
80	a_1	1.848×10^{-6}	1.584×10^{-6}	1.289×10^{-6}	1.060×10^{-6}	9.106×10^{-7}
	K	0.9639	0.9513	0.9488	0.9547	0.9670

Table 4 gives as an example the values of R for an 1500 type car. By carying out similar calculations for the vehicles mentioned in Table 2, it can be found that for a Fiat 126p, at a temperature of 15°C and 20% humidity $R = 108$ m, while for an Ikarus $R = 228$ m. In the atmospheric conditions characterized by a tem-

Table 4. The "critical distances" R[m] (formula (12)) for an FSO 1500 car type for different atmospheric conditions

H [%] \ T[°C]	0	5	10	15	20
20	395	264	197	170	171
40	238	205	209	241	291
60	227	238	201	343	413
80	252	295	362	440	512

perature of 30°C and humidity of 80%, for a Fiat 126 p $R = 358$ m, for an Ikarus $R = 757$ m. The latter case proves that noise propagates very far. Large "critical distances" also occur for Star lorries and for Fiats 125p.

It can be discerned that for most vehicles the "critical distance" increases with increasing air humidity and temperature. However, for particular vehicle types, the temperature $T = 15°C$ and the humidity $H = 20\%$ are the most favourable atmospheric parameters, since the "critical distances" are then the shortest. Noise is most effectively damped by the air in such atmospheric conditions.

Table 5. Values of the sound level drop at the "critical distance" R

Vehicle type	$\Delta L(R)$ [dB(A)]
Fiat 125 p	9.3
Polonez 1500	7.1
FSO 1500	6.3
Zastava 1100 P	7.3
Moskvitch 1500	6.9
Żuk A 151 C	5.5
Ikarus 260	7.5
Jelcz 080	7.1
Star 38	7.2
Star 244 RS	8.9
Star 244	8.8
Star C 200	8.8
Tarpan F 237 R	7.5
Fiat 126p	4.5

The "critical distance" R depends on μ (formula (12)), one of the parameters defining the spectral density of the source (formula (3)). Another parameter, ν, affects the magnitude of the sound level drop. Substitution of the definition of R (formula (12)) into (9) gives

$$\Delta L(r) = 10(\nu+3)\log\left\{1+\frac{r}{R}\right\}.$$

This is a level drop caused only by the air absorption. For $r = R$

$$\Delta L(r) = 10(\nu+3)\log 2 = 3(\nu+3). \tag{13}$$

Putting the values of ν from Table 2 into this formula we get the values of $\Delta L(r)$ for the particular vehicle type (Table 5). A comparison between them and the values of the "critical distance" calculated for these vehicles shows that the highest noise level drop caused by the absorption by the air can be observed for the noisiest wehicles (Ikarus, Star, Fiat 125, with the highest R). Despite this, e.g. at a distance of 300 m, the noisiest vehicles are still Ikaruses and Stars, which is confirmed by everyday experiences.

5. Conclusions

Many measurements of noise propagating in open areas indicate the phenomenon of a "rapid sound level drop with increasing distance". EMBLETON, PIERCY and OLSON [4] showed that close to the source the phenomenon is related to interaction between the accoustic wave and the ground surface.

In the present paper, it has been shown that a rapid sound level drop at longer distances from the source (of the order a few hundred metres) can be caused by the air absorption.

This effect follows from formula (8), which relates the sound level, the distance r, the parameters describing the source (P_0, ν, μ — formula (3)) and the damping by the air (a_1 — formula (5), Table 3). The quantities $W_0 = 1.467 \times 10^{-6}$ and $\delta = 6.141 \times 10^{-4}$, occurring there, describe the frequency correction (Appendix). As follows from this formula the sound level drop for a double distance is much higher than 6 dB(A) when $r \gg R$, where R (formula (12)) is the "critical distance" (Fig. 2). In the case of an Ikarus for which $R \cong 700$ m, the phenomenon of a rapid level drop can be observed a few hund red metres from the road, on the condition that the observation point (O) is located in the way shown in Fig. 1.

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Appendix

Despite the increasingly serious objections, the sound level expressed in dB(A) is generally used as the measure of the annoyance of time invariable noise. It is defined as

$$L = 10\log\left\{\sum 10^{0.1(L_k+\Delta L_k)}\right\}, \quad \text{(A1)}$$

where L_k is the pressure level in the kth 1/3 octave band, characterized by the centre frequency f_k, whereas the quantity ΔL_k corresponds to the correction curve A. For the centre frequencies $f_1 = 50$ Hz, $f_2 = 63, \ldots, f_{24} = 10\,000$ Hz, respectively, $\Delta L_1 = -30.2$, $\Delta L_2 = -26.2$, ..., $\Delta L_{24} = -2.5$ dB. By using futher the definition of the sound level, $L_k = 10 \log (p_k^2/p_0^2)$, formula ($A$ 1) can be rewritten in the form

$$L = 10 \log\{P_A^2/p_0^2\}, \quad \text{(A2)}$$

where

$$p_A^2 = \sum 10^{0.1\Delta L_k} p_k^2 \quad \text{(A3)}$$

is the squared frequency — weighted pressure, according to the correction curve A. It can be seen that the weight function

$$W(f_k) = 10^{0.1\Delta L_k}, \quad k = 1, 2, \ldots,$$

takes values

$$W(f_1) = 10^{-3.02},\ W(f_2) = 10^{-2.62}, \ldots, W(f_{24}) = 10^{-0.25}.$$

It can be discerned that the set $\{f_k, W(f_k)\}$ can be approximated by the continuous function

$$W(f) = W_0 f^2 \exp\{-\delta f\}. \quad \text{(A4)}$$

The application of regression analysis to the set of points $(31, 10^{-3.02})$, $(50, 10^{-2.62})$, ..., $(10\,000, 10^{-0.25})$ gives the following values: $W_0 = 1.467 \times 10^{-6}$, $\delta = 6.141 \times \times 10^{-4}$. Hence, formula ($A$3) can be rewritten in the form

$$P_A^2 = \int_0^\infty W(f) p^2(f)\, df, \quad \text{(A5)}$$

where $p^2(f)$ is the pressure spectral density.