ARCHIVES OF ACOUSTICS
4, 4, 317-330 (1979)

CORRELATION AND PULSE TECHNIQUES FOR IDENTIFICATION OF THE PATHS OF DIFFRACTED AND PENETRATING WAVES THROUGH BARRIERS

STEFAN CZARNECKI

Institute of Fundamental Technological Research, Polish Academy of Sciences (00-049 Warszawa)

ZBIGNIEW ENGEL, ANNA MIELNICKA

Institute of Mechanics and Vibroacoustics, Mining and Metallurgy Academy (30-059 Kraków)

This paper presents a theoretical analysis and the results of measurements aimed at distinguishing in the total energy transmitted by the barrier, the energy of a wave penetrating the barrier due to its limited insulation and the energy of a wave diffracted at the edge of the barrier.

Correlation and pulse techniques have been used in the investigation, to compare the resolution of the two methods for chosen kinds of acoustic signals, i.e. for band noise in the correlation method and for a pulse produced by a spark source in the pulse method. The calculated uncertainty products were the basis for the comparison of resolution agreement between the two methods.

1. Introduction

Problems in the identification of both sound sources and the paths of acoustic waves propagation are among the basic considerations of vibroacoustics. They are primarily significant for vibroacoustic diagnostics and for noise control, since a quantitative determination of acoustic energy at an observation point of an acoustic field permits to find the dominant source or the dominant propagation path.

The basic phenomenon used for identification of the paths of acoustic energy transmission through the barrier is the difference in the arrival times of acoustic waves propagating by different paths from the source to the observation point behind the barrier.

The primary difficulty in the identification of the paths of sound transmission is the limited resolution of a method, which permits the signals reaching the

observation point to be distinguished. Sufficiently large differences in paths are necessary to distinguish distinctly the acoustic signals of a specific kind.

Of different identification methods two methods are noteworthy which are opposed to each other from the point of view of time character of acoustic signals: the correlation method using quasistationary signals and the pulse method using the momentary signals.

The resolution of the two methods is limited by the Heisenberg uncertainty principle which combines the necessary time and frequency intervals of the signal investigated, in order to maintain the adequate analytical conditions. However, due to the differences in the signals, the measuring apparatus, and the purposes of the investigation, the usefulness of the two methods may differ [5].

The aim of this paper is to use both methods for the identification of transmission paths of acoustic waves through the barrier. For the sake of simplification only two kinds of paths were considered: the path of a wave penetrating through the barrier and the path of a diffracted wave on its upper edge.

In addition to the theoretical aspects, the present problem has also a practical significance. The methods that are analyzed in the paper permit a suitable material to be selected in the barrier designing to predict the proper insulation properties of the barrier due to its dimensions. The practical significance of the methods presented in this paper is particularly conspicuous in the measurements carried out under the real conditions.

2. Previous investigations on the use of correlation and pulse techniques for the testing of the barrier

The correlation technique has for many years been used in acoustical research. It was very early used in GOFF's investigations [9] of the effectiveness of IL (Insertion Loss) of boards, which he determined from the measured cross-correlation function between the signal supplying the loudspeaker and the signal of acoustic pressure measured behind the board. Goff obtained experimental results which were close to the calculated results according to the mass law, with a very high precision of 1 dB.

WHITE [13] analyzed the possible uses of the correlation technique as the method for identification of systems involving many paths of acoustic wave propagation. His papers were not concerned with acoustic barriers; however, the approach which he developed can be partly used for the analysis of a wave transmitted through the barrier and of a diffracted wave.

Using a method combining the correlation technique and Fourier analysis, SCHOMER [11] obtained the best results in the identification of diffracted and penetrating waves. He investigated the cross-correlation function of sound pressures measured at given points in front of and behind the barrier. Subsequently, he measured the Fourier transform for relevant sections of the curves of the cross-correlation function, thus determining the transmittance of the *i*th path of acoustic wave transmission through the barrier.

Schomer's results were in agreement with the calculated results only over the frequency range where the source had a flat frequency response, with a deviation of ± 3 dB.

The pulse methods were used to investigate partition walls, with only penetrating waves being analyzed [1, 3, 4]. However, there have been no papers concerning the investigation of waves diffracted on the barrier edge by the pulse methods.

3. Analysis of properties of the barrier

Of many possible propagation paths of acoustic waves trough the barrier, the present paper discusses only two: the path of a wave diffracted on the upper barrier edge and the path of a wave penetrating the barrier due to its limited insulation.

The following quantities have been assumed for the description of acoustic properties of the barrier:

— the barrier effectiveness for a penetrating wave

$$\mathrm{IL}_p = 10\log\frac{p_0^2}{p_p^2}\quad [\mathrm{dB}], \tag{1}$$

— the barrier effectiveness for a diffracted wave

$$\mathrm{IL}_d = 10\log\frac{p_0^2}{p_d^2}\quad [\mathrm{dB}], \tag{2}$$

where individual values of mean-squared acoustic pressures are: p_0^2 — for a direct wave, p_p^2 — for a wave penetrating the barrier, p_d^2 — for a wave diffracted on the upper barrier edge.

A coefficient of weighting of transmitted energies can be introduced as a quantity which would quantitatively define the proportions of energies carried by a diffracted and a penetrating wave to the observation point:

$$\gamma = \frac{p_d^2}{p_p^2}. \tag{3}$$

It is convenient to represent this coefficient on the logarithmic scale as the weighting level of transmitted energies, which will be called the weighting level:

$$L_{pd} = 10\log\gamma = \mathrm{IL}_d - \mathrm{IL}_p\quad [\mathrm{dB}]. \tag{4}$$

The barrier effectiveness for the penetrating wave can be expressed by the law of mass

$$\mathrm{IL}_p = 10 \log \left(\frac{\pi f m}{\varrho c} \right)^2 \quad [\mathrm{dB}], \tag{5}$$

where f is the acoustic wave frequency, m — mass per unit barrier area, ϱ — density of the medium, c — sound speed of acoustic wave.

The barrier effectiveness for a diffracted wave after the **MEAKAWA**'s formula can be expressed as

$$\mathrm{IL}_d = 10 \log 20\, NK = 10 \log 0.12\, f \delta K\, [\mathrm{dB}] \quad \text{for } N > 1, \tag{6}$$

where N is a Fresnel number, $N = 2\delta/\lambda$, δ — difference in paths of a diffracted wave and a direct wave, λ — acoustic wave length.

The coefficient K represents the kind of sound source and its directivity. For the source of spherical wave the coefficient K is given [8] by the formula

$$K = \frac{x_d^2}{x_0^2}, \tag{7}$$

where x_d^2 and x_0^2 are the sound paths of the diffrected and direct wave, respectively. Based on relations (5) and (6), the expression for the weighting level L_U can take the form

$$L_{pd} = 10 \log \frac{f m^2}{\varrho^2 c^2 \delta K} + 9.3 \quad [\mathrm{dB}]. \tag{8}$$

4. Methods for identification of sound transmission paths through the barrier

The basic phenomenon used for the identification of sound transmission paths through the barrier is the difference in arrival times of acoustic waves propagating by various paths from the source and the observation point behind the barrier. Fuzziness of transmitted signals due to the measurement technique or to nonuniform propagation paths is the main difficulty here.

Principal limitations between the resolving powers of the signal in the time and frequency domains result from the Heisenberg uncertainty principle. Filtering the signal with a narrow transmission band Δf causes the signal to be fuzzy in time, making the separation of signals and their quantitative analysis difficult.

(a) **The correlation method.** White noise or filtered noise with a width Δf is the source of acoustic signal in the correlation method. The correlation method which can determine the barrier effectiveness for respective paths can be used to find the transmission paths of acoustic waves through the barrier – in the present case, the paths of a diffracted wave and a wave penetrating the barrier.

As in Fig. 1, the cross-correlation function is determined from two signals delayed with respect to each other: the reference signal $X_1(t)$ received from the point M_1 and the measuring signal $X_2(t)$ from the point M_2. The signal $M_2(t)$ is delayed with respect to the signal $X_1(t)$ by a time dependent on the passage time of acoustic wave from the point M_1 to the point M_2. These delays are: for a direct wave τ_0, for a penetrating wave τ_p, and for a diffracted wave τ_d. Assuming a small barrier thickness relative to a distance r_0 between the points M_1 and M_2, it can be accepted that $\tau_0 = \tau_p$. Thus the barrier effectiveness can be determined after GOFF's [9] relation: for the path of a diffracted wave

$$\mathrm{IL}_u = 10\log\frac{R_{xy0}(\tau_0)}{R_{xyd}(\tau_d)} \quad [\mathrm{dB}], \tag{9}$$

and for the path a penetrating wave

$$\mathrm{IL}_t = 10\log\frac{R_{xy0}(\tau_0)}{R_{xyp}(\tau_0)} \quad [\mathrm{dB}], \tag{10}$$

where $R_{xy0}(\tau_0)$ is the maximum of the cross-correlation function for a direct wave without the barrier with a delay τ_0, $R_{xyd}(\tau_d)$ – the maximum of the cross-correlation function for a wave diffracted on the upper barrier edge with a delay τ_d, and $R_{xyp}(\tau_0)$ is the maximum of the cross-correlation function for a wave penetrating the barrier with a delay $\tau_p = \tau_0$.

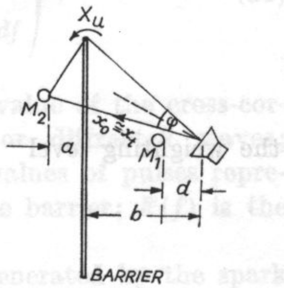

Fig. 1. A schematic diagram of the measuring system

As a parameter defining the ratio of energies transmitted through the barrier by the two paths, the weighting coefficient (expression (3)) will be

$$\gamma = \frac{R_{xyd}(\tau_d)}{R_{xyp}(\tau_0)} \ [\mathrm{dB}]. \tag{11}$$

Thus the weighting level expressed by term (4) will take the form

$$L_{pd} = 10\log R_{xyd}(\tau_d) - 10\log R_{xyp}(\tau_0) = \mathrm{IL}_d - \mathrm{IL}_p \quad [\mathrm{dB}]. \tag{12}$$

(b) **The pulse method.** If the input signal is an acoustic pulse of a sufficiently short duration relative to the difference $\tau_d - \tau_p$, the signal received will consist of two separate pulses corresponding to the pulse penetrating the barrier and the pulse diffracted on the barrier edge.

From the pulse response function $p(t)$ the sought quantities which describe the acoustic properties of the barrier can be determined: the barrier effectiveness for a penetrating wave

$$\mathrm{IL}'_p = 10\log\frac{\int\limits_0^{T_1} p_0^2(t)\,dt}{\int\limits_{T_1}^{T_2} p_d^2(t)\,dt}, \tag{13}$$

the barrier effectiveness for a diffracted wave

$$\mathrm{IL}'_d = 10\log\frac{\int\limits_0^{T_1} p_0^2(t)\,dt}{\int\limits_0^{T_1} p_p^2(t)\,dt}, \tag{14}$$

the weighting level

$$L'_{pd} = 10\log\frac{\int\limits_{T_1}^{T_2} p_d^2(t)\,dt}{\int\limits_0^{T_1} p_p^2(t)\,dt}, \tag{15}$$

where the time interval 0-T corresponds to the interval in which the penetrating wave reaches the observer, the time interval $T_1 - T_2$ corresponds to the interval in which the diffracted wave reaches the observer.

The methods mentioned above for the determination of the weighting level between the diffracted and penetrating waves assume a high sharpness of signals obtained by both correlation and pulse methods. In practice these signals are fuzzy due to the limited resolution of the aparatus in the domains of time and frequency, resulting from the Heisenberg principle,

$$U = \Delta f \Delta t \leqslant A, \tag{16}$$

where Δt is the minimum difference between the passage times of acoustic wave by various paths from the source to the observer, permitting the successive signals to be distinguished, Δf is the minimum band width of the filter which gives correct analytical results for a given value of Δt, A is a constant dependent on the kind of signal. The expression $\Delta t \Delta f$ is called the uncertainty product [2]. Since the envelopes of the cross-correlation curves including maxima are not rectangular, the problem occurs how to establish suitable averaging criteria permitting the inambiguous determination of the values of Δt and Δf. Of many known criteria of signal width, the variance of squared amplitude modulus was used in the present investigation as the measure most convenient for the oscillating signal which appears in the correlation method and to some degree also in the pulse method,

$$(\Delta t)^2 = \frac{\int\limits_{-\infty}^{+\infty} t^2|p(t)|^2 dt}{\int\limits_{-\infty}^{+\infty} |p(t)|^2 dt} - \left(\frac{\int\limits_{-\infty}^{+\infty} t|p(t)|^2 dt}{\int\limits_{-\infty}^{+\infty} |p(t)|^2 dt} \right)^2 \tag{17}$$

and

$$(\Delta f)^2 = \frac{\int\limits_{-\infty}^{+\infty} f^2|F(f)|^2 df}{\int\limits_{-\infty}^{+\infty} |F(f)|^2 df} - \left(\frac{\int\limits_{-\infty}^{+\infty} f|F(f)|^2}{\int\limits_{-\infty}^{+\infty} |F(f)|^2 df} \right)^2, \tag{18}$$

where $p(t)$ in the correlation method is the maximum value of the cross-correlation function corresponding to the penetrating or diffracted waves; in the pulse method — the corresponding maximum values of pulses representing the diffracted wave and the wave penetrating the barrier; $F(f)$ is the Fourier transform of the function $p(t)$.

In the paper, the uncertainty products for noise generated by the spark source U' were calculated from formulae (17) and (18). The values of the uncertainty products can be a basis for comparison of the resolution of the two methods, since a better resolution corresponds to a smaller value of the uncertainty product.

5. The experimental investigations

A pressed chipboard barrier with dimensions 4.1m × 1.8 m and 2 cm thick was used in the investigations. The experiment was carried out under the free field conditions, placing the barrier in an anechoic chamber in order to limit the waves reflected from the surfaces of the room, and also the waves transmitted from sources in adjacent rooms.

The barrier was suspended on a steel rope from the ceiling of the chamber in order to eliminate structure-borne sound carried by the base. The source-barrier-observer geometry was chosen so that at the observation point the energy of the wave diffracted on one edge of the barrier was considerably greater than the energies of waves diffracted on the other edges. The position of the barrier and the measuring points during the investigation is shown in Fig. 1. The investigations were carried out for three positions of the sound source with respect to the barrier (for different distances b).

In the correlation method a reference signal from a reference microphone placed at a distance $d = 10$ cm from the loudspeaker for all the positions investigated was used.

The delays τ_p of the penetrating wave and τ_d for the diffracted wave at the microphone M_2 related to the arrival times of the signal to the reference microphone M_1 were respectively

$$\tau_0 = \tau_p = \frac{x_{p-d}}{c}, \quad \tau_d = \frac{x_{d-d}}{c}, \tag{19}$$

where x_p and x_d are the path lengths of the penetrating and diffracted waves respectively. The delays τ_d, τ_p for correlation method and τ'_d, τ'_p for pulse method calculated for individual positions are shown in Table 1.

Table 1. Delays τ for chosen measuring geometries

Geometry No.	b [cm]	Correlation method			Pulse method		
		τ_p [ms]	τ_d [ms]	$\tau_d - \tau_p$ [ms]	τ'_p [ms]	τ'_d [ms]	$\tau'_d - \tau'_p$ [ms]
I	40	1.5	2.9	1.4	2.1	3.5	1.4
II	60	1.9	3.3	1.4	2.5	3.8	1.3
III	80	2.4	3.7	1.3	3.0	4.3	1.3

The cross-correlation function of sound pressures measured by the microphones M_1 and M_2 was determined using an LT 213 Histomat Intertechnique correlator. White noise filtered in 1/3 octave bands at centre frequencies of 4, 6.3, 8, 10, 12.5 and 16 kHz was used as the signal in the correlation method.

Pulses generated by the spark source filtered in the same bands as in the correlation method were used in the pulse method. The pulse response function of the system investigated was measured using a 7503 type Brüel and Kjaer pulse recorder.

Further calculations aimed at determination of the uncertainty products for the two measurement methods were performed using a digital computer ODRA 1325.

In order to decrease the error resulting from the directional characteristics of the source, the loudspeaker was placed at such an angle with respect to the horizontal surface that its axis coincided with the bisector of the angle between the rays of the direct wave and of the wave falling on the upper edge of the barrier (Fig. 1).

Two methods of estimating the quantities measured were used in the two measuting techniques:

1. Consideration of the maximum values of the functions $R_{xy}(\tau)$ and $|p(t)|^2$ in chosen intervals. This was called the *method of maximum values*.

2. Consideration of the values of the integral from the squared functions $R_{xy}(\tau)$ and $|p^2(t)|$ in the same intervals as in point (1). This was called the *method of averaged values*.

6. The experimental results

The results of measuring the barrier effectiveness for the penetrating wave (formula (10)) and for the diffracted wave (formula (11)) for the three barrier-source-observer geometries and the measurement results obtained using the correlation and pulse methods with the two estimation techniques are shown in Tables 2 and 3. The results of calculations and measurements of the weighting level for the diffracted and penetrated waves for the data in Tables 2 and 3 are shown in Table 4 and Figs. 2 and 3. The values of the uncertainty product obtained by the correlation and pulse methods for individual source-barrier-observer geometries and also the mean values of U_{av} are shown in Table 5.

7. Conclusions

The following conclusions may be drawn from the investigations performed:

1. Determination of the weighting level between the diffracted and penetrating waves in a given frequency band is possible with a single measurement using the correlation or pulse methods.

2. Despite of the common limitation of the correlation and pulse methods due to the uncertainty principle, the two methods show different resolution due to the difference in the acoustic signals used.

3. Quantitative comparison of the resolution of the present methods can be made by calculation of the uncertainty numbers with the assumed signal widths in the domains of time and frequency. A better resolution of the method corresponds to a smaller uncertainty number. In the experiment the pulse technique showed a better resolution.

4. From the separate analysis of the diffracted and the penetrating waves it was found that the resolution of the two methods is better for the diffracted wave than for the penetrating wave. This proves the effect of additional factors such as dispersion or complex impedance which may occur when the wave penetrating the barrier.

5. Investigation of the barrier using the present methods showed a good agreement between the calculated and measured results. The mean absolute deviation of the measured and calculated results did not exceed 1 dB for all the quantities measured. In both methods the choice of the estimate showed a large effect on the investigation results. The method of averaged values showed a better agreement between the measured and calculated results.

6. The present method of identification of propagation paths of acoustic waves through the barrier can be expanded to include other propagation paths, e.g. those of reflected waves. When considering a greater number of paths,

Table 2. The barrier effectiveness for a wave penetrating the barrier

Middle frequency of 1/3 octave band	Geometry I					Geometry II					Geometry III				
	Correlat. method		Pulse method		Cal.	Correlat. method		Pulse method		Cal.	Correlat. method		Pulse method		Cal.
	IL_{pm}	IL_{pav}	IL'_{pm}	IL'_{pav}		IL_{pm}	IL_{pav}	IL'_{pm}	IL'_{pav}		IL_{pm}	IL_{pav}	IL'_{pm}	IL'_{pav}	
Hz	dB														
4 000	29.4	31.7	31.2	30.1	30.8	29.8	31.9	31.1	31.8	30.8	33.2	32.5	32.2	31.6	30.8
6 300	34.2	34.5	34.3	34.9	34.8	35.7	34.5	34.1	35.4	34.8	36.3	33.7	35.4	35.8	34.8
8 000	36.5	37.3	35.7	36.2	36.8	36.1	37.3	37.5	36.6	36.8	37.5	36.6	36.3	37.2	36.8
10 000	38.0	38.2	39.7	38.6	38.8	39.4	39.0	38.1	39.6	38.8	39.7	39.1	38.2	40.0	38.8
12 500	40.0	41.7	40.1	41.4	40.8	41.0	40.3	39.9	41.3	40.8	41.5	40.0	40.5	41.0	40.8
16 000	44.5	43.2	41.7	42.5	42.8	42.0	43.2	43.5	43.1	42.8	42.5	42.1	41.7	43.5	42.8

m – maximum value: *av* – average value

Table 3. The barrier effectiveness for a wave diffracted by the barrier

Middle frequency of 1/3 octave band	Geometry I					Geometry II					Geometry III				
	Correlat. method		Pulse method		Cal.	Correlat. method		Pulse method		Cal.	Correlat. method		Pulse method		Cal.
	IL_{dm}	IL_{dav}	IL'_{dm}	IL'_{dav}		IL_{dm}	IL_{dav}	IL'_{dm}	IL'_{dav}		IL_{dm}	IL_{dav}	IL'_{dm}	IL'_{dav}	
Hz	dB														
4 000	27.2	28.5	28.0	26.6	28.2	26.1	27.7	28.1	27.3	26.9	28.2	26.2	27.4	26.1	25.8
6 300	31.1	30.9	29.9	30.9	30.2	28.5	28.7	28.8	29.3	28.9	28.5	26.1	27.5	29.0	27.8
8 000	32.9	30.7	28.8	31.3	31.2	29.8	30.3	29.8	29.3	29.9	29.2	28.0	29.0	29.6	28.8
10 000	32.2	31.7	32.4	32.2	32.2	33.6	30.8	29.8	30.4	30.9	30.7	30.3	28.2	31.2	29.8
12 500	29.2	34.8	32.0	31.2	33.2	32.5	33.4	31.0	31.8	31.9	30.8	31.1	30.2	31.2	30.2
16 000	34.5	33.5	32.3	35.6	34.2	33.4	32.3	33.5	32.3	32.9	31.4	33.0	31.8	32.4	31.8

m – maximum value; *av* – average value

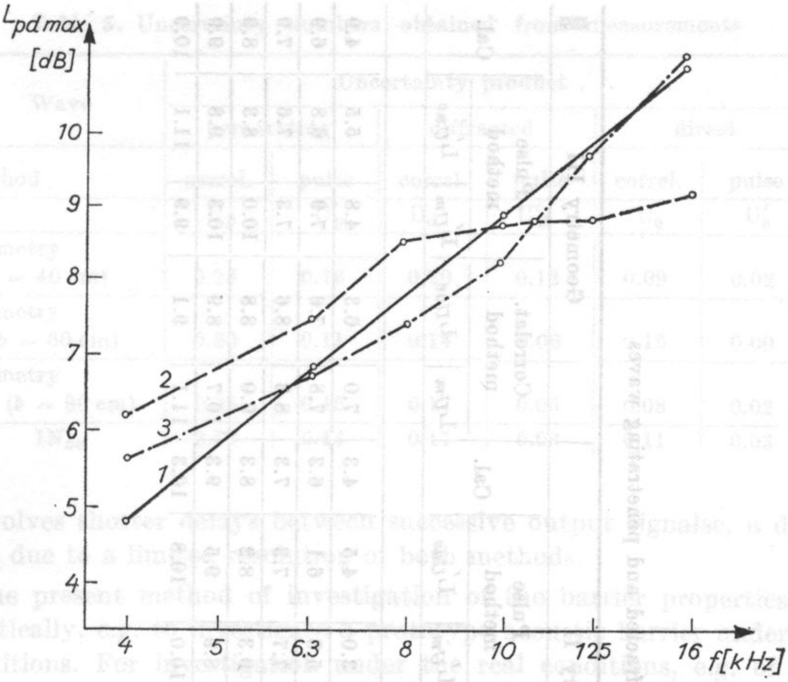

Fig. 2. The weighting level ($a = 10$ cm, $b = 60$ cm), with consideration of the maximum values
1 – calculation results, 2 – results of measurements by correlation method, 3 – results of measurements by pulse method

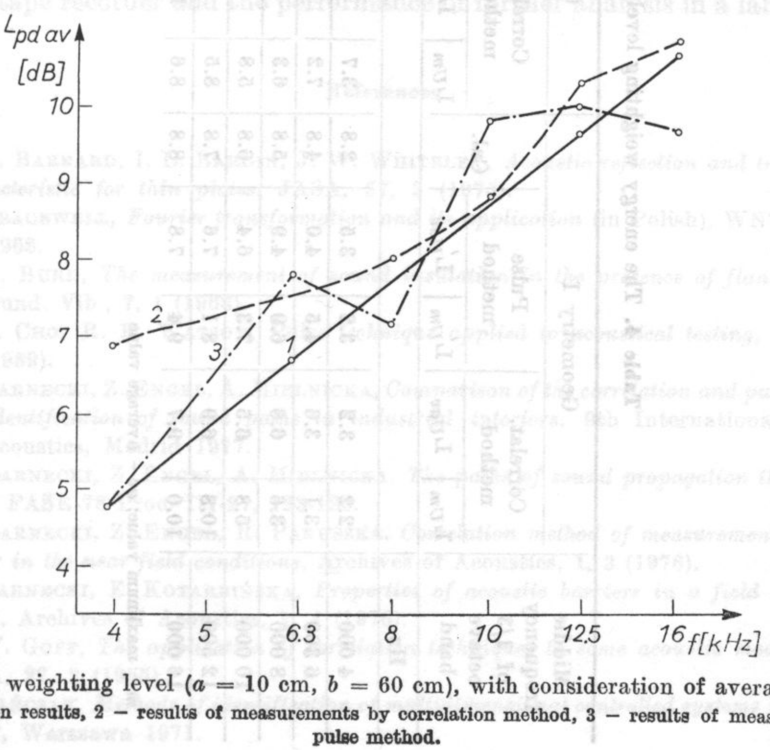

Fig. 3. The weighting level ($a = 10$ cm, $b = 60$ cm), with consideration of averaged values
1 – calculation results, 2 – results of measurements by correlation method, 3 – results of measurements by pulse method.

Table 4. The energy weighting level for diffracted and penetrating waves

Middle frequency of 1/3 octave band	Geometry I					Geometry II					Geometry III				
	Correlat. method		Pulse method		Cal.	Correlat. method		Pulse method		Cal.	Correlat. method		Pulse method		Cal.
	L_{Um}	L_{Uav}	L'_{Um}	L'_{Uav}		L_{Um}	L_{Uav}	L'_{Um}	L'_{Uav}		L_{Um}	L_{Uav}	L'_{Um}	L'_{Uav}	
Hz	dB														
4 000	2.2	3.2	3.2	3.5	2.8	3.7	4.2	3.0	4.5	4.3	7.0	6.3	4.8	5.5	4.9
6 300	3.1	3.6	4.5	4.0	4.8	7.2	5.8	5.3	6.1	6.3	7.8	7.6	7.9	6.8	6.9
8 000	3.6	6.6	6.9	4.9	5.8	6.3	7.0	7.7	7.3	7.3	8.3	8.6	7.3	7.6	7.9
10 000	5.8	6.5	7.3	6.4	6.8	5.8	8.2	9.3	8.2	8.3	9.0	8.8	10.0	8.3	8.9
12 500	10.8	6.9	8.1	7.6	7.8	8.5	9.8	8.9	9.5	9.3	10.7	8.9	10.3	9.8	9.9
16 000	10.0	9.7	9.4	7.8	8.8	8.6	10.9	10.0	10.8	10.3	11.1	9.1	9.9	11.1	10.9

m – maximum value; *av* – average value

Table 5. Uncertainty numbers obtained from measurements

Wave	Uncertainty product					
	penetrating		diffracted		direct	
method	correl.	pulse	correl.	pulse	correl.	pulse
	U_p	U'_p	U_d	U'_d	U_0	U'_0
geometry I ($b = 40$ cm)	0.25	0.16	0.20	0.12	0.09	0.02
geometry II ($b = 60$ cm)	0.20	0.11	0.14	0.08	0.15	0.00
geometry III ($b = 80$ cm)	0.28	0.15	0.17	0.05	0.08	0.02
IN_{av}	0.24	0.14	0.17	0.08	0.11	0.03

which involves shorter delays between successive output signalse, a difficulty may arise due to a limited resolution of both methods.

7. The present method of investigation of the barrier properties can be used practically, e.g. to investigate a prototype acoustic barrier under laboratory conditions. For investigation under the real conditions, e.g. of barriers in industrial interriors with real noise sources only the correlation method seems valid. It involves the recording of the input and output signals on the magnetic tape recorder and the performance of further analysis in a laboratory.

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Received on April 6, 1979