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Accuracy of Assessing the Level of Impulse Sound From Distant Sources

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Impulse sound events are characterised by ultra high pressures and low frequencies. Lower frequency sounds are generally less attenuated over a given distance in the atmosphere than higher frequencies. Thus, impulse sounds can be heard over greater distances and will be more affected by the environment. To calculate a long-term average immission level it is necessary to apply weighting factors like the probability of the occurrence of each weather condition during the relevant time period. This means that when measuring impulse noise at a long distance it is necessary to follow environmental parameters in many points along the way sound travels and also to have a database of sound transfer functions in the long term. The paper analyses the uncertainty of immission measurement results of impulse sound from cladding and destroying explosive materials. The influence of environmental conditions on the way sound travels is the focus of this paper.

impulse sound   noise measurement   long-term average immission level

1. INTRODUCTION

Noise emitted by high-energy impulse sources is characterised by high-level sound (often of above 150 dB) and by short duration (some milliseconds). Most often such noise is caused by explosions of blasting materials (during blasting works), collisions of objects (impact of presses and cutters, forging, stamping, crash tests) or it occurs in industrial technological processes, at violent volume changes of technological gases (explosions, air expansion, steam discharge).

Taking into account the fact that devices and machines are usually located in closed rooms or partially open technological workshops, the hazard caused by impulse noise is especially dangerous. Total duration of a single impulse event is not longer than 50 ms, whereas an impulse rise time to an acoustic pressure peak value can be shorter than 1 ms. High-energy impulses in an open space, where rise time is longer and energy is much higher, are slightly different [1].

Such impulses occur in high-energy explosions of blasting works in open pit mines and military firing grounds. The duration of an event originating from blasting works can even be 2–3 s, whereas rise time to the peak value is directly related to delays and the sequence of firing explosive charges and oscillates between several and a dozen or so milliseconds. Blasting works generate short, high-energy impulse waves—acoustic, blast air and paraseismic—which influence the environment. Propagation of those waves can be hazardous for people, animals, buildings and other structures not only in the vicinity but also far away from the source [2, 3].

In the case of impulse noise (an acoustic wave) powerful, violent changes of air pressure and low-frequency sound are involved. Since low-frequency sound components are much less

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attenuated, they propagate much farther than high-frequency components. That is why noise generated by high-energy impulse events can be heard even in far away places (up to 30 km); this largely depends on atmospheric conditions as well as on the configuration and the development of the environment. The estimation of sound propagation from impulse sources at longer distances can be done on the bases of algorithms contained in ISO standard No. ISO/TS 13474:2003 [4]. They cover methods of calculating sound propagation in an open environment [5, 6], where the level of noise emission is assessed on the basis of information on the power of the source and corrections: the distance, directivity, attenuation in frequency bands as well as meteorological correction (C_{met}).

This paper presents the results of noise measurements at longer distances from blasting works (cladding and destruction of explosive materials) carried out on military firing grounds. It focuses on the uncertainty of the performed measurements resulting from environmental conditions during sound propagation.

2. EXPERIMENTAL

High-energy impulses originated during the cladding and destruction of explosive materials on the military firing grounds near Legnica, Poland, were measured. Cladding is a process of putting protective coating, i.e., thin layers of metal on the base. This is done in order to obtain additional properties of materials, e.g., to increase their resistance to corrosion, acids or resistance to high temperature. Cladding can be done either in a hot-rolling process, flame plating or in explosive stamping. Explosive welding can be applied for materials such as metals or their alloys, which can be joined with traditional methods and for which there is no other technology. Joined materials can have significantly different properties, e.g., steel–aluminium, steel–titanium. Apart from the possibility of producing new materials the main reasons for explosive cladding are economic effects due to a lower consumption of expensive metals and alloys of special properties. However, the main defect of the method is that it generates acoustic impact and paraseismic waves that have an adverse effect on the environment.

2.1. Method

The expected exposure level (with correction) of a single acoustic impulse phenomenon in an arbitrary point in the environment can be calculated from Equation 1 [4]:

$$L_{wRE} = 10\lg\left[\sum_{x\in U} P(L_{wE} = x)10^{0.1(x+\overline{K})}\right] \quad \text{(dB)}, \tag{1}$$

where P—non-zero probability of occurrence of the exposure level L_{wE}; the probability sum of all possible levels L_{wE} equals 1 ($\sum_{x\in U}(x) = 1$); U—set of all possible values of L_{wE}; w—kind of correction filter, e.g., A, C; $\overline{K}$—correction [5].

Sound exposure level L_{wE} is calculated according to Equation 2:

$$L_{wE} = 10\lg\left[\sum_{j=1}^{N\,band} 10^{0.1\left[L_{E(j)}+w(j)\right]}\right] \quad \text{(dB)}, \tag{2}$$

where $L_{E(j)}$—uncorrected sound exposure level for the jth band frequency (dB), $w(j)$—correction for the jth band frequency (dB), N_{band}—number of frequency bands.

Uncorrected sound exposure level originating from the impulse source $L_E(j)$, in the jth frequency band, at further distances of approximately 0.5–30 km is calculated from Equation 3:

$$L_E(j) = S_\phi(j) - A_{tot}(j), \tag{3}$$

where $S_\varphi(j)$—angle-dependent sound exposure level in jth frequency band, measured in the reference point located 1 km from the source (dB), $A_{tot}(j)$—attenuation in bands, resulting from the propagation from the sound source to the receiver.

Attenuation $A_{tot}(j)$ from Equation 3 is determined in Equation 4 and calculated according to Standard No. ISO 9613-1:1993 [5]:

$$\begin{aligned} A_{tot}(j) = {} & A_{div}(j) + A_{atm,k}(j) \\ & + A_{rec}(j) + A_{ex,l}(j), \end{aligned} \tag{4}$$

where $A_{div}(j)$—attenuation caused by geometric divergence (dB), $A_{atm,k}(j)$—attenuation resulting from atmospheric absorption for the *k*th absorption class (e.g., temperature and humidity) (dB), $A_{rec}(j)$—attenuation resulting from the influence of the ground (dB), $A_{ex,l}(l)$—attenuation caused by other phenomena, for the first absorption class (e.g., wind velocity and direction) (dB).

When assuming the steady location of an explosion place, atmospheric attenuation, which depends on temperature and humidity, and attenuation resulting from other phenomena, especially from the velocity and direction of wind, are variables in Equation 4. Assuming that the amount of explosive materials is constant, the L_{wE} level depends on the product of the probability of occurrence of individual absorption classes of two kinds of attenuation:

$$P\left(L_{wE}=x\right)=\sum_{k,l} P_{atm,k} \bullet P_{ex,l}. \qquad (5)$$

Attenuation values $A_{atm,k}(j)$ of all expected classes of meteorological conditions should be developed according to Standards No. ISO/TS 13474:2003 [4], ISO 9613-1:1993 [5], and ISO 9613-2:1996 [6], whereas the occurrence probability of first-class weather conditions should be based on historical data.

2.2. Measurements

Noise measurements were performed in Leszno-Górne, Świętoszów and Trzebień, which are located from 6.5 to nearly 11 km from the site of the explosions. Those sites were chosen because of the inhabitants' complaints; they lived in the vicinity of the military firing grounds, where cladding took place. The area was low-lying, partially afforested; however, the plants were mostly low (grass and bushes). Measuring points were placed at the border of each village, far away from other noise sources, 4 m above the ground. Measurements were done on December 2, 2006, in pleasant, sunny weather: temperature 4–7 °C, humidity 70–80%, pressure 1019–1022 hPa, south-westerly wind of 0–2 m/s. Figure 1 presents the location of the measurement points versus the source of impulse noise.

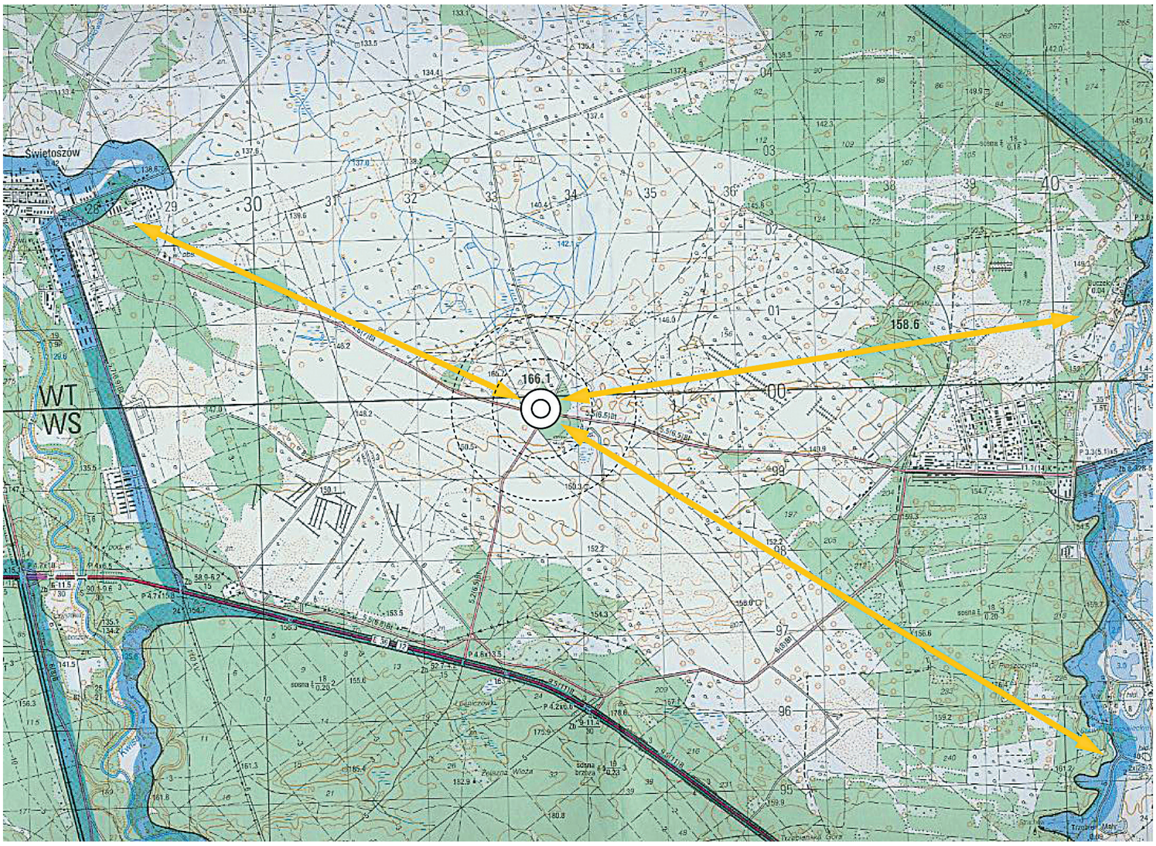

Figure 1. Distribution of points where impulse noise was measured.

Sound analysers SVAN 945A (Svantek, Poland) were used to measure noise. Multispectra were recorded in 1/3 octave bands in the range from 4 to 20 000 Hz and levels A and C with the resolution of $\Delta t = 200$ ms. Thus it was possible to estimate more precisely exposure levels (L_{AE}, L_{CE}) from single, impulse acoustic events (single explosions of explosive materials), after removal of the part not connected with the investigated event. Six explosions related to cladding—during which each firing consumed 600 kg of saletrol—and eight explosions to destroy explosive materials (120–240 kg) were recorded. In addition to noise, parseismic vibrations of the ground and buildings as well as pressure of blast air waves were measured. However, due to a range of problems, the focus remained on assessing hazards related to high-energy impulses.

2.3. Results

Taking into account the safety codes in force in Poland [7, 8, 9, 10, 11, 12, 13], the assessment of environmental noise is based on permissible equivalent sound *A* levels [13] with a division into day- and night-time and the function the location is intended for. Maximum daily number of cladding operations (explosions) is 6. Assuming that all operations are done during the 8 hrs of the day shift, the equivalent sound level ($L_{Aeq,T}$) is determined either from the estimated values of exposure levels L_{ARE} (Equation 1) or from exposure levels measured at the location of the receivers (corrected according to Standards No. ISO/TS 13474:2003 [4], ISO 1996-1:2003 [7], ISO 1996-2:1987 [8], and ISO 1996-3:1987 [9]). $L_{Aeq,T}$ is assessed according to Equation 6:

$$L_{Aeq,T} = 10 \bullet \log\left(\frac{1}{T(s)} \sum_{i=1}^{n=6} 10^{0.1 L_{AEi}}\right), \quad (6)$$

where T—standardised reference time, $T = 8$ hrs; L_{AEi}—exposure level of sound *A* during cladding (firing).

The full set of noise exposure levels (from all detonations) in individual measuring points (villages) is listed in Tables 1 and 2. Changes in sound levels versus time—on filters A and C, and in 1/3 octave bands of frequencies 10, 100 and 1 000 Hz in the measuring point in Leszno-Górne (explosion No. 5: cladding and No. 7: destruction of explosive materials)—are shown in Figures 2 and 3, whereas the spectrum of maximum levels (related to the same events) in Figure 4.

TABLE 1. Results of Impulse Noise Measurements During Cladding

Place		**Trzebień**		**Świętoszów**		**Leszno-Górne**	
Distance From Source		**10.40 km**		**6.50 km**		**10.75 km**	
		L_{wE} (dB)		**L_{wE} (dB)**		**L_{wE} (dB)**	
No. of Blast	**Charge Mass (kg)**	**A**	**C**	**A**	**C**	**A**	**C**
1	600	97.3	117.0	78.2	99.5	76.4	99.2
2	600	102.4	115.5	75.8	95.7	76.8	99.2
3	600	92.2	114.0	75.9	97.5	73.2	97.8
4	600	99.4	120.0	75.5	97.6	69.9	94.6
5	600	95.1	116.4	72.7	93.9	82.4	101.4
6	600	95.1	114.3	73.1	94.6	76.6	100.5
	M	98.4	116.7	74.8	96.1	77.8	99.3
	SD	3.6	2.2	2.0	2.1	4.2	2.4

Notes. L_{wE}—sound exposure level; A, C—filters.

TABLE 2. Results of Impulse Noise Measurements During Destruction of Explosive Materials

Place		**Trzebień**		**Świętoszów**		**Leszno-Górne**	
Distance From Source		**10.70 km**		**6.75 km**		**9.30 km**	
		L_{wE} (dB)		**L_{wE} (dB)**		**L_{wE} (dB)**	
No. of Blast	**Charge Mass (kg)**	**A**	**C**	**A**	**C**	**A**	**C**
1	120	72.3	95.4	66.1	85.8	72.1	98.2
2	150	70.8	95.1	68.3	89.7	72.7	94.7
3	200	71.8	95.9	66.6	85.9	74.9	96.8
4	200	73.4	96.2	65.4	86.6	76.2	97.3
5	200	72.6	94.2	62.8	84.5	79.7	98.8
6	200	—	—	63.5	85.2	77.4	99.5
7	200	—	—	76.4	87.3	78.3	96.4
8	240	—	—	61.4	83.5	85.1	104.5
	M	72.3	95.4	69.6	86.5	79.5	99.5
	SD	1.0	0.8	2.0	1.8	2.9	1.7

Notes. L_{wE}—sound exposure level; A, C—filters.

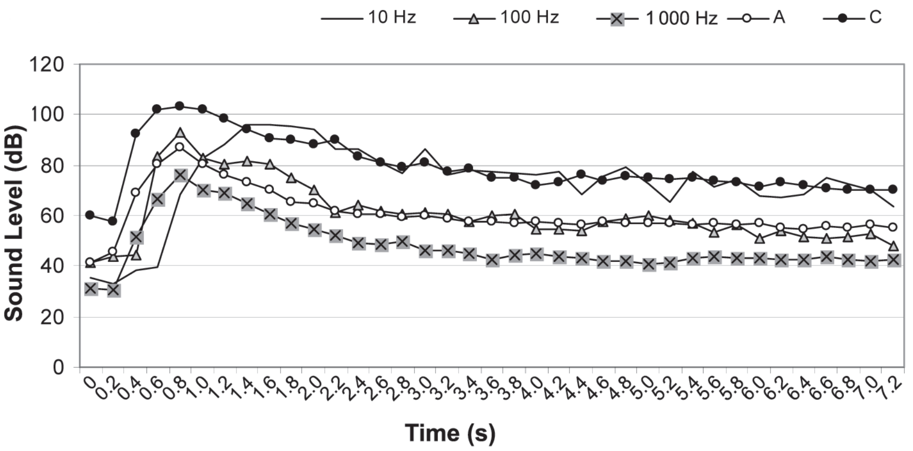

Figure 2. Sound level on filters A, C and in 1/3 octave band 10, 100 and 1 000 Hz versus time (in Leszno-Górne), explosion No. 7 (cladding).

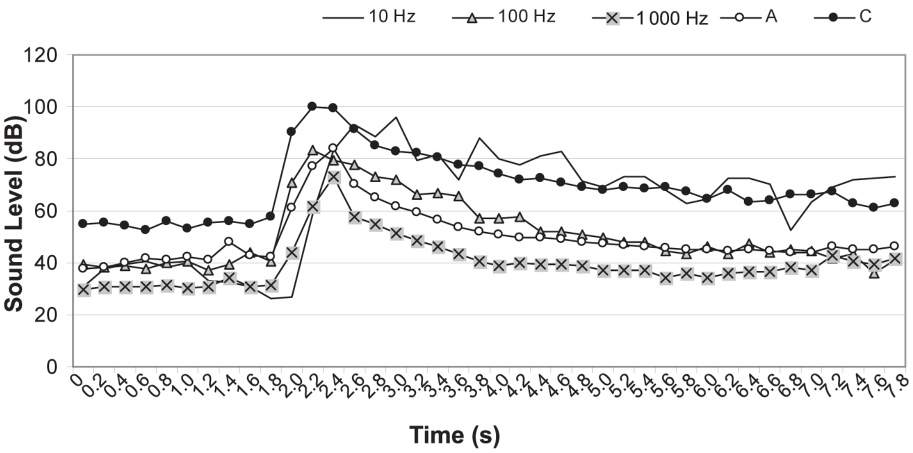

Figure 3. Sound levels on filters A and C, and in 1/3 octave bands 10, 100 and 1 000 Hz versus time (in Leszno-Górne), explosion No. 5 (destroying explosive materials).

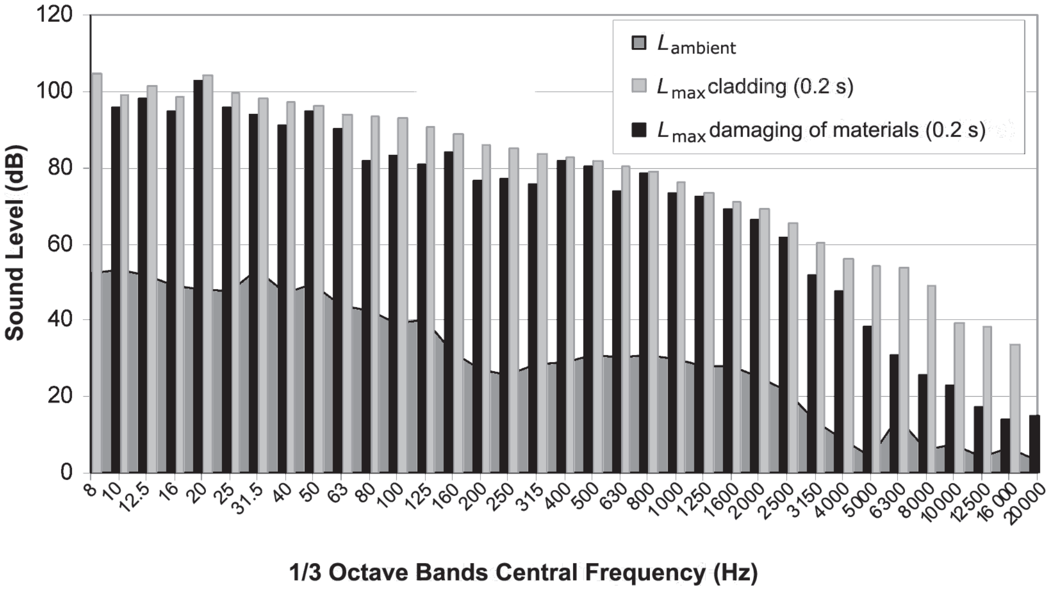

Figure 4. Spectrum of the level of exposure to sound pressure (in Trzebień), explosion No. 2.

2.4. Analysis of the Uncertainty of Measurements

If the measured or forecasted noise level depends on several input values the result is a function of several arguments [11]:

$$L_{wy} = f(X_{we1} + X_{we2} + ... + X_{wem}) \quad (7)$$

and each one carries a standard uncertainty $U(X_{we1})$.

Assuming that the individual arguments in Equation 1 are independent, the combined standard uncertainty $U_c(L_{we})$ can be calculated on the basis of Equation 8

$$U_c(L_{wy}) = \sqrt{\sum_{i=1}^{m} \left(\frac{\partial f}{\partial X_{wei}} \right)^2 U^2(X_{wei})}. \quad (8)$$

Uncertainty given together with the measurement result is a multiple of the combined standard uncertainty and is called expanded uncertainty. The final result of the measurement is presented in the form of Equation 9:

$$L_k = L_{wy} \pm U(L_{wy}), \quad (9)$$

where

$$U(L_{wy}) = kU_c(L_{wy}). \quad (10)$$

The coverage factor value k is assumed in dependence of the confidence index of the assigned uncertainty interval. To calculate the combined standard uncertainty it is necessary to determine partial uncertainties related to all input values and influencing results of measurements or forecasting. For measurements standard uncertainties can be determined with a series of observations, i.e., statistically, with method A [4]. However, repeating measurements several times to collect the required number of observations can often be costly, or—when acoustic signals are measured—the process itself is not repeatable (ergodic) since conditions of propagation can differ or the source can change (e.g., various amounts of explosive material are involved). In those cases uncertainty should be estimated by determining the interval of possible changes of the tested parameter. This is method B [8].

Since measurements at all points were performed simultaneously one can assume that the weather conditions (temperature, humidity and atmospheric pressure) were similar. It was only the direction of the wind and its velocity that varied; this influence was significant and different at each point. Thus, it was assumed that the uncertainty of measurements (the difference of uncertainties at individual points) would be, in reality, related to wind only.

On the basis of the geometrical distribution of the measuring points and the obtained results, it was estimated that the average error (corrected for the influence of wind) in sound propagation was 2.2 dB/km. Standard uncertainty was U = 1.8 dB/km, expanded uncertainty U_c = 3.1 dB/km for a uniform distribution of wind direction, in agreement with Equation 10.

The value of the coverage factor k is assumed in dependence of the confidence index of the assigned uncertainty interval. Method B was used to estimate uncertainty. Further, it was assumed that standard deviations of individual partial uncertainties for measuring instruments were equal to 1/3 of the limiting error value of those instruments, assuming that those errors had a normal distribution. In places where the error distribution was rectangular (e.g., in the case of an uncertainty of reference and in Type B estimation of uncertainty) it was assumed that partial standard uncertainty equalled $1/\sqrt{3}$ of its limiting value.

Thus, at 10 km the scattering of the results—depending on the direction of wind—can reach even 30 dB. Propagation conditions will be more favourable (apart from wind blowing from the direction of the source) at lower temperatures (even by 1 dB/km) and at increased humidity (by approximately 0.25 dB/km). Thus, at a lower temperature and increased humidity the level of noise in the places under testing will be much higher, even 5–10 dB, regardless of the influence of the direction of wind.

3. CONCLUSIONS

This paper discussed accurate assessment of the distribution of high-energy impulse noises (explosive cladding and destruction of explosive materials) at distant locations from the source. A special method [11] related to impulse sound propagation for environmental noise assessment is dedicated to this type of acoustic measurements. For forecasting the equivalent sound A level it is necessary to know exactly the atmospheric conditions on the way of sound propagation. Assuming that blasting works (cladding) are done only in certain weather conditions in the environment where there is a noise hazard, a finite number of meteorological classes can be estimated. Attenuation coefficients for acoustic wave propagation in the environment can be determined for each such class. The possible fluctuation range of expected exposure levels (in dependence of weather conditions), in places under testing, was determined with uncertainty analysis. In order to estimate fully impulse noise at distant locations detailed knowledge of atmospheric conditions not only at the time of measuring but also at blasting works during the whole year is necessary.

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