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PREDICTION OF LOW FREQUENCY IMPULSIVE SOUND PROPAGATION

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ABSTRACT
The prediction of sound propagation at very low frequencies (10 - 100 Hz) is not necessarily straight forward using approximate analytical formulations based on surface impedance models. Often a full-wave solution (FFP, PE) is recommended to handle the interaction with the ground surface. If the sound is impulsive (i.e. from a blast) additional mechanisms may increase the complexity of propagation. In order to test the validity of simple analytical methods regarding blast noise propagation, measurement results from the Norwegian-Trials investigation are used. Blast noise recordings were available from 1 kg C4 charges over distances up to 1400 m above a flat terrain, at summer and winter conditions. Based on these time series, relative attenuation spectra as a function of distance were established. The corresponding spectra can be predicted using analytical methods including surface impedance modelling. In the paper measured and predicted relative attenuation is compared, and the results are discussed regarding the validity of simple prediction methods at low frequencies.

1 - INTRODUCTION
Data from explosive blasts with propagation over unobstructed surfaces such as grass, concrete and water [1] show that the ground surface does influence the air pressure waveform. A common way to present such results is by the overall peak overpressure, or by overall or C-weighted sound exposure levels like the SEL or CSEL. As sound exposure levels are used in characterising the noise nuisance, it is important to establish relevant prediction models.
Analytical prediction models exist for noise sources with stationary and continuous noise emission. Such models are based on linear geometrical acoustics and consider the direct and ground reflected waves and their interaction. The acoustic surface impedance of the ground is an essential parameter.
Blast noise differs from continuous noise in several respects. It has a transient nature, and the peak pressure near the source is often high enough to involve non-linear acoustic processes. Under such conditions it is of interest to investigate the nature of the ground influence especially at low frequencies, and search for possible prediction models. This is the main purpose of this paper.
Blast noise measurement results were available from the Norwegian Trials investigation at Haslemoen (short range trials) during the summer and winter 1994-95, organised by the Norwegian Defence Construction Service. Blasts from detonations of plastic explosives were measured over distances up to 1400 m above flat terrain, through a forest and in the open. The acoustic ground impedance was determined by measurements and modelling.

2 - THE FIELD MEASUREMENTS
The Haslemoen site comprised a large area with flat terrain. The forest part was separated from the open area by a well-defined border line. The firing positions were just outside the forest border during the summer session, but ca. 100 m into the forest during the winter session. In both cases the firing positions were varied to obtain propagation distances in the range $100 - 1400$ m to a microphone tower.

The south tower (relevant to this paper) was situated ca. 100 m into the forest, and was equipped with microphones at heights of 2-4-8-16 and 30 m above ground level. Meteorological data were registered at several positions and heights. The measurements in the summer 1994 were carried out during 15-16 of June. In the winter 1995 the measurement period was 20-23 of February. The details of the measurement set-ups and the measurement results are reported in [2,3,4,5]. Some analyses of the results are also carried out, see [6] and references herein.
The analysis in this paper is based on the time series of selected shots made available on data-files.

3 - THE INVESTIGATION

The present analysis was restricted to study the influence of the ground surface on blast noise propagation through forest, at summer and winter conditions. The propagation distances ranged from 200 m to 1300 m. The low frequency range of $5-300$ Hz was of main interest. Selected shots at three different distances were analysed. The charge weight was 8 kg of C4 explosive, fired at a height of 3.5 m above ground level.

3.1 - Blast description

In order to quantify the ground influence the blast time history was transformed into the frequency domain. The power spectrum level (PSL) in dB was used [7]:

$$\mathrm{PSL\,(dB)} = 10 \cdot \log\{(2 \cdot \Delta \mathrm{t/N}) \cdot [\mathrm{abs\,(X)} / 2 \cdot 10^{-5}]^2\} \tag{1}$$

N is the number of samples in the time record, Δt is the time spacing between them. X is the discrete Fourier transform coefficients. The PSL is the frequency description related to the signal energy dose (SEL). The sampling frequency was 10 kHz for the summer records, 4 kHz for the records made in the winter. PSL measured at 100 m above hard ground (i.e. ice and water above frozen ground) compared generally well with reference values reported in [8], as shown in Figure 1.

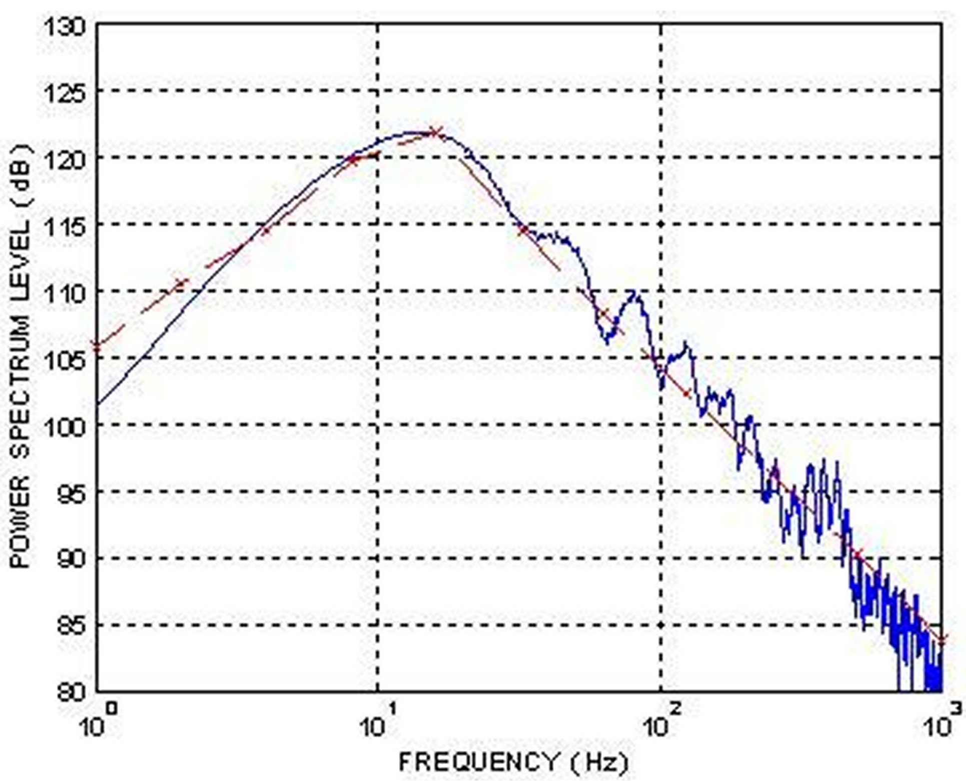

Figure 1: Power spectrum level measured at 100 m distance over hard ground (solid line); reference values (dashed line/crosses) adjusted to 100 m.

3.2 - Methods

The main idea was to compare measured blast attenuation with predicted attenuation calculated according to an analytical model. The relevant source strength is however not known. The PSL difference (called *measured* spectrum level difference (SLD) in the following) between two vertically and in-line mounted microphones was then taken as a proper indicator. If the ground influences the blast propagation, this influence is likely to be height dependent. In a prediction model the corresponding spectrum level difference (*predicted* SLD) can be determined provided the ground impedance is known. The measured SLD between the heights 2 m and 30 m for selected shots was then evaluated from the measured time records according to Eq. (1). The predicted SLD were established by using the analytical model of Nobile et al. [9].

3.3 - Ground impedance

The acoustic ground impedance had to be determined for the forest floor in summer condition, and in winter condition with snow cover. The forest floor consisted of short vegetation (grass, moss, some heather) with a well developed root system, above a substrate of sandy soil.

For the summer condition direct measurement of the reflection coefficient was carried out and the ground impedance determined [10]. This was done at two main sites within the forest, and at 5 locations within each site. The mean values in the frequency range 40 − 1250 Hz was determined [11]. The two-parameter low-frequency model based on flow resistivity and exponential decreasing porosity [12] was then applied. The parameters (σ_e=4350 Pa $\times$s/m^2, α_e=4.35 1/m) were determined in an investigation at a similar site. The corresponding impedance compared well to the measured mean values in the range 40 −200 Hz, so it seemed reasonable to use the model impedance from 200 Hz and downwards. Above 400 Hz the model of Delaney & Bazley [13] with an appropriate flow resistivity (σ = 16000 Pa $\times$s/m^2) came very close to the measured mean values. As a result, the combination of the two impedance models were applied in the frequency range 5 − 1000 Hz, with a transition in the range 160 − 400 Hz.

Impedance data for the snow cover at the time of the firings were not available. The snow cover was a layered mix of old and new fallen snow. Below the snow was a layer of ice and/or frozen soil. During the blast measurements the air temperature was below zero (°C). The situation was reasonable similar to conditions at a site in the Finnskogen area some kilometers away, the next winter [11]. The impedance model of Attenborough [14] was used, with parameter values: (tortuosity) ^{2} − 1.46, porosity − 0.82, ($S_p{}^2$ σ) − 1240 Pa $\times$s/m^2, determined in a special investigation. S_p is the pore shape factor, σ is the flow resistivity. The impedance for the snow cover will depend on the cover depth.

Figure 2 shows the impedances, for snow assuming a cover depth of 0.35 m. The problem of variable snow cover depth in the forest will be discussed later.

3.4 - Blast shot selection

The shots were selected according to meteorological indications, including moderate to low wind-speeds and crosswind or downwind (negative temperature gradient) conditions. This was assumed to yield a meteorological condition close to neutral (and thus minimising acoustic refraction).

4 - THE RESULTS

The presentation of measured and predicted Spectrum Level Differences (SLD) between the heights 2 m and 30 m comprise the main results. Comparisons of such spectra for the summer situation are made for the distances 259 m, 431 m and 1307 m. For the winter situation the distances were 200 m, 750 m and 1300 m.

4.1 - Summer conditions

The results are shown in Figure 3. The predicted SLD fits the measured SLD fairly well at frequencies below 100 Hz, at all distances. A small deviation at frequencies between 15 − 30 Hz is seen. The discrepancies at and above 100 Hz are most probably caused by the trees in the forest, and are not of any concern here.

4.2 - Winter conditions

The variable snow cover depth in the forest caused problems for the prediction. Unfortunately, a detailed snow depth profile along the propagation line was not available. Some snow data were available [15], giving a rough indication of the snow depths. The depths given were 0.1 m (distance 25 m), 0.3 m (distance 90 m), 0.5 m (distance 250 m) and 0.5 m (distance 800 m). The distances are measured from the microphone tower. The greatest depths here are probably maximum values, so the mean depths will be less. The variation in snow cover depth will significantly influence the propagation of blasts fired from distance 200 m, less for firings at 750 m and 1300 m. A simple snow depth profile was established based on this data, with some adjustments according to the results obtained at 200 m distance. The snow depth profile included four ranges (with assumed snow depths in parentheses): 0 − 25 m (0.1 m), 26 − 85 m (0.15 m), 86 − 1000 m (0.4 m), 1001 − 1300 m (0.375 m). This profile is quite likely, as regards the sparse information that is given. In the prediction of SLD the ranges were treated as ground

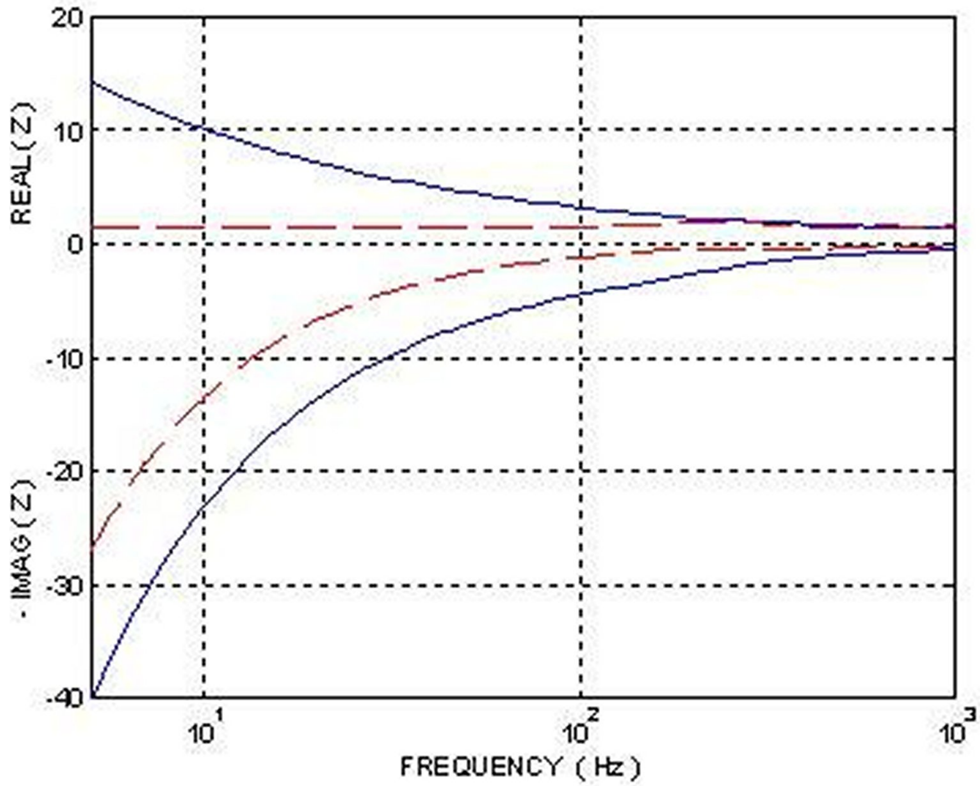

Figure 2: Normalised acoustic impedance (Z) for the forest floor (solid line), and snow cover (0.35 m depth) above frozen ground (dashed line).

with varying acoustic impedance. The contributions from these ranges were added according to a simple Fresnel zone consideration, as described for example in [16]. The results are shown in Figure 4. It is seen that with the established snow depth profile, the results at all distances compare fairly well. It should also be noticed that the SLD at comparable distances shows significant differences between summer- and winter conditions. At very low frequencies (i.e. below 10 Hz) the SLD are close to zero. This is due to the fact that the microphone separation is of the order of one wavelength or less. In this frequency range the sensitivity to detect differences between measured and predicted results is low.

5 - SUMMARY AND DISCUSSION

Estimates of the acoustic ground impedance at low frequencies were established by means of impedance modelling and measured results. The relative sound level spectra above flat ground could then be predicted by means of an analytical model normally used for sources emitting continuous sound. The usefulness of this model when applied to blast noise propagation was evaluated by comparing measured and predicted spectrum level differences between 2 m and 30 m height, for several ground impedances and distances.

The results in Figures 3 and 4 seem quite promising. The agreement between measured and predicted spectrum differences is good in general, in the frequency range below approximately 100 Hz. It is to be noticed that this seems valid for different distances and ground impedances. At very low frequencies the spectrum differences will be insensitive to changes in ground impedance due to physical limitations in the test layout. The lower limiting frequency in this investigation is thought to be approximately 20 Hz. This indicate that the analytical prediction method should be valid for blast noise propagation down to this frequency, provided that the acoustical ground impedance can be determined and the blast's source strength is described properly. The findings mentioned above are limited to blasts from 8 kg C4 explosive, fired 3.5 m above ground level.

The results found here also indicate that the ground does influence the propagation of blast noise significantly. If the analytical prediction model can be used for blast noise propagation, a distinct separation between direct and ground reflected wavefronts should be the case. This may indicate that blast noise propagation (in this investigation) above acoustically "soft" ground does not develop the mach stem situation.

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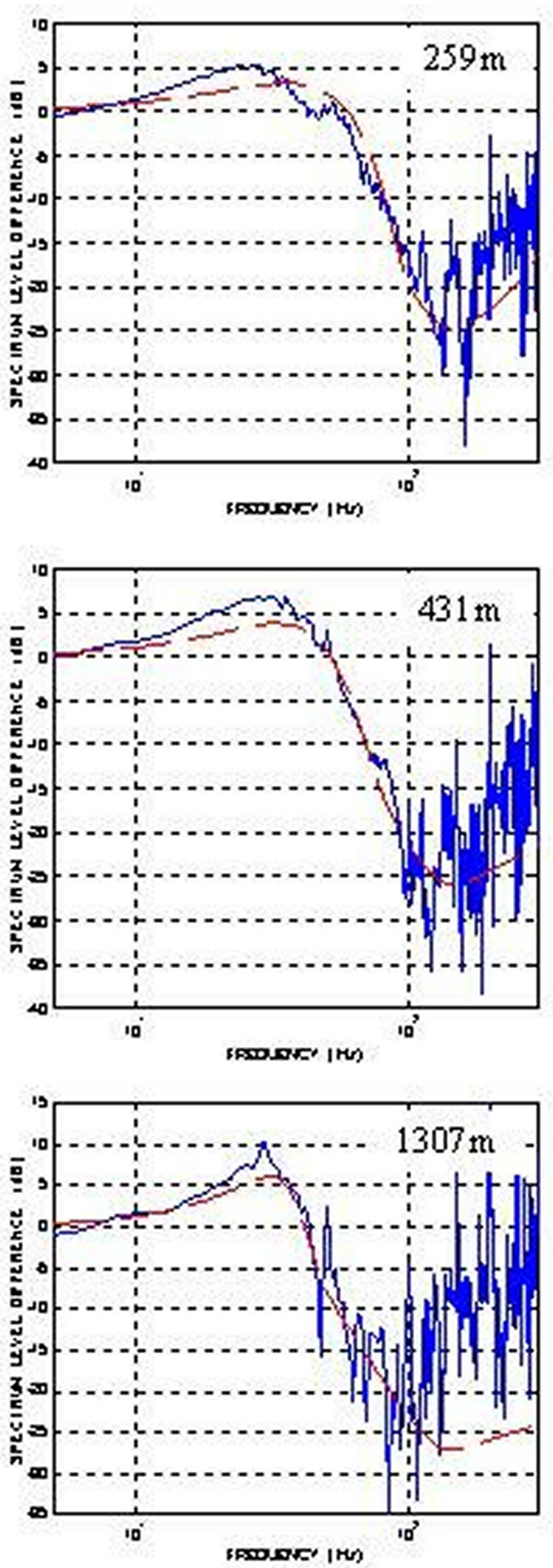

Figure 3: Spectrum level differences, June 94; measured (solid line), predicted (dashed line).

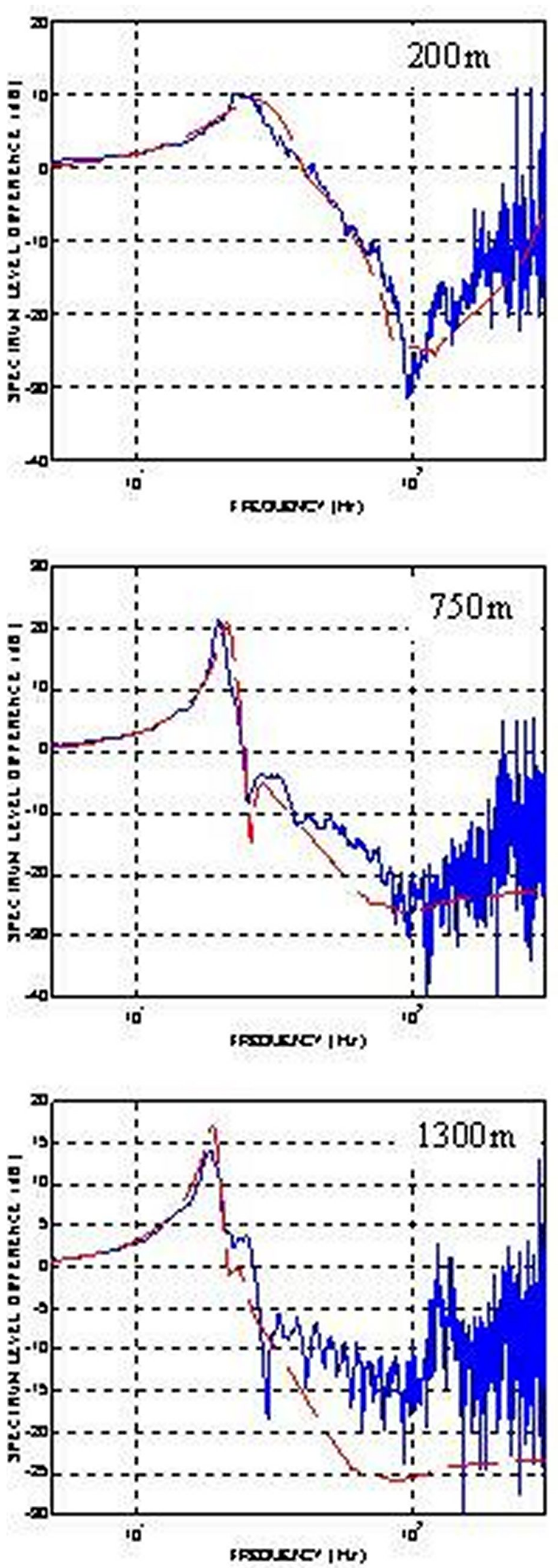

Figure 4: Spectrum level differences, Feb 95; measured (solid line), predicted (dashed line).