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THE ACOUSTIC SOURCE STRENGTH OF HIGH-ENERGY BLAST WAVES: COMBINING MEASUREMENTS AND A NON-LINEAR MODEL

Frits van der Eerden and Frank van den Berg

TNO Science and Industry, Acoustics Department, Stieltjesweg 1, 2628 CK Delft, The Netherlands

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ABSTRACT

In the densely populated area of the Netherlands, the objective of the Netherlands Ministry of Defence is to find an optimal balance between military training and the impact on the surrounding civilian community. A special case concerns large weapons, such as artillery or demolitions, which create high-energy blast waves. These waves have a low frequency content, typically between 15 and 125 Hz, and can propagate over large distances. As a result it is a relative important cause for annoyance. The challenge is to determine accurately the acoustic source strength. This source is then used in a dedicated model for military training facilities, to calculate rating sound levels around the facility for different training situations and to calculate the effect of measures. This model uses a linear sound propagation and an equivalent linear source strength. The source strength is measured at a large distance, where the sound propagates linearly. As a consequence the ground and the meteorology have an important effect, and one has to correct for it. A more efficient approach has been tested, where the sound pressure measurements have been performed close to the source, at typically less than 10 meters distance. The linear source strength is then calculated by applying a non-linear propagation model. The results are compared to the conventional measurement method. Another advantage of applying the non-linear model, and the nonlinear source strength, is that the effect of mitigation measures close to the source can be determined.

INTRODUCTION

The Netherlands Ministry of Defence uses a measurement technique for the "determination of the acoustic source strength of a muzzle blast or detonation by measurement". It has been decribed by TNO. This technique defines how the source strength and its angular distribution can be obtained from the measurement of sound exposure levels and how these measurements have to be carried out (see Figure 1). The source strength, its angular distribution and spectral structure, are used as input for sound propagation models for environmental noise assessment. It can also be used for a comparison of different types of guns or different types of ammunition used in the same gun. The procedure is meant to supply, via sound measurements and calculations, the acoustic source strength in a reproducible way.

The procedure consists of three methods:

Method I: *Direct source strength determination*

Method II: *Short range indirect source strength determination*
Method III: *Long range indirect source strength determination*

For Method I the undisturbed direct blast wave and the ground reflected wave can be separated in the time domain. The source strength is determined from analysis of the direct wave only. Method I can be used for arms having a small calibre.

Method II is used when the direct wave and the reflected wave cannot be separated in the time domain. In this case the difference between the path lengths of these waves is not large enough. This is the case when the muzzle blast or detonation is close to the ground or the distance between the source and microphones is large.

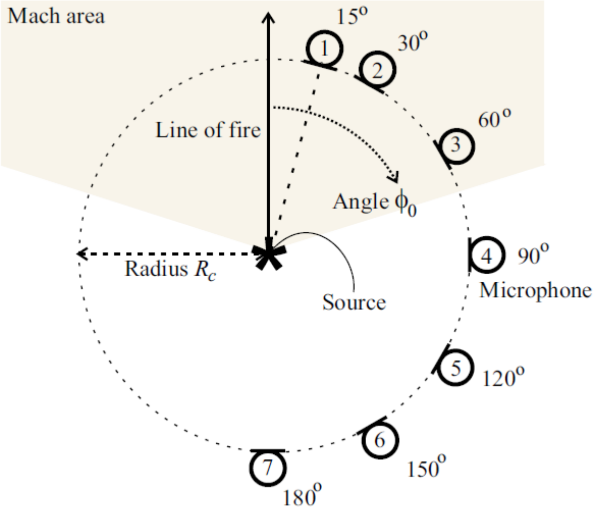

Figure 1. Schematic top-view of set-up for source strength measurements (a horizontal line of fire is assumed).

Method III is used when the horizontal distance from the source to a microphone is typically beyond 100m. Method III can be used for large calibre weapons and takes meteorological effects into account.

All three methods are used to prevent measurement in a region where the sound propagates (weakly) non-linear. Therefore, the measured peak levels need to be below 150 dB (~600 Pa).

A Mach area is indicated in Figure 1. It represents the area where projectile sound is observed if the projectile leaves the muzzle with a speed larger than the speed of sound.

It is important to determine the (linear) source strength accurately, as it is further used to calculate the sound levels around military training facilities. In the next section, Method III is described. It is shown that the ground and meteorology play an important role.

Next, an alternative approach is described where the ground and meteorology can be neglected. Measurements are done close to the source, in the non-linear region. With the combination of a non-linear model (FCT) the linear source strength can be determined. An example of measurements and numerical results is presented.

Finally, the FCT model is applied to design mitigation measures close to the source. The interaction of shock waves with sound absorbing material is accounted for.

METHOD III: INDIRECT SOURCE STRENGTH DETERMINATION

Measurements and Excess attenuation

Method III uses a horizontal distance of typically 100m between the microphones and the source. Other reasons, such as safety, may also require a distance from the source of more than 100m. In general, this method is used for calibres larger than 50mm or explosive charges of for instance 1 kg TNT equivalent.

For this relatively long range, the direct sound wave and the reflected wave cannot be separated in the time domain. Furthermore, meteorological effects on the wave propagation from the source to the microphones cannot be neglected. Therefore, Method III compensates for the excess attenuation between the source and the microphones. The excess attenuation includes losses due to interaction with the ground and atmospheric refraction.

The one-third-octave-band spectrum of the *sound source exposure level* L_{Es} is determined from the measured sound exposure level L_E, for 7 angles ϕ_j at distances x_j, according to:

$$L_{Es}(f_{\mathrm{i}},\phi_{\mathrm{j}}) = L_E + A_{\mathrm{div}} + A_{\mathrm{atm}} + A_{\mathrm{excess}}$$

where:

f_{i}	nominal midband frequency of the i$^{\mathrm{th}}$ one-third-octave-band (12.5 – 5000 Hz);
ϕ_{j}	angle with respect to the line of fire projected on a horizontal plane, for a horizontal line of fire;
A_{div}	= 10 log($4\pi x^2$), attenuation of the sound level in the free field;
$A_{\mathrm{atm}}(f_{\mathrm{i}})$	attenuation caused by absorption processes in the atmosphere as the sound propagates over a distance x, according to ISO 9613-1;
$A_{\mathrm{excess}}(f_{\mathrm{i}})$	is the excess attenuation which includes losses due to interaction with the ground and atmospheric refraction.

The sound exposure level L_E is specified in ISO 17201-1 and represents the sound exposure compared to the reference sound exposure of $(20\mu\mathrm{Pa})^2(1.0\mathrm{s})$.

The excess attenuation should be calculated with a sound propagation model which takes into account a sound absorbing ground and a refracting atmosphere. For example, the Parabolic Equation (PE) model. Figure 2 gives an example of upward refracting sound waves for a logarithmic profile of the effective speed of sound (4.6 m/s at 10m height). Two microphones are indicated, one inside and one outside the shadow region.

For reliable measurements, the microphones have to be located outside the shadow region, i.e. for a typical downwind condition.

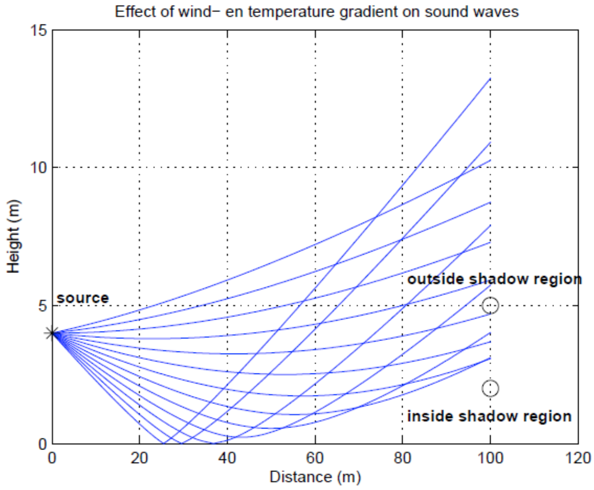

Figure 2. Example of upward refracting sound waves as the result of a sound speed which decreases with height.

Furthermore, the interaction (of refracted sound) with the ground needs to be accounted for. In general a minimum occurs for the frequency where the difference between the direct and ground reflected wave is half a wave length.

In Figure 3 examples of measurements are shown for 7 angles. An interference minimum can be seen between 125 and 250 Hz. In Figure 4 the corresponding calculated excess attenuation is shown. For this example the ground absorption is characterised with the flow resistivity of the ground (Delany and Bazzley model). The measured flow resistivity, at a single location, was found to be 200 kPa s m^{-2}. However by slightly adapting the flow resistivy for each angle the measured interference minimum matches the calculated one. The results as shown in Figure 4 were found (with flow resistivity of 150, 200, 150, 150, 150, 100 and 200 kPa s m-2, respectively).

One can conclude that for Method III the meteorology and the ground have a major effect on the source strength determination, so that a carefull correction is needed to compensate for these effects.

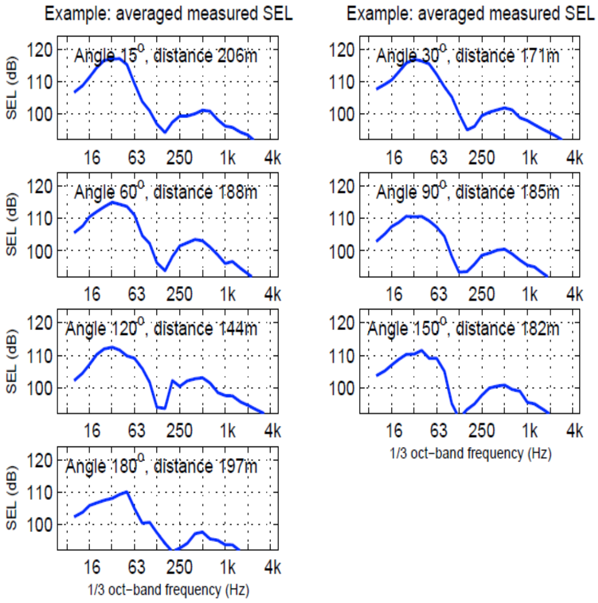

Figure 3. Example of measured one-third-octave-band spectra for 7 angles (average of 15 measurements).

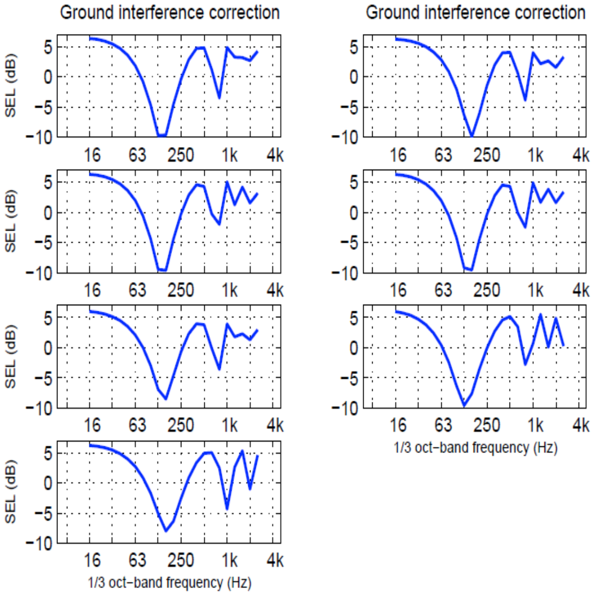

Figure 4. Ground interference correction based on PE-calculations (including wind/temperature effect) for the set-up as shown in Figure 3.

SOURCE STRENGTH DETERMINATION WITH A NON-LINEAR MODEL

Approach

Figure 5 shows two measurement locations to measure the source strength. The microphone in the acoustic linear region is used for the "indirect source strength determination". As shown in the previous section, the effect of the wind, temperature and the ground has to be taken into account when the source strength is determined.

This effect can be omitted when the measurement is performed close to the source, typically around 10 meters. As a consequence there is no need for detailed measurements of the meteorology and the ground absorption. However, a non-linear acoustic model is needed to propagate the shock wave into the linear region (so that the "linear source strength" can be determined). This is schematically shown in Figure 6.

The so-called FCT method has been adopted for the shock wave propagation. This numerical method also allows for the calculation of shock waves that interact with mitigating measures in the vicinity of the source.

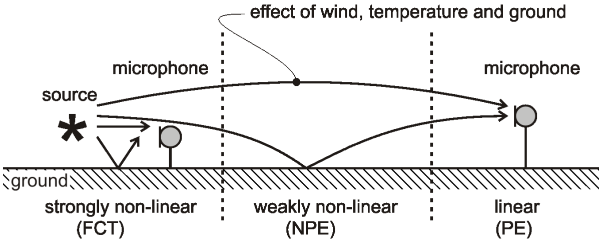

Figure 5. Measurements in the acoustic non-linear and linear region (numerical methods are indicated between parenthesis).

In Figure 5 also a weakly non-linear region is indicated. The non-linear progessive wave equation (NPE) can be used as an intermediate numerical technique, before the linear parabolic equation (PE) is used for the shock wave propagation. The NPE and PE techniques allow for the effects of meteorology and ground absorption (see also [4]).

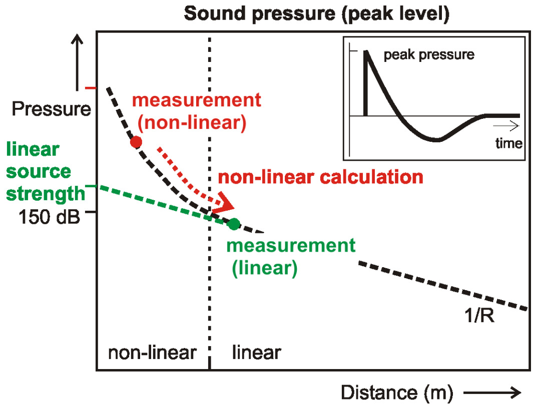

Figure 6. Schematic view of the determination of the "linear source strength" of a high-energy blast wave. Green: conventional measurement and source determination. Red: source determination via measurement in the non-linear region.

The base of the FCT method is the numerical solution of the three dimensional unsteady Euler equations:

$$\partial_t \mathbf{Q} + \partial_x \mathbf{F} + \partial_y \mathbf{G} + \partial_z \mathbf{H} = 0$$

where $Q = (\rho,\rho u,\rho v,\rho w,E)^T$ is the vector of flow variables, respectively the density, momentum components and total energy density $E = p/(\gamma - 1) + 0.5\rho\,(u^2 + v^2 + w^2)$. The vectors F, G and H are flux vectors (see [3]).

The solution technique relies on a finite volume space discretization, an explicit time integration scheme, and makes use of a "flux corrected transport algorithm" (FCT), developed by Boris [2]. This technique is designed to accurately reproduce strong flow discontinuities, such as shocks, without producing oscillations or overdamping the solution, as can be the case with more classical discretization schemes.

In order to start an FCT computation, the pressure, velocity, density and energy need to be specified. First, a Gaussian pulse is used at time t=0s, with a starting peak amplitude and a Gaussian width. This pulse is propagated with a fast one-dimensional version of the FCT code, using spherical coordinates, up to several tens of meters (see Figure 7).

At one or more distances from the source the numerical pressure is displayed as a function of time. This numerical pressure is compared to measurements. By changing the starting peak amplitude and Gaussian width, the numerical pressure is tuned to match the measurements.

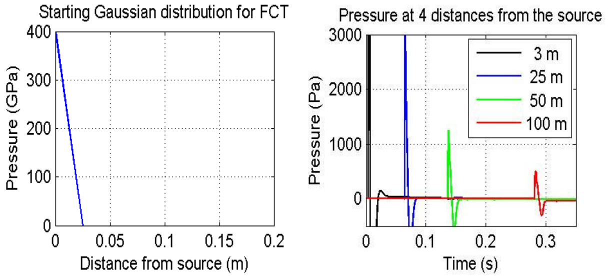

Figure 7. Gaussian starting condition for FCT (left) and numerical results at distances further from the source for a comparison with measurements (right).

When the starting conditions for the pressure, velocity, density and energy are found, an axisymmetric FCT computation (2D) can be done (to take into account the ground or a mitigating measure). An example of these starting functions, for a source at 2m height above the ground, is shown in Figure 8.

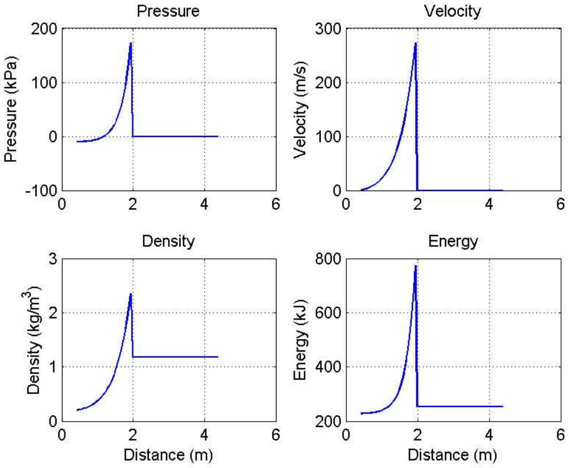

Figure 8. Example of starting functions for the pressure, velocity, density and energy, for a FCT computation (starting at 2m).

Application to 35mm calibre muzzle blast

Source strenght measurements, for the muzzle blast, were performed for a new 35mm calibre cannon of the Netherlands Ministry of Defense. For the measurement set-up Method III was applied and the microphones were located at a distance of 50m. Also, measurements close to the source were done, at a distance of 6m and 4.8m height. The angle with respect to the line-of-fire was 90 degrees.

Figure 9 shows measurement results at 6m distance. Both the direct (0.002s) and ground reflected (0.01) shock wave can be seen, as well as some smaller refletions from the body carrying the cannon.

Also shown is the numerical FCT result. The one-dimensional version has been used, so there is no ground reflection. The numerical results have been matched with the measurements.

Consequently, the starting conditions for a 2D simulation were obtained. The comparison of measurements (averaged) and numerical results are shown in Figure 10. Notice the higher peak level for the ground reflection. This is due to some ground absorption which is present for the measurements (ground = loose sand).

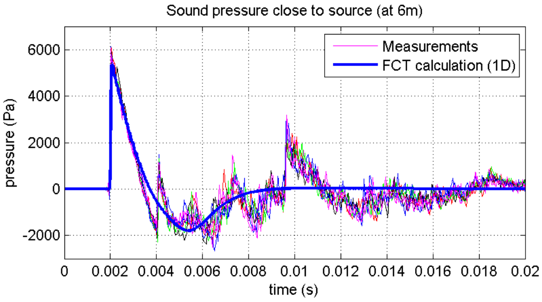

Figure 9. Comparison of blast wave measurements and a one-dimensional FCT simulation (without the ground).

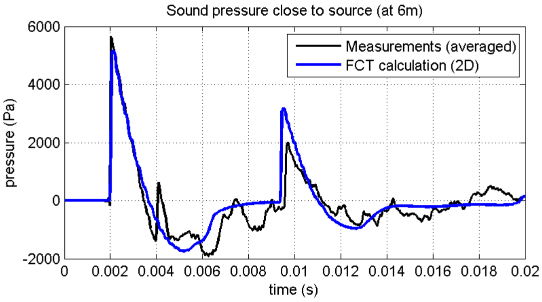

Figure 10. Comparison of blast wave measurements (average of several recordings) and an axi-symetric FCT simulation (2D, with the ground).

Next, the shock wave is propagated to 50m with the FCT method, where the peak pressure level is below 150 dB. The *spectral* results for the measurements and the FCT simulation are shown in Figure 11, for the 90 degrees angle. The results have been shifted vertically (both measurements and FCT results with the same level), so that also the groud effect can be seen. The ground effect equals *minus* the excess attenuation (for low frequency the pressure is doubled, i.e. +6 dB).

The simulated result is representative for a free field propagation, whereas the measurements show effects of the ground and the meteorology. This explains the differences between the measurements and the simulation.

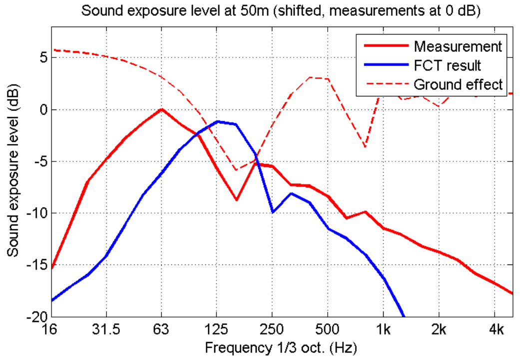

Figure 11. Sound exposure level, for 1/3 octave bands, at 50m from the source. A single shift has been applied to the measurements and the FCT results. Also shown is the calculated excess attenuation, to be applied to the measered results.

As a final step the linear source strenght is shown in Figure 12. For the measurements at 50m, Method III has been applied. For the simulation results at 50m, only A_{div} and A_{atm} have been corrected for (see equation for Method III).

A good correspondence can be seen for frequencies below 500 Hz. The results obtained with the non-linear method show a more pronounced source level around 125 Hz, whereas the results for Method III are more distributed around this frequency. The broadband difference is 1.4 dB

(1.0 dB up to 1000 Hz), which is a small difference considering the measured distance, the ground (heathland) and meteorology effects.

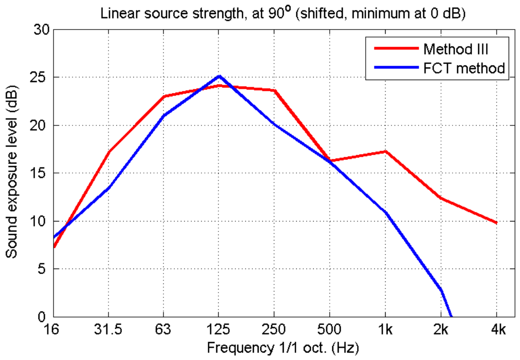

Figure 12. Linear source strength, determined according to Method III and by using a non-linear FCT method. Vertical axis has been shifted to start at 0 dB.

The difference for frequencies above 500 Hz is large. Further investigation is needed to explain this. However, for large calibre weapons the frequency content is typically between 15 and 125 Hz. Furthermore, at larger distances the frequencies above 500 Hz are attenuated by absorption in the air (e.g. at 5km the attenuation for 1000 Hz can easily reach 20 dB).

DESIGN OF MITIGATION MEASURES

Another application of the FCT method is the possibility to design mitigation measures. These measures need to be close to the source for best effectiveness, but due to the high sound pressure levels the interaction of the sound field with barriers and sound absorbing material cannot be described with a linear model [5].

In the FCT method the acoustic properties of the absorbing material are defined by three parameters: the porosity, the flow resistivity and the Forchheimer nonlinearity coefficient. The effects of these properties on the flow field is accounted for by a simple forcing term in the momentum equation, representing the resistance of the material to the flow.

In Figure 13 a snapshot of the pressure results interacting with a barrier is shown. Behind the barrier, gravel filled gabions are used to mitigate the shock wave as it travels relatively easy over the barrier.

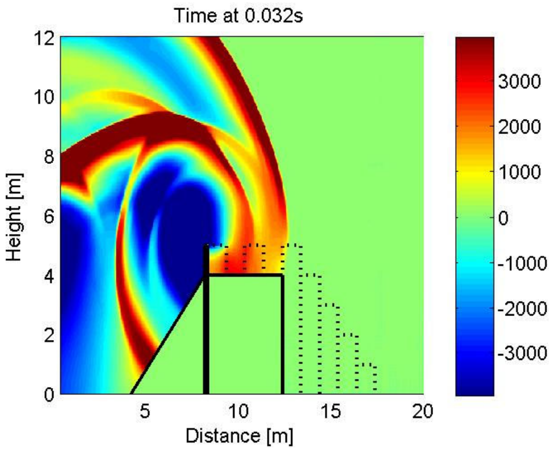

Figure 13. Snapshot of the direct and ground reflected shock wave travelling over a 5m high barrier with a sound absorbing structure behind it. Source at 0m and 2m height.

In Figure 14 a smaller barrier is shown, to be applied for small calibre weapons. The pressure interacting with a sound absorbing T-top is shown. The objective is to enhance the screening effect by adding a suitable absorbing material to the screen.

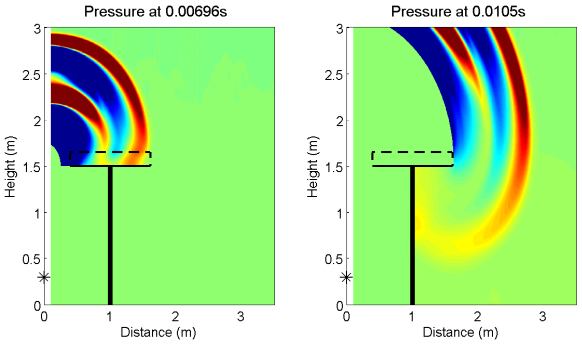

Figure 14. Snapshots of the direct and ground reflected shock wave travelling over a barrier with a sound absorbing T-top. Source at 0m and 0.3m height.

CONCLUSIONS

Two methods have been presented to determine the acoustic linear source strenght for large weapons. By using these source strengths in a dedicated model for military training facilities, rating sound levels around the facility can be calculated for different training situations and also the effect of measures can be determined.

For the application of a 35mm calibre muzzle blast, it was shown that both methods showed similar results up to 500 Hz. The second method uses near-by measurements and a non-linear model to determine the linear source strength. This method avoids the correction for meteorology and ground effects, which can be a cause for errors of several dB's.

ACKNOWLEDGEMENTS

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