Estimation Of The Directivity Pattern Of Muzzle Blasts

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Introduction

Sound prediction schemes are often dedicated to a certain scope of application. They are called ‘engineering’ models if they consider the features of the source, of the propagation and of the receiver separately. Typically, such schemes start from a compatible source model to sum up the correction due to the various physical phenomena based on particular models as separate terms to yield the dedicated output measure. The ISO 9613-2 describes such a prediction scheme for the A-weighted long term average sound pressure level for correlation purposes with annoyance. In general, the acoustic source model is therefore a decisive feature for any sound prediction scheme.

For many sound sources, scheme compatible sources are elementary point sources having a source strength S and a directionality D. Assuming linearity, these two basic features are separated using the approach in formula 1.

$$Q(r,\alpha,f) = S(r,f) \cdot D(\alpha,f) \qquad \text{Formula 1}$$

In equation, let Q denote the output of the source, r the distance, α the direction and f the frequency. Hence, the task to make a source model also normally separates into two parts, (1) to model the source strength S and (2) to model the directivity D.

For blasts from free explosions in air the so-called WEBER model is a well-known and reliable approach for the source strength. This model only depends on the mass of explosives denoted as a certain radius, the so-called WEBER radius. Such sources have no directionality, $D(\alpha,f) = 1$.

Muzzle blasts are not free explosions; they do have a strong directivity. Nevertheless, the spectrum of the muzzle blast looks at all relevant directions to the line of fire like the WEBER spectrum of an explosion produced by an equivalent mass of explosives. Therefore, the relevant standard ISO CEN 17201-2 [1] introduces the WEBER model to give guidance on how to estimate the source strength in terms of angle dependent sound energy of the muzzle blast from the total mass of explosives in the cartridge and provides two sample directivity patterns, one for typical pistol and one for typical long rifle, to complete the source model. The present paper proposes to model the source strength and the directivity of the muzzle blast using the directivity pattern of the equivalent WEBER-Radius.

WEBER Model

In 1939, WEBER [2] developed a model primarily to describe the source strength of sounds from spark gaps from electric discharge between electrodes. The general idea of the model is that the plasma forms a sphere that is expanding into the ambient air with decreasing speed. As long as the expansion speed is higher than the sound speed no sound is radiated. The instance when the expansion speed falls below the speed of sound, the blast is radiated from the surface of the sphere of the plasma gas. At that very moment the particle velocity is the sound speed of the surrounding air and the shape of the source is the sphere. Hence, also the pressure is well-known introducing the radiation impedance of the breathing mode of the sphere. As a consequence, the intensity of all blasts is the same and is a constant in this model. Only the size of the sphere determines the sound energy and the spectrum of the blast of the source. Therefore, the only free parameter of the WEBER model is the radius of the sphere at that very moment. WEBER also showed that his model can describe the blast sound from a small pistol. HIRSCH applied the model to weopon blasts [3].

The WEBER model yields full information about the sound of an explosion: The radiating body is a sphere of defined size. The source strength is given as a FOURIER spectrum determining the frequency dependent sound pressure in magnitude and phase. This spectrum can be used to calculate any desired acoustical measure of the source.

For a muzzle blast, the body of radiation is certainly not a sphere. Due to the basic rotational symmetry around the barrel axis, the radiating body still needs to be a body of revolution but estimating its shape and its radiation impedance is a rather challenge. The gases leaving the barrel with supersonic speed develop a so-called MACH-plate. The body of radiation will be wider to the front than looking from the rear giving reason for a strong frequency dependent directivity pattern.

Measurements

The WTD 91 conducted detailed measurements on the directivity pattern for a military rifle [4]. On two measuring circles (10 m and 20 m radius) centered geometrically at the muzzle, the shooting sounds of flat rifle shots a 2 m height (muzzle speed $v_0 \approx 920$ m/s) were measured at two heights (1 m and 2 m) for a series of 3 shots at 35 equally spaced directions (10° angle steps) relative to the line of fire. The pressure time history for each shot was recorded over a period of time of 156,5 ms (15646 samples every 10 µs).

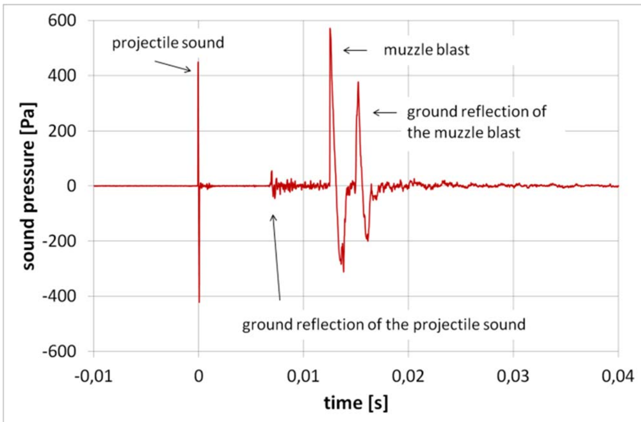

Figure 1 Pressure time history of the shooting sound projectile sound and muzzle blast at 10 m distance, 2 m height and at 10° re. line of fire

Figure 1 indicates a typical sample signal for the sound of a shot recorded at 10° re. the line of fire at 2 m height and 10 m distance. The projectile sound and its ground reflection come first followed by the muzzle blast and its ground reflection. The projectile sound is a clear N-shaped wave; the muzzle report is a WEBER-blast-shaped signal. Both ground reflections are disturbed through scattered sounds at the ground in the case of the projectile sound and at the support of the rifle in the case of the muzzle blast. These observations hold for all recorded pressure time histories except for the projectile sound which is missing at the directions to the the rear.

Analysis

Due to the recorded signal length and because the main frequency content of the muzzle blast of a rifle is above 315 Hz, the frequeny analysis is restricted here from to 315 Hz to 10 kHz. Figure 2 confirms that the directionality of muzzle blast is frequency dependent.

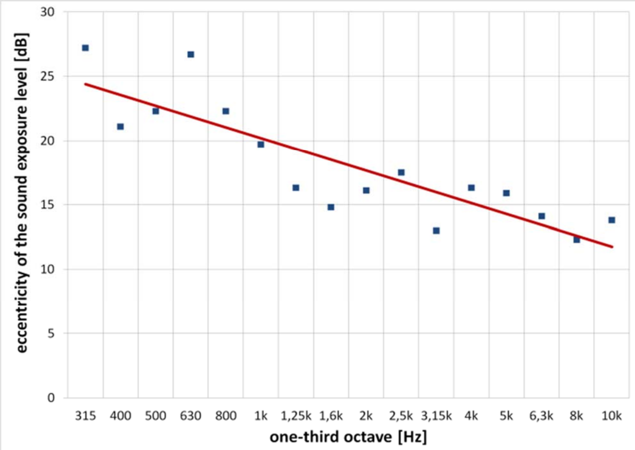

Figure 2 Difference of the one-third octave sound exposure level at 0° and 180°, distance 20 m, height 1 m

The difference between the sound exposure at the line of fire and at 180°, the so-called eccentricity of the directivity pattern, decreases from round about 25 dB at 315 Hz to 13 dB at 8 kHz. Applying A- or C-weighting does not change the eccentricity but will change the eccentricity of the overall exposure levels. This effect is of course much more important for larger guns where the relevant levels are at significant lower frequencies.

An available dedicated procedure that relies on a least square fit in the frequency domain to find the optimal WEBER radius of an equivalent blast signal of an explosion was applied to the relevant section of the muzzle blast and its ground reflection for all recorded signals. Throughout the series and for all directions the procedure yields WEBER radii that leaves on the average a maximum error of 1,5 dB for the deviation between measured and calculated one-third octave sound exposure levels for the given signal section. This uncertainty includes the unavoidable influences of the reflections from the support of the rifle as shown in Figure 1. This is remarkable good agreement between the WEBER model and measured muzzle blast suggesting to apply the WEBER model also to these blasts.

Due to the strong directivity, the WEBER radius strongly depends on the direction relative to the line of fire. Obviously, the body of radiation looks different at each direction, larger to the front and smaller to the rear of the rifle shot. Figure 3 depicts the calculated WEBER radius versus the measuring direction relative to the line of fire grouped by the four receiver positions. To generate an easily interpreted graphic image of the directionality, the angle axis in Figure 3 covers -360° to +360° and shows some results twice, mirrored at -180° and extended at 180° respectively. Around the line of fire (0°, ±360°) the WEBER radii vary stronger within the measurements at the given position as well as between the different positions. At angles to the side and to the rear these variation die out neglecting the one measurement at -130° (-230° and +230°).

Figure 3 indicates that is sufficient to use a Cosine function according to Formula 2 as a first approach to describe the general features of the directivity pattern in terms of the WEBER radius R_W.

$$R_W(\alpha) = R_{W0} (1 + e_W \cos(\alpha)) \qquad \text{Formula 2}$$

Therefore, the determination of the source strength and the directivity reduces to two parameters, the WEBER radius R_{W0} at 90° (or 270°) and the eccentricity e_W. It should be noted that this approach not only gives the directivity pattern for the sound exposure or energy level for example. This approach includes the prediction of the pressure time histories as well as a natural explanation of the frequency dependence of the directivity. It indicates in agreement with measurements that lower frequency components have a stronger directionality than higher frequencies. This is a special feature of muzzle blasts compared to other typical sound sources modeled as point sources.

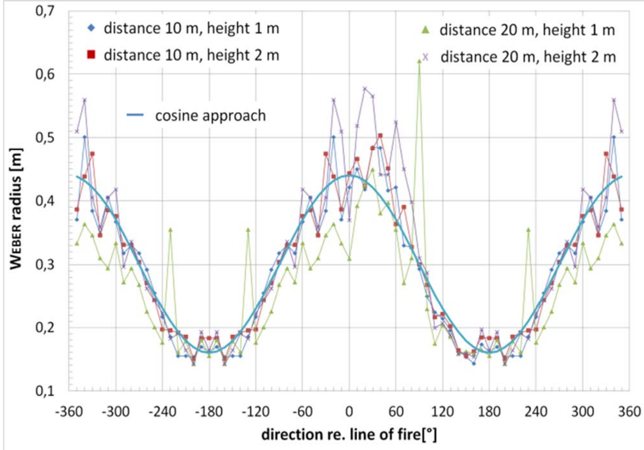

Figure 3 WEBER radius versus direction re. line of fire at four measuring positions and an optimized Cosine-fit R_{W0} = 0,3 m, e_W = 0,45

According to Figure 3, the ratio between the WEBER radius at 0° and at 180° is $(1 + e_W)/(1 - e_W)$. The volume of the equivalent WEBER sphere is a measure for the equivalent energy. Therefore, the ratio of the energy radiated to the front to the energy to the rear is $[(1 + e_W)/(1 - e_W)]^3$ or ≈ 13 dB in case of the results in Figure 3.

Considering available measurements according to the rules of ISO 17201-1 for sporting and hunting guns (including one shotgun) give evidence that e_W = 0,4 is a good approximation for the eccentricity for such small arms. For pistols e_W ranges between 0,3 and 0,35. Therefore, the relevant table in ISO 17201-2 providing two sample directivity patterns, one for a rifle and one for a pistol, is not a bad practice to distinguish between a long barrel and a short barrel gun.

Conclusion

Modeling the muzzle blast of small arms using the proposed Cosine function of the equivalent WEBER radius is a simple but very powerful approach to predict the source features of such blasts. The model reduces the complex frequency dependence of the source strength and of its directivity to the specification of two parameters. The first parameter is the equivalent WEBER radius at 90° (or 270° respectively). The second parameter follows from ratio between the WEBER radii at 90° and at 180°.

This new source model for muzzle blasts - relying on the Cosine approach or any other function to describe the directivity pattern of the Weber radius - does not fully comply with the separation approach in Formula 1. Engineering prediction schemes for shooting noise need to be adapted to the source description in terms of the angle dependent equivalent WEBER radius. In principle, the new source model is superior to the methods in ISO 17201-2 because it provides the complex FOURIER spectrum of the sound pressure in magnitude and phase at every direction.

References

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