Frequency- and Angle-dependent Source Models of Muzzle Blasts close to the Gun

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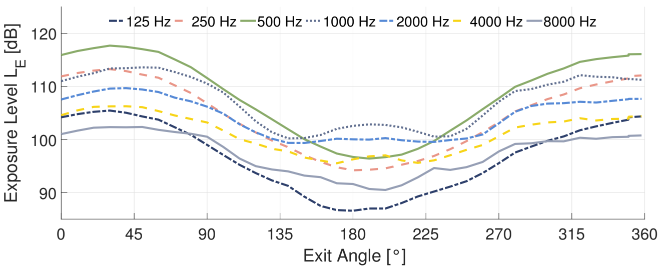
Introduction

The exposure of the shooter's hearing when firing handguns is primarily caused by the muzzle blast. The key input variable of models for assessing the exposure and the risk of hearing damage is the sound pressure time curve at the ear. For the investigation of such exposure models, reliable source models of the muzzle blast are required that provide the sound pressure time signal. The Weber model[1] is a proven and simple approach for describing explosions in air. For its application to muzzle blasts, the directional characteristic must be taken into account, see ISO 17201-2[2] and LeitGeStand[3]. This article presents an approach based on the Weber model that describes the sound pressure time signal as a function of direction. For this purpose, the so-called Weber radius - the only parameter of the model - and a scaling level are determined angle-dependently by cosine transformation.

Fundamentals of a Muzzle Blast

First, the special features of the directivity of the muzzle blast are discussed.



(a) Gun muzzle blast

(b) Loudspeaker

Figure 1: Level of octave bands as a function of the exit angle in the transversal plane for a gun muzzle blast and a loudspeaker (Genelec 8020c)

The level deviations of the octave bands over the azimuth angle in the transversal plane of a rifle muzzle blast and a loudspeaker are shown in Figure 1. Measurement data from the Genelec 8020c from the BRAS project was used for the loudspeaker directivity[4]. The following aspects become clear from the comparison of the level deviations of the octave bands.

- The octave band-dependent level deviation of the muzzle blast is up to 20 dB depending on the angle of exit and is therefore many times greater than that of the loudspeaker
- The eccentricity - the level difference between the front (firing direction) and the rear - of the muzzle blast is most pronounced in the low frequency bands of 125 Hz to 500 Hz and decreases towards high frequencies from approximate 20 dB to 10 dB
- Most of the energy of this rifle is emitted between 500 Hz and 1 kHz

The propellant gases escaping from the tube during the muzzle blast resemble a massively deformed sphere, as indicated in the schlieren photography from Figure 2.

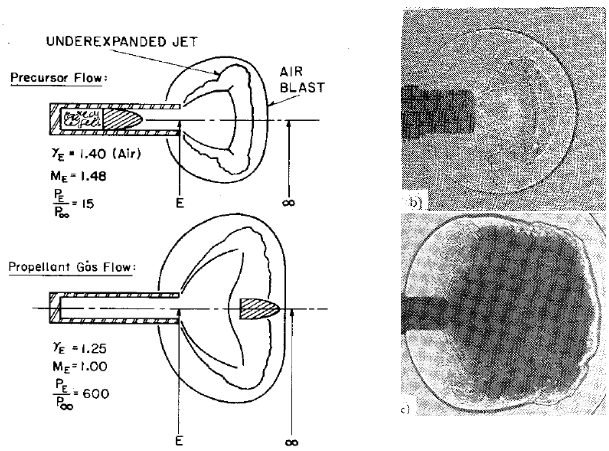


Figure 2: Flows occurring during the muzzle blast [5]

The spherical first sound front recognizable in the schlieren photography is the so-called *precursor*, which originates from the air pushed out by the projectile at supersonic speed. The actual muzzle blast is formed by the propellant gases behind the projectile. These also emerge from the pipe at supersonic speed and flow into the still air. This forms a so-called Mach plate, a well-known phenomenon in fluid dynamics[5]. The muzzle blast is therefore emitted neither from the muzzle itself nor from a sphere around it, but from a disk[6]. This explains why the directional effect is also directed forwards at longer wavelengths, while it tends to remain round at shorter wavelengths.

Raw Data - 360° Measurement

In Figure 3 the 36 measuring points are outlined in the horizontal plane. There are three recorded shot signals per measuring point. The distance between the microphones and the muzzle is 10 m. The weapon used is a rifle on a fixture with a muzzle brake[1]. Both the muzzle and the respective measuring points are positioned 2 m above the approximately reverberant grass ground. This means that the ground reflection hits approximate 2.1 ms after the direct sound. For the investigations presented here, only the direct sound component windowed out using Hamming windows is considered. The full metal jacket ammunition corresponds to the caliber 5.56 mm × 45 mm. In the calculations, an exit velocity $v_0 = 1200\,{}^{m}/_{s}$ and a projectile mass $m_p = 3.7$ g were assumed for this ammunition.

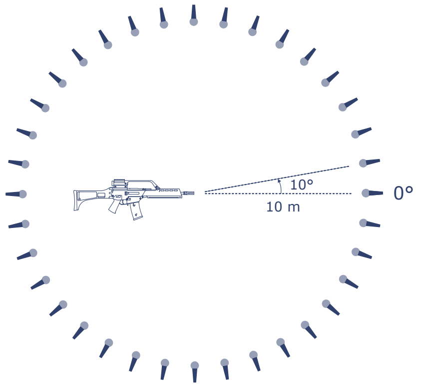


Figure 3: Sketch of the measuring points

The Source Models

In this section, the three investigated source models are examined with regard to angle-dependent signal generation. The methods are all based on the Weber model [1] which was introduced by Walter Weber in 1939. Basically, the Weber model is a spherical equivalent source with the Weber radius R_W as a parameter. Sound, i.e. the muzzle blast, is emitted via the impedance of a sphere at the point in time at which the expansion velocity of the explosion falls below the speed of sound. Therefore, the radiation impedance of the sphere at this point in time determines the spectrum of the Weber blast. The larger the sphere, the lower the frequency of the energy center of the blast. The sound pressure time curve $p_\mathrm{W}(t)$ of a Weber blast can be determined using Equation (1). For P_W, 14.4 kPa can be used, ω represents the circle number, c the speed of sound and α can be determined according to Equation (2) (formula A.2 of ISO 17201-2[2]).

$$p_\mathrm{W}(t) = \int_0^\infty \frac{P_\mathrm{W}}{\pi(\alpha^2+\omega^2)} \alpha \left(\cos(\omega t) + \omega \sin(\omega t)\right) d\omega \tag{1}$$

(Corresponds to the corrected formula A.3 of ISO 17201-2)

$$\alpha = \frac{3c}{R_\mathrm{W}} \sqrt{1 + \left(\frac{c}{\omega R_\mathrm{W}}\right)^2} \tag{2}$$

I. LeiGeStand

The german *guideline for the authorization of shooting ranges* -LeitGeStand- [3] contains an angle-dependent source and propagation model. This model is used to predict octave band levels in the far field of a weapon for the assessment of immissions. Weapons are classified according to Table 1. Using the Weber radius R_W and the Equations (1) and (2), the omnidirectional Weber sound pressure time response $p_\mathrm{W}(t)$ of a weapon class can be determined. Equation (3) specifies the output angle-dependent gain $\Delta L(\phi)$, from which the angle-dependent time signal $p_\mathrm{W}(t, \phi)$ results according to Equation (4).

$$\Delta L(\phi) = a_0 + \frac{\epsilon_{dir}}{2} \cos(\phi) \tag{3}$$

$$p_\mathrm{W}(t, \phi) = p_\mathrm{W}(t) \cdot 10^{\Delta L(\phi)/20} \tag{4}$$

Table 1: Acoustic source data of the hand weapon classes

Weapon class	$\mathbf{L_Q}$ /dB	$\epsilon_{\mathbf{dir}}$ /dB	$\mathbf{a_0}$ /dB	$\mathbf{R_W}$ /m
Rifle	142	11	−1.10	0.53
Pistol	138	18	−2.76	0.39
Machinegun	143	11	−1.10	0.57
Submachine gun	138	16	−2.23	0.39

II. ISO 17201 Part 2

This method is also based on the Weber model and has been validated in the acoustic far field for a large number of explosions in the air for charge masses from 0.5 g to 20 kg[2]. In contrast to the LeitGeStand, a direction-dependent Weber radius is determined for each angle of exit. The calculation is carried out in Chapter 4 of the ISO using the flow chart shown in Figure 2. There, the projectile mass m_p and the projectile launch speed at the muzzle v_{p0} are used to determine a Weber radius $R_\mathrm{W}(\phi)$ dependent on the angle of exit ϕ. In Figure 4 and Table 2 a reduced flowchart and the terminology are listed.

Table 2: Nomenclature

m_p	projectile mass
v_{p0}	projectile launch speed
Q_{p0}	projectile muzzle translational kinetic energy
σ	efficiency multipliers
Q_m	muzzle source energy
c_N	directivity cosine-coefficients
Q_e	total acoustic source energy
ϕ	exit angle
$Y(\phi)$	directivity factor
$R_\mathrm{W}(\phi)$	angle dependent Weber radius

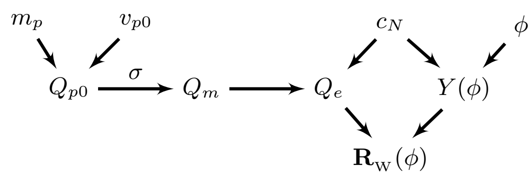


Figure 4: Reduced flow chart for calculating the Weber radius according to ISO 17201-2 (Fig. 2)

[1] According to the current state of the investigation, the muzzle brake influences the emitted sound from an angle of ≈ 140°, so that no clean blast is measured there

III. Two stage cosine transformation

This method is a combination of the two procedures described above. For this purpose, the Weber radius $R_W(\phi)$ in Equation (5) and the peak level $L_{p,z,peak}(\phi)$ in Equation (6) are both determined angle-dependently by cosine transformation. On the one hand, a scalar gain measure analogous to the LeitGeStand is used and, on the other hand, the spectrum is adjusted via the Weber radius as in ISO 17201-2. The coefficients c_i for the rifle considered in this article are listed in Table 3.

Table 3: Coefficients of 5th order at 1 m muzzle distance

Index i	c_{i,R_W}	$c_{i,L_{p,z,peak}}$
1	21.9 cm	165.3 dB
2	2.7 cm	7.1 dB
3	−0.1 cm	−0.6 dB
4	2.0 cm	−1.7 dB
5	−1.1 cm	0.4 dB

$$R_W(\phi) = \sum_{i=1}^{N} c_{i,R_W} \cos(\phi \cdot (i-1)) \quad (5)$$

$$L_{p,z,peak}(\phi) = \sum_{i=1}^{N} c_{i,L_{p,z,peak}} \cos(\phi \cdot (i-1)) \quad (6)$$

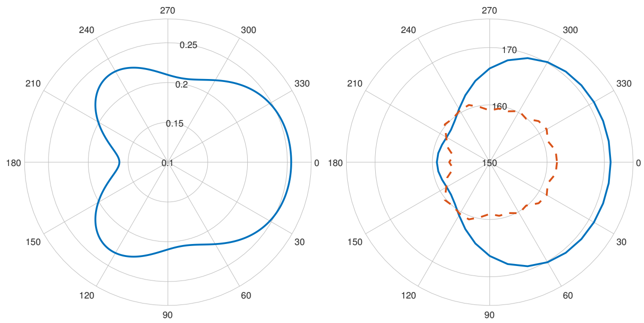


Figure 5: Weber radius and peak level per angle of exit (blue curves)

The Weber radii and peak levels resulting from these 10 parameters are shown above the angle of exit in Figure 5. The red dashed line corresponds to the peak levels that result directly from the Weber radii.

Examination of the Source Models

In this section, the source models presented are examined with regard to their applicability in the vicinity of the muzzle. For this purpose, the predicted hearing load as well as the sound pressure time curves and frequency responses are considered.

Predicted hearing load

The AHAAH model[7] used to determine the hearing load was developed explicitly for shooting noise. It is an appropriate damage risk criteria and is currently used by the US military, among others[8]. The AHAAH settings unwarned, no hearing protection and frontal sound incidence were used consistently for all calculations.

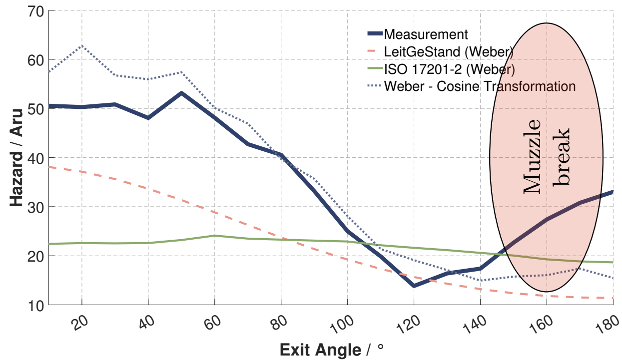


Figure 6: hearing load above the angle of exit[2]

From Figure 6 it can be seen that the predicted hearing load of the measurement signals decreases with increasing angle until the influence of the muzzle brake from ≈ 140° causes it to increase again. The values according to the LeitGeStand model also fall with the angle of exit, but significantly underestimate those of the measurement. According to ISO 17201-2, the hearing load is approximately constant over the angle of exit and is also significantly lower than the target values. With the III. method, the two stage cosine transformation, an appropriate and conservative exposure is predicted for angles $< 140°$. The cause of the enormous deviations of the standardized source models I and II compared to the measurement signals is considered in the following subsection.

Reconstructed muzzle blasts

In Figure 7 to Figure 9 the sound pressure time curves and frequency responses of the source models and measurement signals at representative measurement points are discussed. It is clear from the signal curves that the source models I and II increasingly overestimate the peak levels as the angle of exit increases. The deviations are up to 6 dB at the positions considered here. The spectra show that the standardized source models generate significantly too low-frequency signals for all angles of exit. With regard to the III. method, both the frequency responses are reconstructed realistically and the peak levels deviate only slightly from those of the measurement.

[2] The angle-dependent hearing load from the Weber blasts according to ISO 17201-2 leads to interesting artifacts with regard to the AHAAH model. The hearing load remains approximately constant, although the peak level increases by approximate 9 dB over the angle of exit. This suggests that the energy shift associated with the level decrease towards higher frequencies causes an increase in the risk of hearing damage, which roughly equalizes the level decrease

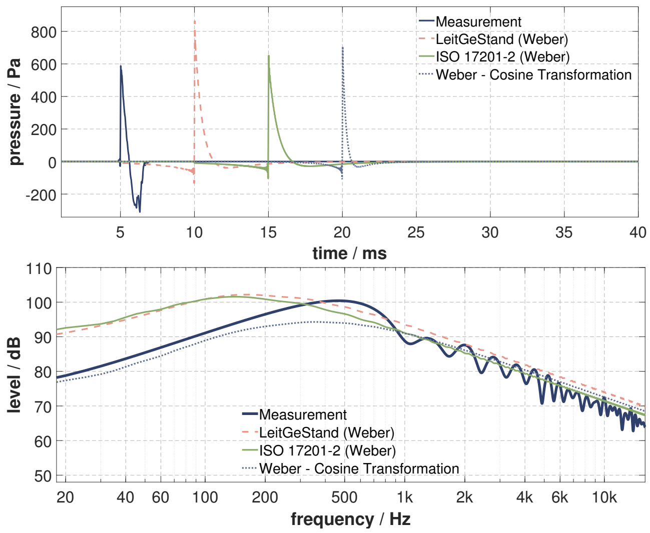


Figure 7: Sound pressure time curve and frequency response under 10° in 10 m distance

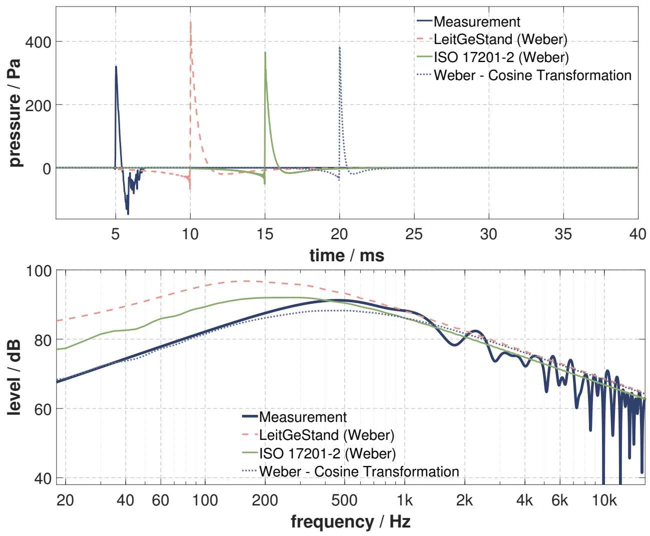


Figure 8: Sound pressure time curve and frequency response under 90° at 10 m distance

Conclusion

The standardized models I and II predict too low-frequency signals at a distance of 10 m from the muzzle, regardless of the angle. In the LeitGeStand method, this results from neglecting the frequency-dependent directivity. The source model according to ISO 17201-2 takes into account the frequency dependence of the muzzle blast, but is designed for too low a frequencies. Consequently, the standardized source models do not provide appropriate signals for calculating the risk of hearing damage in the vicinity of the muzzle.

From Figure 5 it is also clear that at least two parameters must be determined directionally with the Weber model in order to synthesize realistic muzzle blasts in the close range of the weapon. If, for example, only the Weber radius is set as angle-dependent, the peak levels of the reconstructed signals are too low by up to 10 dB.

The III. method addresses this aspect. With the two

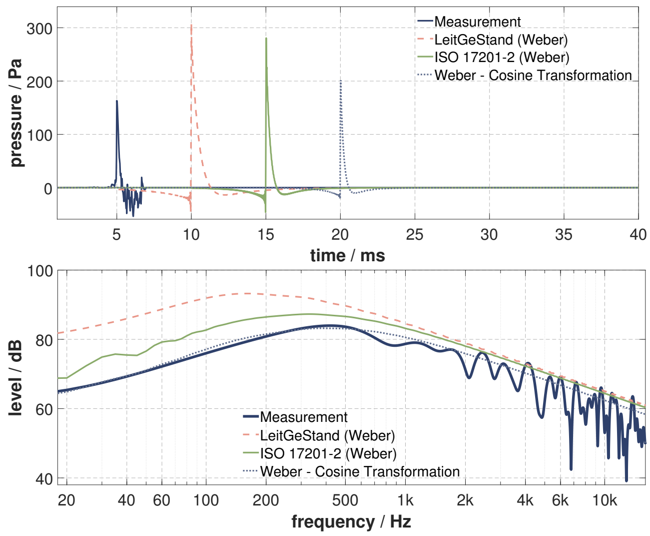


Figure 9: Sound pressure time curve and frequency response under 130° at 10 m distance

stage cosine transformation, realistic signals can be generated at 10 m muzzle distances. This source model also enables an appropriate and conservative prediction of the hearing loads.

Acknowledgments

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