Acoustic Considerations within a Tendering Procedure for the Construction and Upgrading of Military Firing Ranges

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Introduction

Military firing ranges are usually set up outdoors. However, due to noise issues affecting nearby areas, there is a growing shift toward indoor shooting facilities. This change, while reducing external noise pollution, results in increased noise exposure for personnel inside these facilities. When planning shooting ranges, the first priority is to ensure internal and external shooting safety. Acoustics therefore take second place, with two main objectives being pursued: minimising noise exposure for personnel to protect their hearing and reducing noise nuisance for the surrounding population. Ideally, these acoustic factors are incorporated early in the design phase. This paper discusses the practical implementation of the acoustic directive *Acoustic Safety* of the armed German forces, covering material and measurement standards. It presents insights and results from a recent competitive dialogue where various companies had the opportunity to create acoustic wall and ceiling solutions for indoor shooting ranges.

Acoustic Safety

Since 2022, the appendix Anwendung Baulicher Lärmschutz für Schießanlagen der Bundeswehr der Baufachlichen Richtlinie (BFR) [1] (Application of structural noise protection for Bundeswehr firing ranges of the Bundeswehr Construction Guideline) is available, which was initiated by IUD I 5 of the German Ministry of Defense. The appendix is currently divided into the parts Akustische Sicherheit (*Acoustic Safety*) and Immissionsschutz (*Immission Control*).

The BFR chapter *Acoustic Safety* describes the procedure for classifying a shooting range[1] with regard to its additional hearing exposure due to the structural conditions. The facility under investigation is compared with a reference facility. The decisive factor here is that hearing exposure data for various weapon, ammunition and hearing protection combinations is available for open facilities with only a very small number of reflective surfaces (reference facility). However, this data cannot be transferred directly to indoor firing ranges or open ranges with a higher degree of protection. A conversion factor is required.

Quality Number

The so-called quality number Q_S represents the factor used to calculate the permissible number of shots in a facility with an increased number of reflections. It indicates the percentage by which the maximum number of shots must be increased or reduced to ensure the same hearing exposure as on a reference shooting range:

$$Q_S = \frac{N_S}{N_A}. \tag{1}$$

Here, N_A denotes the maximum number of shots on a reference shooting range, while N_S represents the maximum number of shots determined at a relevant shooter position on the investigated shooting range. Usually, an open shooting range with inclined sidewalls serves as the reference shooting range. The quality number can be determined through both prediction and measurement. The required shot numbers N_S and N_A are calculated from predicted or measured sound pressure time histories using the AHAAH model [2].

Load Classes (Belastungsklassen)

According to table 1 the quality number Q_S is classified into load classes. The table shows the relative number of shots for each load class A to F.

Table 1: Classification of the load classes.

Class	Quality Number	Relative number of shots
A	$0{,}9 \leq Q_S$	90 %
B	$0{,}7 \leq Q_S < 0{,}9$	70 %
C	$0{,}5 \leq Q_S < 0{,}7$	50 %
D	$0{,}3 \leq Q_S < 0{,}5$	30 %
E	$0{,}1 \leq Q_S < 0{,}3$	10 %
F	$0 \leq Q_S < 0{,}1$	0 %

Determination of the Quality Number

The hearing exposure of the training personnel is crucial for assessing the acoustic safety of a system. As shown in Figure 1, the sound pressure time histories are determined at the assessment positions P_{B1} and P_{B2}. The first position is assumed to be one meter away, while the second is two meters away from the shooter position P_S. The muzzle — depicted as a red star in Figure 1 — is located 1 m in front of the shooter position P_S.

For a standing shooter, the muzzle is at a height of 1.6 m, whereas for a prone shooter, it is at a height of 0.2 m. This also influences the height of assessment position P_{B1} but does not affect P_{B2}. Crouched shooting positions are not considered.

Reflective Properties

The accurate consideration of reflections within a facility is a fundamental prerequisite for the entire procedure presented here. Since absorption coefficient measurements from reverberation chambers provide insufficient key figures for surface materials when used to mitigate shooting

[1] This applies to shooting ranges as well as shooting rooms

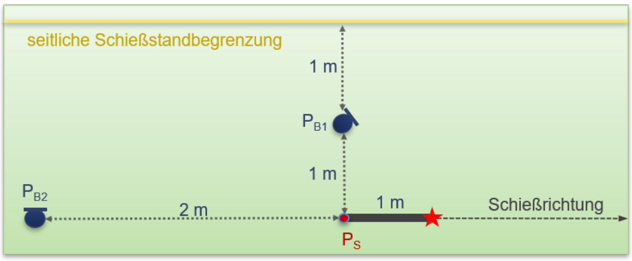


Figure 1: Assessment positions top view

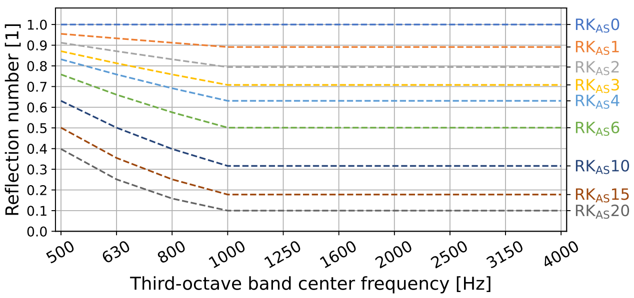


Figure 2: Third-octave specific reflection values of the reflection classes.

noise, a standardized method was selected to meet these specific requirements.

DIN EN 1793-5:2018-12 [3], a standard commonly applied in road construction, was utilized. Additionally, purpose-driven simplifications were introduced to allow for smaller sample sizes. Near-field holography methods are also permitted [4]. However, the overriding principle remains that measurements conducted according to DIN EN 1793-5 take precedence if both methods are used.

Reflection Classes

After determining the angle- and frequency-dependent reflection properties, the wall and ceiling systems are classified into the so-called reflection classes according to Figure 2 (Reflexionsklassen). The reflection coefficient shown in the figure corresponds to the measured reflection coefficient. To meet a specific reflection class, the values for each third octave between 500 Hz and 4 kHz must remain below the corresponding horizontal curves in Figure 2. For instance, to satisfy reflection class $RK_{AS}6$, a wall system must have a reflection coefficient of at least 0.5 in the frequency range from 1 kHz to 4 kHz. Below 1 kHz, the requirements are slightly lower, as this frequency range is less critical in terms of hearing hazard.

The use of reflection classes offers significant advantages, particularly during the planning process. The system operator specifies certain requirements for capacity utilization, which determine the necessary quality parameters. Computer-aided forecast calculations are then used to determine the minimum reflection classes that the various surfaces of a shooting range must meet in order to fulfill these requirements.

Competetive Dialogue

In the competitive dialogue presented here, a quality number Q_S of 50 % was defined to achieve the intended utilization of the planned facility. To meet this value, the wall and ceiling systems must comply with specific acoustic reflection classes (RK) according to the requirements of *Acoustic Safety*. These reflection classes were determined in advance through computer simulations.

The geometry of the shooting range, which is shaped by the planned training and exercise scenarios, plays a crucial role in this process. The specially developed web application *Chaser* [5] utilizes three-dimensional CAD models of the shooting range to accurately assess sound propagation. The location-dependent quality factor is then optimized by adjusting the reflection classes of the wall and ceiling systems.

The model of the specified shooting range used in the analysis is 66.5 m long with a constant width of 16 m. The ceiling height was estimated to be 3.80 m. In general, small components such as doors or lamps, as well as movable structures, were disregarded, and only larger, solid building enclosure elements were considered.

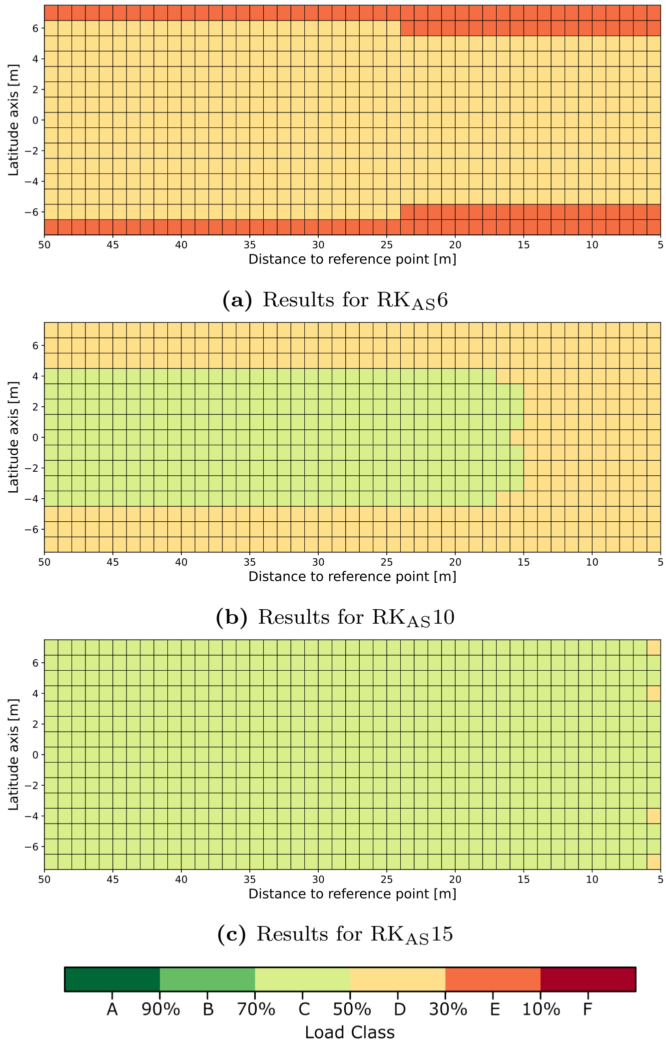
All surfaces were assigned reflection classes (RK_{AS}) to evaluate quality numbers using the application *Chaser*. By varying the reflection classes of wall and ceiling elements, the impact of the acoustic properties of surface materials on hearing exposure becomes evident. During this process, the reflection classes of the floor and the surfaces within the bullet trap chamber remained unchanged. Thus, in the model, the bullet trap chamber was treated as an empty space with sound-reflective surfaces that meet the criteria of reflection class $RK_{AS}0$. A conservative estimate was also applied to the floor, which was therefore assigned $RK_{AS}0$ as well. For each simulation run, the rear wall, side walls, and ceiling were successively assigned the reflection classes $RK_{AS}6$, $RK_{AS}10$, and $RK_{AS}15$.

To determine the quality number, the hearing exposure on an open shooting range was used as a reference and compared with the hearing exposure inside the shooting room. In this case, the only relevant reflective surface was the gravel floor, which was measured and classified under reflection class $RK_{AS}6$.

For the *Chaser* simulations, a pistol class with a standing firing position was used as the sound source, while $P_{B,2}$ served as the assessment point, as shown in Figure 1. The hearing impairment risks required to calculate the quality number were determined using the AHAAH model [2]. The AHAAH settings unwarned, no hearing protection, and frontal sound incidence were applied consistently for both free-field and indoor simulations.

Determination of Requirements

With the previously defined boundary parameters, the next step was to determine the location-dependent quality number in the indoor shooting range, considering the influence of surface cladding. The personnel load maps for the different shooting room variants are shown in Fig-



(a) Results for $RK_{AS}6$

(b) Results for $RK_{AS}10$

(c) Results for $RK_{AS}15$

Figure 3: Personal load maps of representative surface cladding variations.

ure 3 for the assessment point $P_{B,2}$, which is located 3 m behind the muzzle. These maps indicate that, at a minimum, wall and ceiling systems meeting $RK_{AS}10$ must be installed to achieve load class C in the center of the room. This would allow for 50 % of the shots compared to the reference system.

Available Products

Existing surface cladding systems were tested. The reflectance values of expanded glass granulate panels, glass wool panels and wood wool panels (whose sound absorption coefficient α_W is between 0.7 and 0.95) were measured as 18 mm to 40 mm thick cover layers on approximately 50 mm mineral wool. The classification of these systems into reflection classes showed that the expanded glass granulate panel system is assigned to $RK_{AS}1$, the glass wool panel system to $RK_{AS}4$ and the wood wool panel system to $RK_{AS}3$. No product was found that meets the requirements for interior fittings.

Product Development within the Competitive Dialog

In order to find a suitable product for the surface cladding of the ceilings and walls, a competitive dialog was initiated. In this process, the client and the applicant work together to find solutions on the basis of which the applicant can then submit a bid. Out of nine applicants, five were selected on the basis of business parameters such as company size, experience with shooting ranges or field of activity.

In the next phase, preliminary acoustic tests were carried out. These were used to estimate the reflection properties of individual samples for the special case of shooting noise. A measurement system based on near-field holography was used as an alternative measurement method to DIN EN 1793-5[3][1]. The measuring probe specially developed for this application enables sound field separation and the associated determination of a complex reflection factor.

Various panels made of mineral wool, glass wool, wood wool, melamine resin foam and PET acoustic fleece were tested as materials. Combinations of the individual materials were also measured. Several of these products achieved the required reflection class $RK_{AS}10$ and some even almost achieved $RK_{AS}15$. The problem with these acoustically permissible systems was that the top layers were not robust enough to be used in shooting ranges. This gave rise to the task for the companies of finding a combination between a hard and robust top layer and the acoustic requirements.

All companies had the opportunity to have their revised systems measured again. This process revealed that PET acoustic panels were the most promising materials for the top layer. Additionally, valid arguments for and against the inclusion of individual companies in the next stage of the competitive dialogue were evaluated.

For the final stage, two remaining companies were asked to build a prototype measuring 3.6 m × 2.4 m. The build-up depths of the prototypes ranged from 170 mm to 250 mm, with the individual material layers being a maximum of 60 mm thick. The top layer panels of the multilayer systems, approximately 1000 mm × 500 mm in size, were clamped with hat profiles about 30 mm wide. These constructions met the requirement for standardized measurements based on DIN EN 1793-5 [3]. Once again, the prototypes were also measured using the near-field holography method with the measuring probe.

Final Stage

Two measurement and optimization rounds were required in the final stage. In the first round, only one of the five measured prototypes met the requirements of the competitive dialogue. As an example, the third-octave band-dependent reflection coefficients of such a system are shown as the blue line in Figure 4. The curve indicates that the reference value for the 3.15 kHz third-octave band is exceeded.

Fortunately, individual areas of the test structures could be examined more closely using the near-field holography measuring probe [6]. The cause of the phenomenon at 3.15 kHz was identified as the hat profiles with a width of 30 mm, which corresponded to approximately 1/4 of

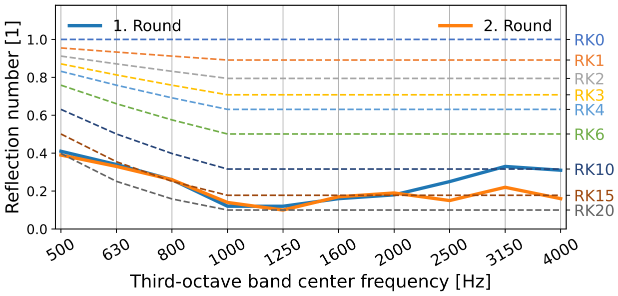


Figure 4: Third-octave band-dependent reflection coefficients of a prototype according to DIN EN 1793-5 before and after optimization.

the wavelength of the critical frequency band. As shown in Figure 5, the hat profiles were subsequently filled with PET fleece strips. Following measurements demonstrated that these strips addressed the issues at 3.15 kHz (orange line in Figure 4).

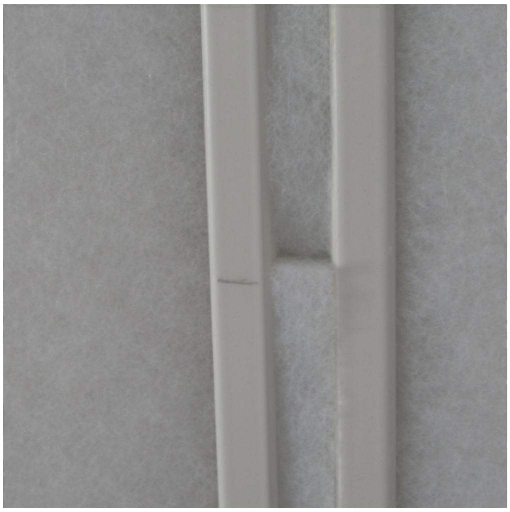


Figure 5: Hat profile with PET fleece strips.

Final Evaluation

The final personnel load map - which was deducted by using the measured reflection values inside the *Chaser* simulation - in Figure 6 shows that for the observation point $P_{B,2}$ in the middle of the room 70 % and otherwise 50 % of the shots of the reference system are permissible.

This means that the desired target from Figure 3c is even exceeded with the actual RK10 system. The reason for this lies in the combination of the 315 Hz weapon center frequency of the pistol class and the frequency range relevant for shooting noise, which spans 1 kHz to 4 kHz. As a result, the frequency range around 1 kHz is particularly critical, as the source signal still exhibits relatively high energy in this range, coinciding with the onset of the sensitive range in the AHAAH model.

In Figure 4, the frequency-dependent reflection loss of 1 kHz to 1.25 kHz, measuring approximately 20 dB, is significantly better than that of RK15. This also explains the higher quality numbers.

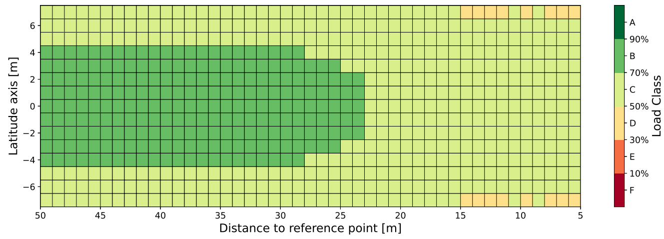


Figure 6: Personal load map for the final product

Conclusions and Outlook

The relationship between the surface cladding, the permissible number of shots, and the associated optimization possibilities was clearly demonstrated.

A metrological validation of the personnel load maps through shooting noise measurements could not yet be carried out in this project, as the facilities are still under construction. Since *Chaser* consistently provides conservative predictions, the actual facility may achieve even better quality numbers.

The floor and bullet trap represent the most significant factors for further reducing hearing exposure in indoor shooting ranges. These surfaces have not yet been acoustically optimized and are therefore acoustically reflective. Even small improvements in these areas could lead to significantly higher quality numbers.

ACKNOWLEDGEMENTS

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