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Room acoustic modeling and auralization at an indoor firing range

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Reverberation time measurements were conducted in the 21-lane indoor firing range at Wright Patterson Air Force Base. Long reverberation times resulted in poor speech transmission indices (STI) which required acoustical treatments within the range. After treatment, reverberation times were significantly reduced and STI was dramatically enhanced. Standard Sabine and Eyring models failed to accurately predict the reverberation times. A computer simulation of the range was developed to predict room acoustic conditions and auralize speech performance for perceptual evaluation in the range. https://doi.org/10.1121/1.5132286

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I. INTRODUCTION

This paper reports reverberation time measurements and a simulation of room-acoustic conditions before and after noise control treatments in an indoor firing range. The simulations also provide auralizations for auditory evaluations of the treatment efficacy.

Noise exposures for law enforcement officers and military personnel who train and qualify in the use of small-caliber firearms at indoor firing ranges can be excessive (Fausti *et al.*, 2009; NIOSH, 2009). Kardous *et al.* (2003) reported on the noise exposures at a typical indoor range. Kardous and Murphy (2010) proposed possible noise control treatments for indoor firing ranges. Jokel (2013) evaluated the noise exposures for military personnel in a treated and an untreated firing range. Based upon the 8-h A-weighted equivalent energy (L_{Aeq8}) of gunshot recordings from the two ranges, the acoustically treated range was predicted to allow as many as two to five times more rounds to be fired before a shooter would reach a 100% daily dose (85 dBA) compared to the untreated range. Peak impulse levels do not change significantly with treatment conditions because they are largely the consequence of the direct path from the muzzle to the ear. Equivalent energy is determined as an integral over a time period and can incorporate the effect of the reverberant field.

Indoor firing ranges for law enforcement and military personnel typically have a range instructor and range controller. The range instructor directs the personnel when to commence and cease firing and when to load and secure weapons. The range controller directs the range instructors regarding the sequence of qualification exercises. Miscommunication and unintelligible commands pose a potentially lethal risk for all persons in the range. Acoustical treatments reduce the reverberation times, lower the noise exposures for personnel, and improve the communication efficiency within the range.

Geometrical room-acoustic modeling has been well developed over past decades (Savioja and Svensson, 2015). This paper applies a room-acoustic simulation model to estimate room-acoustic parameters, including reverberation times and speech transmission indices for a 21-lane indoor firing range. Speech transmission indices are calculated and contrasted for the treated and untreated firing range. Comparisons of the room-acoustic simulation results with the Sabine and Eyring theory is also highlighted. The room-acoustic simulation model is used to create binaural auralization samples of the speech transmission within the firing range in the treated and untreated condition.

This paper is organized as follows: Sec. II describes measurement methods and the simulation methods. Section III describes the results for the reverberation times and speech transmission indices, and Sec. IV discusses the implications of these findings.

II. METHODS

In 2009, acoustical treatment was undertaken for the 2-lane and 21-lane indoor firing ranges at the Wright Patterson Air Force Base (WPAFB), Combat Arms Training Facility (CATF). National Institute for Occupational Safety and Health (NIOSH) personnel conducted pre- and post-treatment noise surveys to measure gunshot noise and to evaluate the reverberation times in both ranges in November 2009 and February 2010, respectively. In November 2012, a third room-acoustic assessment was conducted in the 21-lane firing range with a research team from Rensselaer Polytechnic Institute (RPI) to develop a more accurate room-acoustic simulation model of the range for both objective and subjective evaluations. The RPI survey measured the room impulse responses of the ranges using maximum length sequences. (Xiang and Schroeder, 2003) Since the 21-lane

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indoor range presents as big flat enclosure, much more challenging than the 2-lane range in terms of experimental measurements and computer simulation (Jing and Xiang, 2008), only the measurements and results from the 21-lane range are reported.

A. Overview of the training facility

The WPAFB CATF 21-lane firing range is designed for group training and qualification exercises. Before the acoustic treatment, the interior of the range had poured concrete walls, a finished concrete floor and armored plating along much of the ceiling and some of the walls. Figure 1 illustrates the layout of the CATF. The range is 36.6 m long and an armored bullet trap comprises the last 6.1 m. The bullet trap is shaped like an isosceles triangle, reaching a height of about 3.0 m at their opening with slanted armored panels meeting at half this height, 6.1 m downrange. For 7.3 m before the bullet trap, the walls of the range are armor plated. The safety ceiling above the shooters is armor plated and extends for most of the length of the range. Above the shooters, the safety ceiling is approximately 2.7 m and increases in height to 3.5 m about 7.0 m downrange. This elevated ceiling then extends to a distance of about 24.4 m downrange.

After the acoustical treatment, the entirety of the safety ceiling and baffles, as well as the back wall and the first 22.6 m of the side walls were covered in 5 cm thick sound absorbing boards (Troy Board$^{\mathrm{TM}}$) with a 3.8 cm layer of sound absorbing batting (Troy Wool$^{\mathrm{TM}}$) behind. Figure 2 shows a layout of the range.

Due to the complexity of the space, the room-acoustic simulation model can only approximate the range with some necessary details of the geometry, but a better estimate can be achieved with fine adjustments to the material properties. The space above the safety ceiling is coupled to the occupied portion of the range. The openings into the space are treated as surfaces with nearly perfect absorption. The sound projected into this space is assumed to be completely absorbed by the exposed absorbing materials in this space. Figure 2(B) does not illustrate the additional space above the overhead baffles. The ceiling of the building was 5.7 m high and the baffles were at 3.7 m above the floor.

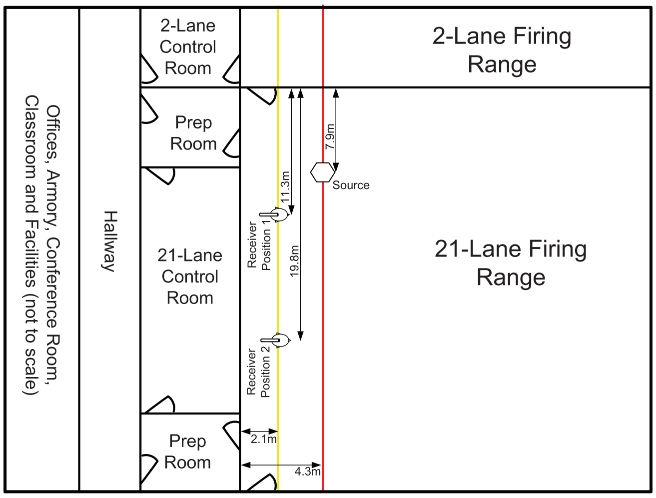

FIG. 1. This image gives the approximate configuration of the WPAFB CATF indoor firing ranges. The range areas and control rooms are to scale, the hallway and other rooms are not to scale.

B. Data acquisition system

Measurements conducted in 2009 and 2010 were performed with a Peavey Stage speaker and a power amplifier driven by one-third octave bands of noise with center frequencies at 100 to 10 000 Hz. The source was turned on for at least 30 s and turned off while the measurement microphones were sampled. The speaker was located in lane 11 and the four 1/2 in. Brüel and Kjær 4165 microphones sampled at 100 kHz, 16-bit resolution and ±10 V range. The microphones were sequentially placed in each of the lanes (e.g., lanes [1, 10, 12, 21] or lanes [3, 10, 12, 19]). The time constants for each third-octave band were determined by fitting the amplitude envelopes of the reverberation decay curves. The average and standard deviation of the reverberation times across all lanes were calculated at each frequency band. The 95th percentile confidence intervals were determined as 1.96 times the standard deviation.

In 2012, a single-channel source drove a pair of high-frequency and mid-frequency omnidirectional dodecahedral speakers and a subwoofer. The input signals were maximum length sequences. The receiver station was a 4-channel system consisting of an Earthworks M30 BX omnidirectional microphone, a Schoeps CMC 6 U adjustable microphone with omnidirectional and figure-eight settings, and a Head Acoustics MHS-II.1 measurement system for collecting binaural recordings. Through well-controlled acoustic excitations using maximum length sequences, and four receiving channels, the experimental measurements were able to derive room impulse responses of the range and therefore a number of relevant room-acoustic parameters, such as the reverberation time (RT_{60}) and speech transmission index (STI). Binaural room impulse responses were prepared for later comparison of auralization. Two measurements were taken with the source located on the firing line in stall 6, with the receiver located on the yellow waiting line (see Fig. 2) behind stall 16 for the first test and stall 9 for the second test.

C. Room-acoustic modeling

The purpose of the room-acoustic simulation is to create a good approximation of the space with a computer model and to replicate the acoustics of the space. The computer modeling employs a cone-tracing-based approach within a hybrid, geometrical acoustics framework originally proposed by Vorländer (1989), and further developed by (Dalenbäck, 1996). This method is implemented within the CATT acoustic modeling tools as The Universal Cone-Tracer (TUCT) (CATT, 2010) which includes several different efficient algorithms. Particularly it offers effective ways to predict and auralize big indoor venues with high absorption which is exactly the case of the current study. The cone-tracing algorithms are based on various levels and combinations of actual and random diffuse ray splits and are universal so that as the algorithms are further refined and computer speed increases as additional levels of actual ray splits are

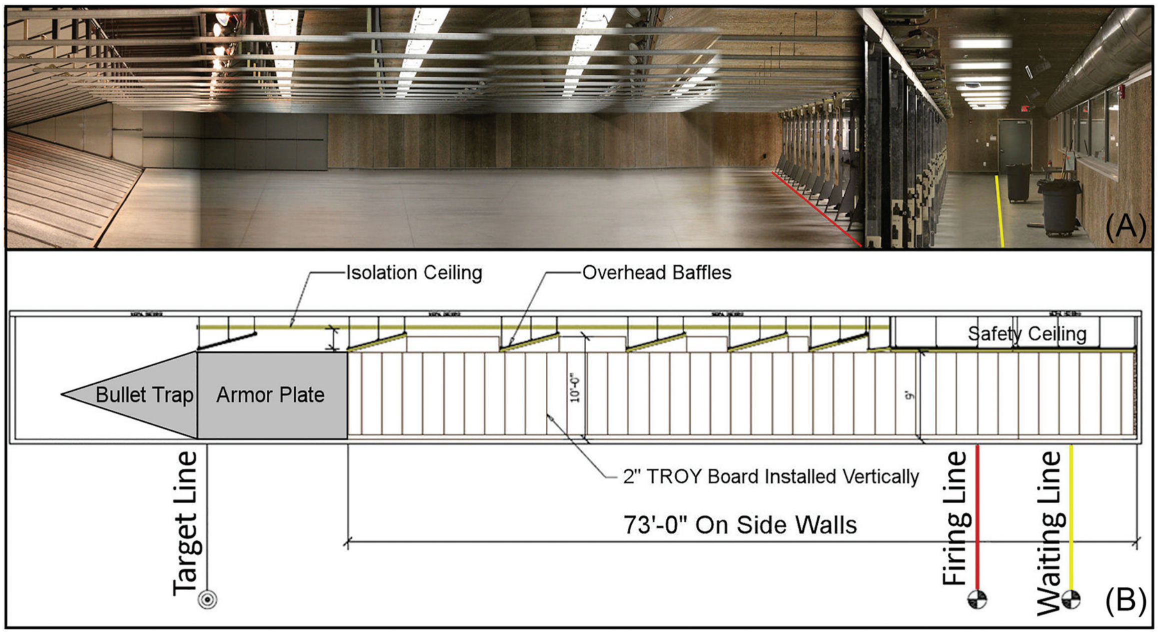

FIG. 2. In panel A, an elevation view of the 21-lane firing range. Photographs of the firing range were stitched together to create a composite of the range corresponding to the architectural drawing. The yellow waiting line is evident on the right of panel A, just in front of the garbage can. In panel B, the isolation ceiling, safety ceiling, side walls and overhead baffles of the firing range were acoustically treated in the 21-lane ranges. The firing line and target lines are indicated in panel B.

incorporated. Armed with an accurate model, one can investigate the effects that the treatments might have on the room-acoustic properties. The absorption coefficients of the materials are taken from the CATT Acoustic material library and the Troy Acoustics test reports (CATT, 2010; Riverbank Acoustical Laboratories, 2011). A classical room-acoustic models for the range was developed based on the measurements in 2009 and 2010.

D. Auralization

Binaural auralizations were produced to provide comparisons of the perceptual changes in the 21-lane range due to the acoustic treatment. For the measured data in the treated firing range, room impulse responses are convolved with the same anechoic sound signals used in the modeled auralizations. Section IV discusses the comparison of these auralizations. For the untreated range, the room model with the fitted parameters was used to create auralizations from the parameters from the CATT-TUCT software.

III. RESULTS

From these geometries, acoustic models of the range are created in CATT-Acoustic and the Source/Receiver prediction module in CATT-TUCT (CATT, 2010) is employed to develop the auralizations of the spaces. The most detailed ray tracing option of the CATT-TUCT model is used to simulate the treated space resulting in the room impulse responses. For the untreated model, a more basic simulation option is used that generates fewer reflections to estimate the room impulse response (adding additional reflections for the untreated range would not significantly change the room response). Using these acoustic models, the RT_{60} and STI values are calculated. For the STI estimation, the measured background noise values are used. The RT_{60}, STI, and room auralizations are reported in Secs. III A and III B.

A. Room-acoustic parameters

Table I and Fig. 3 show the measured and modeled reverberation times for the treated and untreated 21-lane range. The untreated range averaged measurements from 2009 are shown as a dashed black line with the 95% confidence interval shown in gray shading. The treated range measurements from 2010 are shown as a dotted black line with the confidence interval in gray shading. The measurements using the MLS sequences from 2012 are shown with purple diamonds. The initial model results are shown as blue triangles pointing downwards and the model results after the parameters were modified are shown in green upwards pointing triangles. Since the measurements in the untreated range could not be repeated when the RPI personnel conducted the

TABLE I. Comparison of predicted reverberation times from the Sabine, Eyring, and computer models at octave band frequencies with the measured values.

Method	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Untreated Sabine	1.25	0.60	0.55	0.45	0.41	0.40	0.36
Untreated Eyring	1.20	0.48	0.42	0.35	0.31	0.30	0.25
Untreated model	4.69	4.54	3.78	3.40	2.99	1.91	0.98
Untreated measured	3.02	3.70	3.07	2.72	2.47	1.82	0.92
Treated Sabine	1.30	0.60	0.54	0.45	0.41	0.39	0.32
Treated Eyring	1.20	0.48	0.43	0.35	0.30	0.29	0.25
Treated model	0.63	0.49	0.73	0.67	1.21	0.54	0.71
Treated measured	1.47	1.06	1.14	1.16	0.91	0.70	0.37

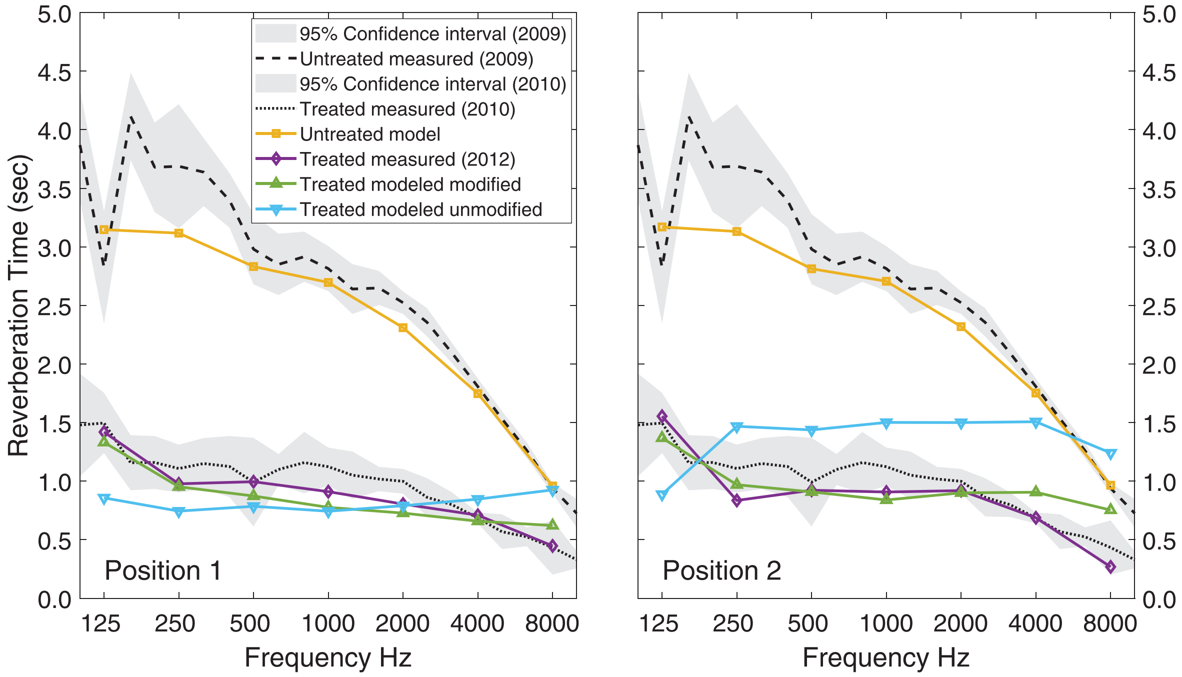

FIG. 3. Measured and predicted reverberation times, RT_{60}, for the treated and untreated 21-lane firing range at two different microphone positions.

room-acoustic measurements, the measured reverberation times from the NIOSH data previously collected in 2009 and 2010 are used for the untreated range at the positions that most closely match the recent ones. Table I indicates that the Sabine and Eyring equations fail to predict correct reverberation times.

The CATT-TUCT model produced reasonable estimates for the measured data (see Fig. 3). The greatest discrepancies were at 125 and 250 Hz for the untreated range. For the treated range, the differences were greatest at 8000 Hz. Variations in the exact source and receiver placement are the likely cause of these differences. For this case, the rough approximation is deemed satisfactory. Without significant modifications to the material compositions, a more accurate result would be unlikely. The CATT-TUCT predictions clearly provide a better approximation to the actual reverberation times of the treated space than the Sabine or Eyring equations, which are not applicable to long and flat spaces (Kang, 2017).

Table II lists the STI values for the treated/untreated models at both measurement positions as well as the STI calculated for both experimental measurements. The model slightly overestimated the STI value for the room by 0.05 in the first measurement and by 0.12 in the second measurement. However the IEC quality rating for both cases is the same and showed the same degree of improvement over the untreated modeled results (IEC 60 268-16, 2011).

TABLE II. Speech transmission index (STI) values (and IEC 60268-16 quality rating) and for measured and modeled 21-lane range.

Measurement position	Treated measured	Treated modeled	Untreated modeled
1	0.69 (good)	0.74 (good)	0.36 (poor)
2	0.83 (excellent)	0.95 (excellent)	0.47 (fair)

B. Binaural auralizations

Auralizations of the range are created from the CATT-Acoustic and CATT-TUCT modeling software (CATT, 2010) The talker remains in a fixed position in the firing range as the listener moves away from the speaker down and across the 21-lane firing range. Upon listening to Mm. (1) and Mm. (2), the virtual person moves about in the range, the acoustic treatment provides a marked improvement in 21-lane range. The simulations illustrate the effect of the reverberation within the untreated range and how it can degrade speech intelligibility.

Mm. 1. Talker in a fixed position while the listener moves across and down the 21-lane firing range without acoustic treatments. This is an mp4 file (0.94 Mb).

Mm. 2. Talker in a fixed position while the listener moves across and down the 21-lane firing range with acoustic treatments. This is an mp4 file (0.78 Mb).

IV. DISCUSSION

The standard Sabine and Eyring models fail to adequately predict the reverberation times for the 21-lane firing range due to the long and flat disproportionate dimensions. The measurement of the room's impulse response allows for the acoustic simulation of the treated room to be fit to the experimental data and then the acoustic treatments can be removed so as to arrive at the untreated auralizations. This acoustic model permits the comparison of the relative risk for hearing loss when firing weapons in an untreated versus a treated range. Using the impulse response for the range, anechoic recordings of a gunshot could be convolved to estimate the noise at multiple locations. Anechoic gunshot recordings are difficult to obtain because reflections from the shooter or the gun stand, the ground or shooting platform will inevitably exist. They would require time-windowing or other modeling to remove the reflections.

A follow-on analysis of gunshot recordings from the WPAFB CATF could examine the change in the noise-dose that might be expected for a single shooter or multiple shooters in the firing range. The reduced reverberation should lower both the L_{Aeq8} predicted doses. Brueck *et al.* (2014) reported on measurements from an untreated indoor firing range versus outdoor firing range where the same weapons were evaluated with the same recording system. For comparable peak impulse levels at the instructor position, the M4 rifle with a peak impulse level of 149 dB in both environments yielded an unprotected L_{Aeq8} of 83 dB for the indoor range and 77 dB for the outdoor range, a 6-dB difference.

Because of the high levels of firearm noise, 150 to 170 dB peak sound pressure level (SPL) at the shooter's ears, clear instructions are given prior to any shooting exercise. When multiple shooters are using the range, the communication from the range master and the instructor(s) to the shooters is important. While conducting the noise surveys in 2009 and 2010, one of the range instructors was asked about the utility of the level-dependent earmuffs that were available for shooters to use. The response was enlightening. Before the range was treated, the level-dependent earmuffs were essentially useless. Communication within the range was difficult due to the long reverberation time. The instructor elaborated that after the range was treated, he found that the level-dependent earmuffs did not impair communication with personnel within the range and afforded protection from unexpected discharge of a weapon.

V. CONCLUSIONS

Overall, the room-acoustic models of the range are effective in estimating the relevant room-acoustic parameters of the space, such as reverberation times and speech transmission indices (STIs) at least within the mid frequencies. While the simulation models are not perfect they provided a much closer approximation than is possible using the Eyring and Sabine equations. Likewise, the STI values for the treated cases, while showing a relatively large difference, agree for the IEC quality rating and show a similar difference from the untreated case. The auralizations show possibly one of the biggest discrepancies between the measured and modeled data through the lack of significant low frequency energy in the modeled case.

Regardless, the room-acoustic modeling reflect the marked improvement in STI and decrease in reverberant energy resulting from the acoustic treatment. The auralizations of the space before and after treatment help provide an auditory reference point from which similar modeling can be done for other spaces to determine the effect of a given amount of acoustical treatment and the types of effects it can produce.

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