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DESIGN AND ACOUSTIC CHARACTERIZATION OF A PSYCHO-ACOUSTIC LISTENING FACILITY

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The design, development, and acoustic characterization of the Psychoacoustic Listening Laboratory (PALILA) recently established at Delft University of Technology are presented in this manuscript. This laboratory comprises a soundproof room with a modular design and specialized audio equipment. Its primary objective is to conduct experimental investigations into the human perception of aeroacoustic noise sources, such as aircraft, drones, or wind turbines. Furthermore, PALILA is certainly suited for studying other sound sources (e.g. household appliances, ground vehicles, etc.). The manuscript outlines the fundamental characteristics of the facility (i.e. dimensions and materials). A thorough acoustic characterization is provided, including assessments of the background noise levels, reverberation time, free-field sound propagation, and transmission losses of the walls (with respect to the exterior). Overall, PALILA is deemed to be a suitable quiet environment to conduct high-quality psychoacoustic listening experiments.

Keywords: Listening experiments, Psychoacoustics, Human perception, Acoustic characterization

1. Introduction

Noise pollution represents the second-largest environmental health threat after air pollution, according to a report by the World Health Organization [1]. Excessive noise exposure not only causes annoyance, but also severe, irreversible health effects, such as sleeping disorders, hearing issues, and cardiovascular diseases [1]. An increasing number of industrial stakeholders are paying special attention to the sound signature of their products. Aircraft and wind turbines are particularly critical noise sources given their complexity, the amount of population affected, and the expected growth in both respective sectors [2].

Despite the importance of noise emissions, they are often underestimated and assigned a secondary role in conventional design processes. The acoustic footprint of devices, such as aircraft or wind turbines, is usually assessed during certification and (posterior) enforcement of environmental noise laws. Nevertheless, these procedures employ conventional, physics-based sound metrics based on the sound pressure level L_p, which have been criticized [3] for neglecting important sensitivities of the human ear to sound aspects [4], such as tonality, sharpness, etc. As a result, these conventional metrics often fail to properly model noise annoyance. Recent research [4–7] encourages combining novel sound quality metrics (SQMs) based on human perception into global psychoacoustic metrics to represent noise annoyance more accurately.

To firmly establish these novel SQMs as a more accurate noise annoyance assessment alternative than current approaches, it is crucial to conduct psychoacoustic listening experiments [4, 6–9]. Given

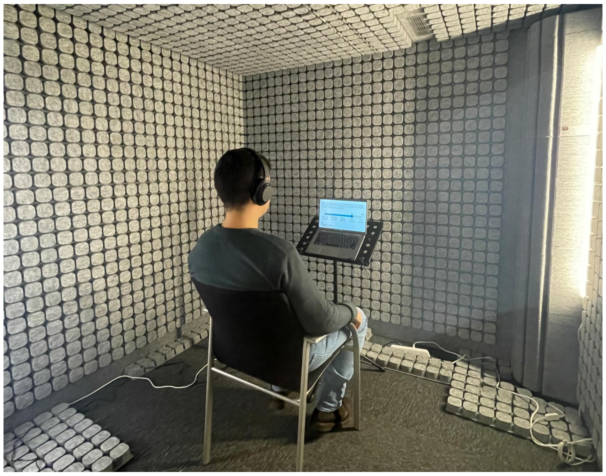


Figure 1: Example of a listening experiment performed inside PALILA.

the significant perceptual differences in the sound signatures of the different noise sources aforementioned (aircraft, wind turbines, household appliances, etc.), it is required to evaluate empirically whether any proposed noise-annoyance prediction model for a certain noise source is extendable and also valid for other applications. Psychoacoustic listening experiments require dedicated research facilities with suitable acoustic conditions (low background noise and, ideally, an anechoic environment) and the appropriate audio equipment.

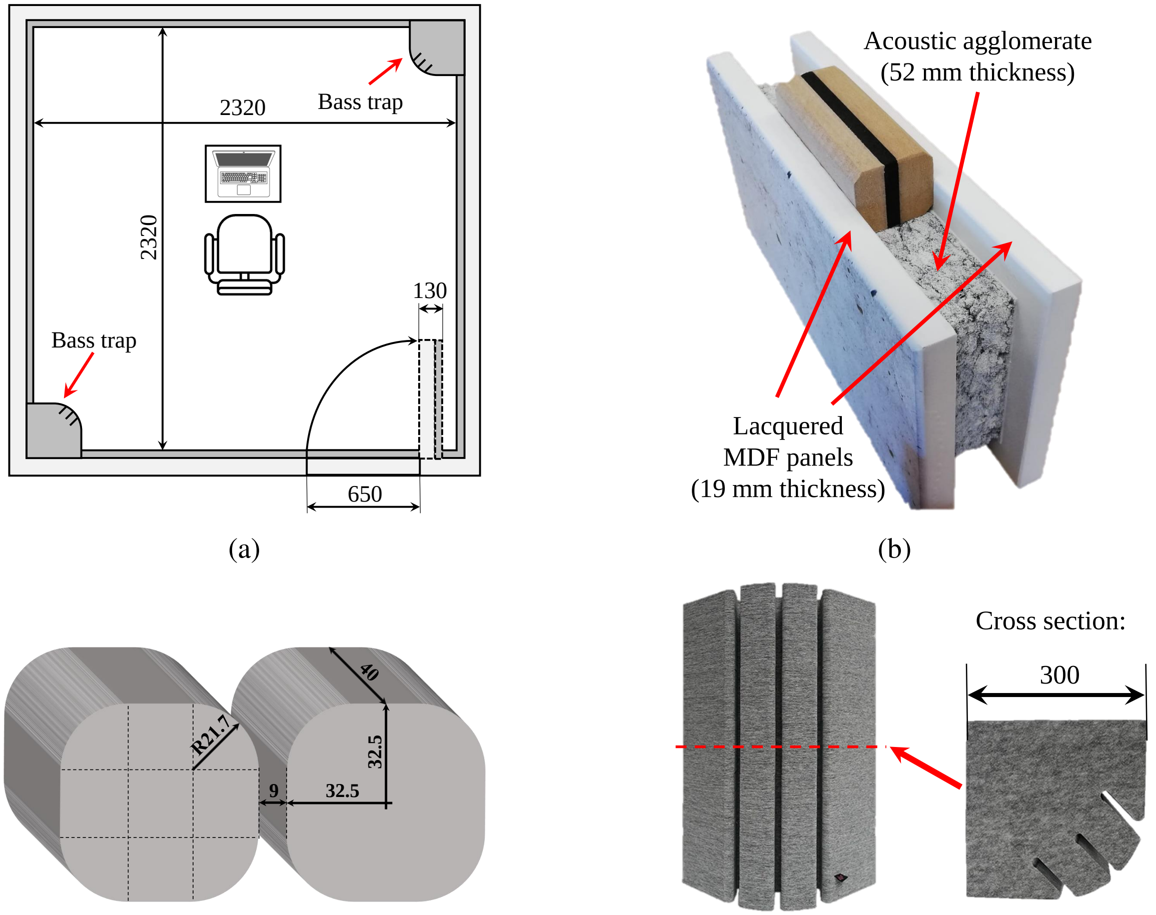
This manuscript describes the design and acoustic characterization of the PsychoAcoustic LIstening LAboratory (PALILA) at Delft University of Technology (TU Delft), see Fig. 1. The primary aim of this laboratory is to conduct empirical research on the human perception of aeroacoustic noise sources, such as aircraft, drones, or wind turbines. This facility complements well current experimental aeroacoustic research conducted at TU Delft in the anechoic wind-tunnel [10] or low-turbulence wind-tunnel [11] facilities.

The overarching goal of the facility is to investigate the societal impact of these noise sources, determine the main triggers for noise annoyance, and ultimately develop more accurate noise-annoyance prediction models with respect to current practice. These new models would be of paramount importance for more accurate environmental noise law enforcement and to enable future low-noise-annoyance designs.

2. Facility description

The design of PALILA is based on the box-in-box concept, which consists of a quiet, soundproof booth located inside a dedicated room at the Aerospace Engineering faculty of TU Delft. The interior layout of PALILA (accounting for the space taken by the acoustic absorbing padding on walls and ceiling) is a square plan form of 2.32 m (length) × 2.32 m (width) with a height of 2.04 m, see Fig. 2a.

The booth was manufactured by the company *StudioBricks* using 90-mm-thick modular wall bricks consisting of a double-wall sandwich structure with two outer lacquered medium-density fibreboard (MDF) panels of 19 mm thickness and an interior core of acoustic absorbing agglomerated polyurethane foam and fibers of 52 mm thickness made out of recycled denim and upholstery, see Fig. 2b. The laboratory has a 650-mm-wide, inward-opening door (Fig. 2a) made of the same materials as the wall bricks (Fig. 2b). The door has a special sealing system to ensure maximum sound insulation from the exterior. The ceiling and floor are made of the same sandwich structure shown in Fig. 2b. The whole booth is



(a) (b)

(c) (d)

Figure 2: (a) Top view of the listening laboratory (the light gray areas denote the wall bricks, whereas the darker gray areas indicate the acoustic absorbing foam panels), (b) cross-sectional view of a wall brick, (c) detail of the square shapes of the acoustic-absorbing foam panels, and (d) detail of the bass trap with the cross-sectional view. Dimensions expressed in millimeters.

connected to the floor of the exterior room via a vibration-damping system and the hollow volume below the floor is filled with *Akotherm Basic D40/50* sound-absorbing foam to prevent cavity resonances.

To minimize acoustic reflections inside PALILA, the inner walls and ceiling are fully covered with A-B-C-D level acoustic-absorbing foam panels (see Fig. 1). This setup also provides an almost-anechoic environment for the calibration of acoustic equipment, see section 3.3. These foam panels are made from recycled PET (polyethylene terephthalate) bottles converted into felt-like fibers and molded into rounded square shapes. The side of each square is 65 mm long, the rounded corners have a radius of 21.7 mm (i.e. one-third of the side), and the thickness of the square shapes is 40 mm, see Fig. 2c. The spacing between two neighboring square shapes is 9 mm. These foam panels are especially effective to absorb mid-to-high-frequency sound, particularly for frequencies higher than 500 Hz.

To also reduce low-frequency sound reflections, two sets of bass traps were placed in diagonally-opposite corners adjacent to the door's corner, see Fig. 2a and Fig. 2d. Each bass trap module is 300 mm (length) × 300 mm (width) × 600 mm (height) and has three vertical cut-outs to create a wedge-like structure, see Fig. 2d. To cover most of the interior height of the room (1.80 m), a set of three bass trap modules were employed in each corner. These devices are most effective in the frequency range between 200 Hz and 400 Hz. In addition, behind the foam panels, the ceiling is covered with a 50-mm-thick layer of Flamex Facet acoustic-absorbing foam with a weight of 475 g/m^2. The floor inside the booth is covered with a sound-absorbing loop-pile carpet with a weight of 460 g/m^2.

2.1 Sound reproduction equipment

PALILA is equipped with an audio reproduction system consisting of a *Dell Latitude 7420* laptop (with an *Intel® Core^{TM} i5-1145G7 vPro®* processor and 16 GB of RAM memory) connected to a set of *Sony WH-1000XM4* over-ear, closed-back headphones via a universal audio jack connector. These headphones enable binaural hearing and have a 40 mm diameter dome-type driver unit, a frequency response between 4 Hz and 40 kHz, and a sensitivity of 105 dB/mW at 1 kHz. The whole sound reproduction system is calibrated using a *G.R.A.S.* 45BB-14 *KEMAR* head and torso simulator.

In the current setup, participants in psychoacoustic listening experiments would sit on a chair placed in the center of the booth and input their subjective opinion after listening to each sound stimulus using the graphical user interface (GUI) on the laptop in front of them, see Fig. 1.

The principal aim of PALILA is to evaluate the human perception (e.g. short-term noise annoyance) of different noise sources, but in the near future, it is intended to expand its capabilities by implementing a virtual reality (VR) reproduction system to also investigate the visual impact of devices, such as drones or wind turbines, to provide more realistic scenarios, in which the noise source is both audible and visible.

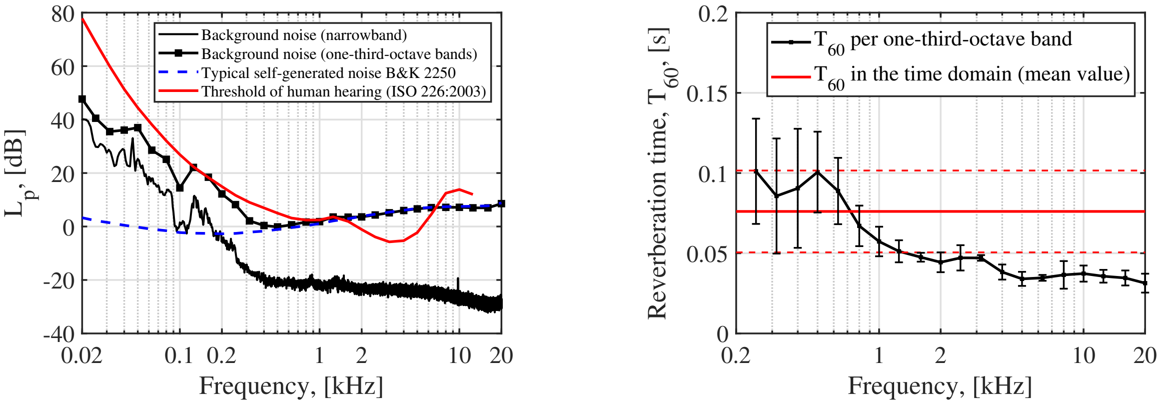
3. Acoustic characterization

This section describes the acoustic characterization experiments and the results obtained. The acoustic recordings were performed using a *Brüel & Kjær* 2250-G4 Sound Level Meter (SLM)/Analyzer calibrated externally and also with a *Brüel & Kjær* 4226 Multifunction Acoustic Calibrator. All sound recordings were 15 s long and were performed with a 24 bit resolution and a 40 kHz sampling frequency.

For the assessment of the free-field propagation and transmission loss of the walls, a *Visaton FRWS-5* 8-ohm speaker coupled to an amplifier and emitting broadband noise was employed as a sound source. The speaker has a frequency response between 150 Hz and 20 kHz and a maximum power of 3 W.

3.1 Background noise levels

The background noise levels inside PALILA were measured with the door closed and the SLM placed in the center of the facility at a height of 1 m. The frequency spectrum was estimated using Welch's method with time blocks of 1 s (i.e. 40,000 samples) with Hanning windowing with a 50% overlap. Hence, the frequency resolution Δf was 1 Hz. The measured noise levels are presented as sound pressure levels L_{p} in Fig. 3a as both narrowband (with $\Delta f = 1$ Hz) and one-third-octave frequency band spectra. The measured background noise levels are very low and of a broadband nature. For reference, the threshold of human hearing (in one-third-octave frequency bands) according to the ISO 226:2003 norm is also included in Fig. 3a. The measured background noise is below the threshold of human hearing for the whole spectrum, except for the range between 1.6 kHz and 6.3 kHz. However, the background noise levels inside PALILA are so low that the measured spectrum for frequencies higher than 500 Hz coincides with the typical noise floor of the SLM due to the self-generated noise (see dashed blue line in Fig. 3a). Hence, the actual background noise levels for those frequencies are likely to be even lower than the ones depicted in Fig. 3a. This is subject to future work. The equivalent, overall A-weighted sound pressure level $L_{\mathrm{p,A,eq}}$ measured by the *Brüel & Kjær* 2250-G4 SLM (and hence subject to the aforementioned noise floor issue) averaged over a period of 15 s was 18.5 dBA. Overall, the measured noise levels



(a) (b)

Figure 3: (a) Background noise levels inside PALILA. (b) Reverberation time (T_{60}) of PALILA per one-third-octave frequency band and mean value (denoted as a solid red line).

are considered sufficiently low to not contaminate or interfere with psychoacoustic listening experiments.

3.2 Reverberation time

The reverberation time T_{60} inside the laboratory was estimated by recording six consecutive claps approximately in the center of the booth measured with the SLM 1 m away. The measurements were performed with the door closed and in an empty room (i.e. without the chair, laptop, and laptop stand inside the room). The claps can be approximated as broadband percussions that excite all the frequencies in the range of interest considered (200 Hz to 20 kHz). The lower frequency bound is selected due to the properties of the acoustic-absorbing foam panels and the higher is defined by the limit of human hearing.

A frequency analysis was conducted but this time with considerably shorter time blocks of 0.02 s to improve the time resolution to better capture the percussions at the cost of a coarser frequency resolution ($\Delta f = 50$ Hz). For each clap, the value of T_{60} is estimated as the time it takes the raise in L_p over the background noise (up to approximately 100 dB) due to the percussion to get damped by 60 dB. The calculated reverberation times in both the time and frequency domain in one-third-octave frequency bands are presented in Fig. 3b. The mean value of T_{60} in the time domain averaged over the six claps is 0.0761 s $\pm$ 0.024 s (standard deviation, depicted as dashed red lines in Fig. 3b). Figure 3b also contains the mean reverberation times per one-third-octave frequency band and their respective standard deviations as error bars. In general, all the mean T_{60} values in the frequency range of interest are below 0.1 s (even below 0.05 s for frequencies higher than 1600 Hz), making PALILA belong to the acoustically *dead-space* category according to the ISO 3382 norm.

3.3 Free-field propagation assessment

An important feature of anechoic rooms is the region of space where the inverse square law spreading holds, i.e. where the free-field sound propagation conditions are present without significant sound reflections of the walls, floor, or ceiling. The expected L_p value at a distance r from the sound source in the free field can be calculated using the following expression which considers omnidirectional spherical spreading of sound:

$$L_\mathrm{p}\left(r\right) = L_\mathrm{p}\left(r_0\right) - 20\log\left(\frac{r}{r_0}\right), \tag{1}$$

where r_0 is a reference distance to the source, normally considered as 1 m. The atmospheric absorption of sound is neglected in this equation due to the relatively small distances considered.

To assess the free-field propagation, the deviation from the expected free-field decay (using Eq. (1)) $\Delta L_{\mathrm{p}} = L_{\mathrm{p,exp}} - L_{\mathrm{p,ref}}$ for every distance r was measured and evaluated. $L_{\mathrm{p,exp}}$ and $L_{\mathrm{p,ref}}$ are the measured and modeled sound pressure levels, respectively.

To assess the free–field conditions, a simple setup was employed (see Fig. 4a) consisting of:

- The *Visaton FRWS-5* 8-ohm speaker mounted on a tripod 1 m high situated close to the bass trap opposite to the door with the baffle facing the center of the booth. The speaker played the same broadband noise signal for each measurement. The door was kept closed for all measurements.
- The *Brüel & Kjær* 2250-G4 SLM aligned with the center of the baffle of the speaker and facing it. For each measurement, the SLM was displaced 0.2 m away from the speaker, starting from an initial distance r_0 of 1 m until a distance of 2 m.

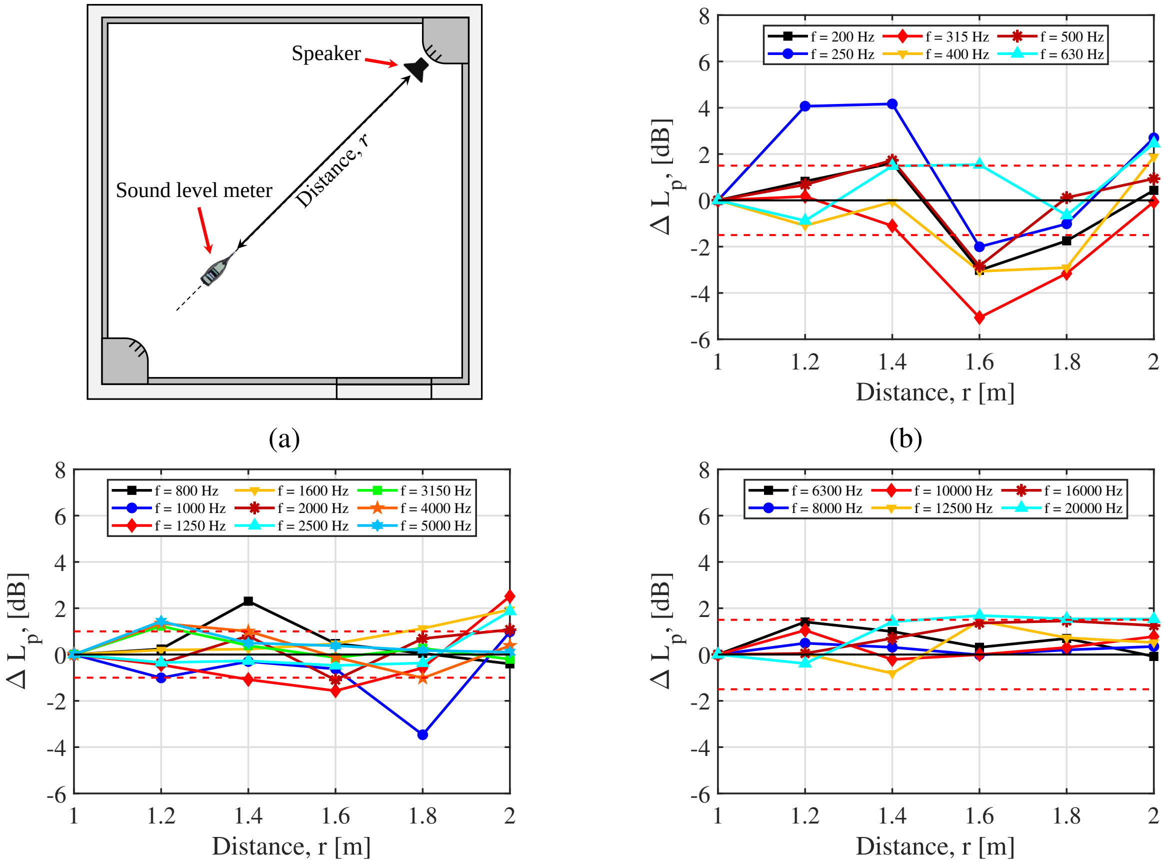
The measured ΔL_{p} values for each one-third-octave frequency band of interest with respect to the distance to the source r are presented in Fig. 4. The maximum allowable ΔL_{p} values for an anechoic room according to the ISO 3745 standards are plotted as horizontal red dashed lines. The free-field propagation characteristics for low frequencies (Fig. 4b) only hold for certain frequency bands for distances to the source up to about 1.4 m (except for the 250 Hz band). The results improve for the middle (Fig. 4c) and, especially, for high (Fig. 4d) frequencies. In general, for frequencies higher than 1600 Hz, free-field propagation conditions hold for most of the distances considered, except for the largest distance of 2 m for frequencies below 2500 Hz, where the reflections from the corner opposite to the speaker are expected to contaminate the measurements.

3.4 Transmission loss of the walls

The room hosting PALILA is located in a relatively quiet office corridor without any major sound sources present. Nevertheless, should any external noise source be present, it is desired to attenuate it as much as possible so the psychoacoustic listening experiments or any acoustic measurements inside PALILA are not contaminated. Therefore, another important acoustic characterization criterion is the quantification of the transmission loss (TL) of the walls and door of the booth. The experimental setup consisted of the speaker placed outside of the booth mounted on a tripod 1 m high and facing the door of the booth and reproducing broadband noise with an overall L_{p} of roughly 60 dB, first with the door open and then with the door closed, see Fig. 5a. The same sound signal was employed in both measurements and the sound levels inside the booth were measured using the SLM. The TL per one-third-octave frequency band can then be estimated by subtracting the sound spectrum measured with the door closed from that measured with the door open. The results are presented in Fig. 5b compared with the data provided by the manufacturer for a smaller-size booth without sound-absorbing foam panels. With some discrepancies, both curves present similar behaviors and values. The weighted average TL value according to the ISO 717-1 standard measured by the manufacturer is 45 dB, which is considered a sufficiently high value to dampen potential exterior noise sources. It should be considered that the gypsum wall and door of the room (outside the booth) would provide some additional transmission loss in practice.

4. Conclusions

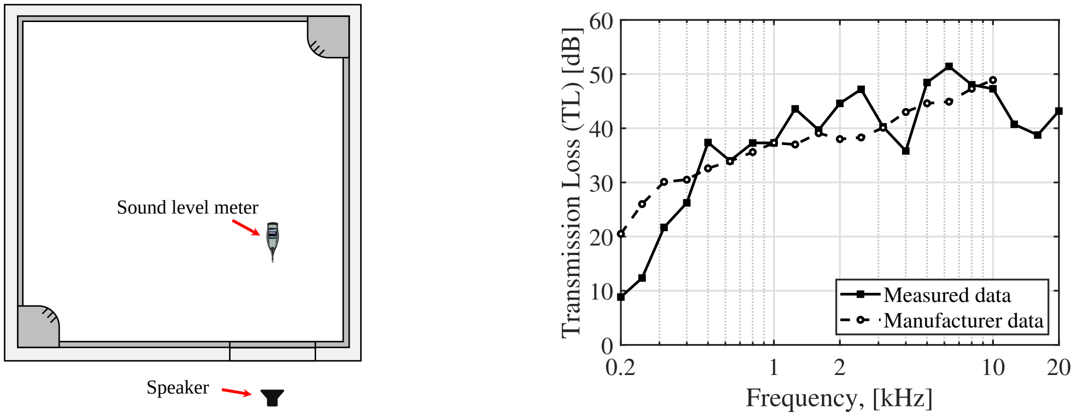
This manuscript explains the design and acoustic characterization of the recently-commissioned PsychoAcoustic LIstening LAboratory (PALILA) at Delft University of Technology. The laboratory consists of a soundproof room with very low background noise levels and a reverberation time below 0.1 s (i.e. it is an acoustically *dead-space*). Free-field sound propagation holds for frequencies higher



(a) (b)

(c) (d)

Figure 4: (a) Experimental setup for characterizing the free-field propagation. Deviations from the expected free-field decay due to spherical spreading with respect to the distance to the sound source for: (b) low frequencies, (c) middle frequencies, and (d) high frequencies. The tolerances according to the ISO 3745 standard are depicted as horizontal dashed red lines.



(a) (b)

Figure 5: (a) Experimental setup for characterizing the transmission losses of the wall and door. (b) Comparison of the measured transmission loss with the data provided by the manufacturer for an observer inside the booth.

than 1600 Hz. Overall, PALILA is considered a suitable quiet environment to conduct high-quality psychoacoustic listening experiments. Its modular and relatively simple and low-cost design will hopefully enable more researchers to develop similar laboratories to perform psychoacoustic listening experiments.

Future work includes expanding PALILA's capabilities with a VR reproduction system and performing listening experiments as a validation case study.

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