Simulator for the reproduction of “Low Sonic Boom”-signatures

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Introduction

Supersonic aircraft produce a sonic boom when flying faster than the speed of sound. In order to rule out detrimental effects for inhabitants of overflown areas, civil supersonic flights (like the Concorde) were allowed over water only. Due to progress in aircraft design, the super sonic boom may be reduced considerably in the future. Such “Low Sonic Boom”-signatures will be considerably quieter and sound completely different compared to conventional sonic booms [1]. Although a lot of research was carried out to better understand the effects of classical sonic boom on humans, the sensation and subjective response of humans to future “Low Sonic Boom”-signatures is currently under investigation [2, 3]. A level of acceptability is not available at the moment and it is the question how to define it such that the effects on humans are reflected [1, 4]. For an assessment of human responses to “Low Sonic Boom “-signatures, a Sonic-Boom simulator has been built at the University of Oldenburg in the framework of the EU-project RUMBLE [5]. Another simulator, which is used for a sleep study in the RUMBLE project, has been built by the Institute Jean Le Rond d’Alembert at the Sorbonne University in Paris [6].

Simulator Setup

For an accurate reproduction of “Low Sonic Boom”-signatures, the simulator in Oldenburg is constructed as a pressure chamber, similar to older facilities at NASA [7] and at JAXA [8]. The pressure chamber design allows for high pressure amplitudes at very low frequencies with a reasonable technical effort. It is considerably smaller than the newer NASA Interior Effects Room, which is not built as a pressure chamber. The Interior Effects room is also used for investigations of sonic boom effects on humans simulating a living room environment in the laboratory [9, 10].

Room Setup

The indoor low-boom simulator of the University of Oldenburg is installed in two small neighboring rooms. One room acts as a pressure chamber and the other room acts as a loudspeaker enclosure (Fig. 1). The pressure chamber has a width of 1.15 m, enlarging to 1.44 m in the entrance area. The room is 2.60 m deep and it has a tilted ceiling with an average height of 2.80 m. The volume of the pressure chamber is about 9 m^3. The loudspeaker enclosure is about 1.88 m wide, 2.75 m deep, and about 3 m high with a slightly tilted ceiling. The

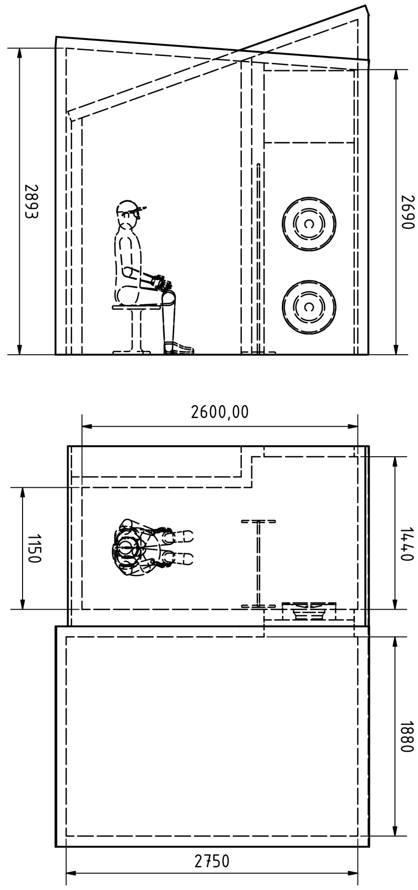

Figure 1: Side view (top) and floor plan (bottom) of the pressure chamber and the neighboring room (acting as a loudspeaker enclosure) in millimeters.

Figure 2: Inside the pressure chamber of the simulator.

two loudspeaker chassis are installed in a thick wooden plate that is mounted in the door frame between the two

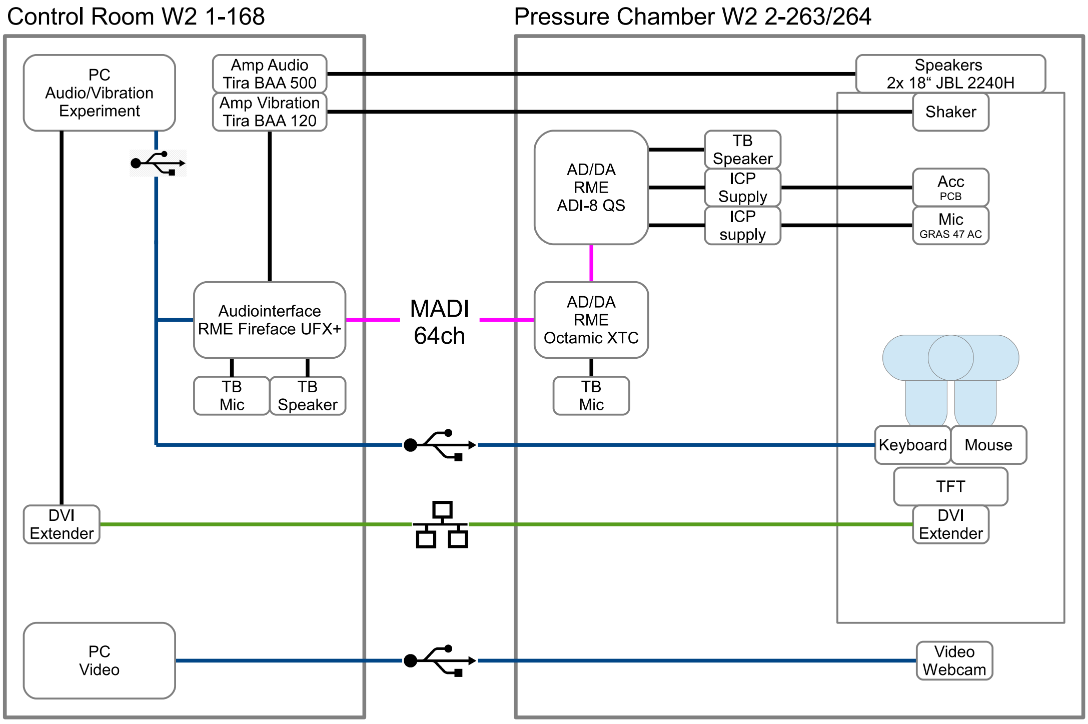

Figure 3: Schematic of the technical setup driving the simulator and the connections between control room and pressure chamber.

rooms with an airtight sealing. During the planned listening tests, participants will sit in the pressure chamber room, which can be accessed by another door leading to a small balcony at the edge of the building. The room is not connected to any ventilation system and opening the door allows a direct exchange of air with the outside. The technical systems driving the low-boom simulator are placed in a separate control room one floor below the pressure chamber.

Technical Setup

Figure 3 shows a schematic overview of the technical system of the indoor low-boom simulator. Two 18-inch loudspeaker chassis (JBL 2240 H) are installed in the pressure chamber. They are driven in series by one amplifier (Tira BAA 500, DC-coupled input) which is connected to a DC-coupled output of an audio interface (RME Fireface UFX+, output 9). The electric playback chain has a flat frequency response down to 0 Hz and is in principal capable to reproduce signals with DC-components. Recordings in the chamber are made with a 1/2 inch infra sound microphone (GRAS 47 AC, sensitivity: 8 mV/Pa) at the listening positions. The microphone is connected to a custom ICP supply and amplifier (UOL 127/09, coupling capacitor of 22 nF, -1 dB@1 Hz) that is linked to an AD-converter (RME ADI-8 QS, -3 dB@1 Hz). The AD-converter is connected to the audio interface over an optical MADI cable. An FIR filter was designed to invert the measured transfer function at the listening position. The filter has a FFT-size and a filter length of 32768 samples for a sampling rate of 48 kHz. The filter length is a trade-off between low frequency resolution and temporal distortion of the filtered signal. The inverse filter was designed with a third octave smoothing. A Hann window was applied to the impulse response of the filter. In this way, a flat frequency response from 1.5 Hz to 2 kHz was achieved at the listening position in the simulator. This frequency range is similar to the NASA Indoor Effects Room, covering most of the relevant frequency range for sonic boom reproduction [10]. The -3 dB cut-off point to lower frequencies at 1.5 Hz is only about 1 Hz higher compared to the older NASA pressure chamber [7] and about 0.5 Hz higher than that of NASA Indoor Effects Room .

A small vibration platform is installed in the chamber to simulate whole-body vibration that may occur in connection with “Low Sonic Boom”-signatures [11]. The platform consists of a board of medium-density fibreboard (MDF) that is placed on four foam springs. The MDF board has a width of 1 m, a depth of 1.2 m and a thickness of 76 mm. The mass of the board is about 60 kg. The four foam springs (Sylomer S11) have a length and a width of 160 mm and a thickness of 50 mm each. The platform is driven by a custom built inertial shaker system that is connected to an amplifier (TIRA BAA 120). The DC-coupled input of the amplifier is connected to a DC-coupled output of an audio interface (RME Fireface UFX+, output 10) as shown in Fig. 3. Recordings of the platform’s accelerations are made with the z-channel of a tri-axial accelerometer (PCB Model 356A15, sensitivity: 100 mV/g). The accelerometer is connected to a custom ICP supply and amplifier (UOL 127/09, coupling capacitor of 22 nF, -1 dB@1 Hz) that is linked to an AD-converter (RME ADI-8 QS, -3 dB@1 Hz). The AD-converter is connected to the audio interface over an

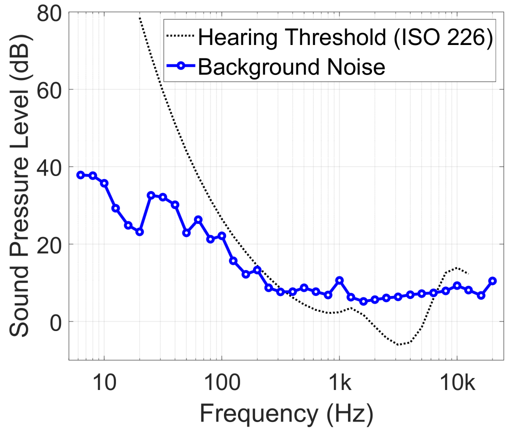

Figure 4: Background noise level in 3rd octave bands and absolute threshold of hearing.

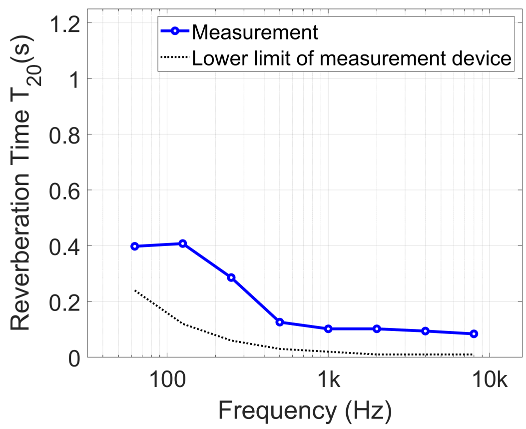

Figure 5: Reverberation time T_{20} for octave bands from 63 Hz to 8 kHz.

optical MADI cable. An FIR filter was designed to invert the measured transfer function. The filter has a FFT-size and a filter length of 32768 samples for a sampling rate of 48 kHz. The inverse filter was designed with a third octave smoothing. A Hann window was applied to the impulse response of the filter. In this way, a flat frequency response from 12 Hz to 90 Hz was achieved for the vibration platform.

Background Noise

The background noise level in the chamber averaged over 10 seconds of $L_{\mathrm{Aeq}} = 21$ dB(A) is very low. Figure 4 shows the background noise level in third octave bands. The background noise is only slightly above the absolute threshold of hearing in the frequency range from 300 Hz to 6 kHz. The background level of the present indoor low-boom simulator is similar to the background noise level in the NASA Interior Effects Room [12] below 100 Hz and about 10 dB higher above 100 Hz. The overall background noise level of $L_{\mathrm{Aeq}} = 21$ dB(A) is about 13 dB below an older NASA simulator [7].

Reverberation Time

To reduce the influence of the room acoustics and reduce the reverberation time for higher frequencies (above 300 Hz), absorbing material was placed on the walls and the ceiling of the pressure chamber. The walls left and right to the listening positions were covered with pyramid foam absorbers (10 cm thickness). The wall at the end of the room (right side in Fig. 2) has been outfitted with soft foam loops (25 cm depths) to absorb low mid frequencies. The resulting reverberation time of the chamber is $T_{20} = 0.2$ s averaged over octave bands from 63 Hz to 8 kHz. Figure 5 shows the reverberation time T_{20} for octave bands from 63 Hz to 8 kHz. The reverberation time below frequencies of 250 Hz is comparable to the NASA Interior Effects Room [10]. Above 250 Hz, the reverberation time is considerably shorter than that of the NASA Interior Effects Room. A further reduction of the reverberation time for frequencies below 300 Hz is difficult because suitable dissipative absorbers would be very large compared to the dimensions of the pressure chamber.

Acoustic Signature Reproduction

Figure 6 and Fig. 7 show two exemplary sonic boom signatures in the time and the frequency domain. Figure 6 shows the reproduction without equalization and the reproduction including an FIR filter to equalize the playback system is shown in Fig. 7. The boom signatures are already quite well reproduced without any equalization applied to the playback system because of the acoustic damping of the pressure chamber. Nevertheless, the time signals of the reproduction deviate from the target signals especially for the under-pressure part and some post-ringing (with a periodicity of about 0.015 s) is visible in Fig. 6. The post-ringing periodicity is found as prominent peaks in the spectrum around 66 Hz and 132 Hz with a considerable dip in between the two. The signals are spectrally quite well reproduced below 50 Hz complying with the expected pressure chamber behavior up to the first room mode at around 66 Hz.

The equalization of the playback system leads to a more accurate reproduction of the time signal in particular for the under-pressure part. Especially for the second example, the asymmetry of over- and under-pressure is better reproduced. Furthermore the post-ringing is reduced to a very low frequency component of about 2.5 Hz. In the spectral domain, the gaps around 40 Hz and 100 Hz (in Fig. 6, right) are filled by the equalization as expected in Fig. 7 (right).

Acknowledgement

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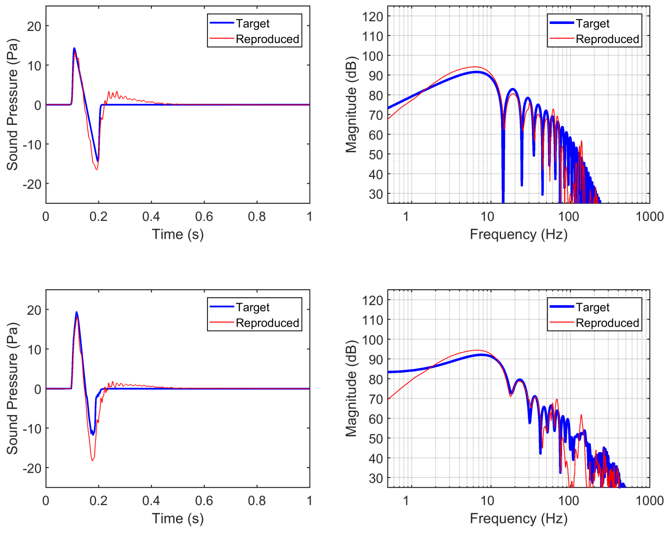

Figure 6: Target signatures (blue) and simulator reproduction (red) in the time domain (left) and spectral domain (right) for two exemplary boom signatures **without** equalization of the playback system.

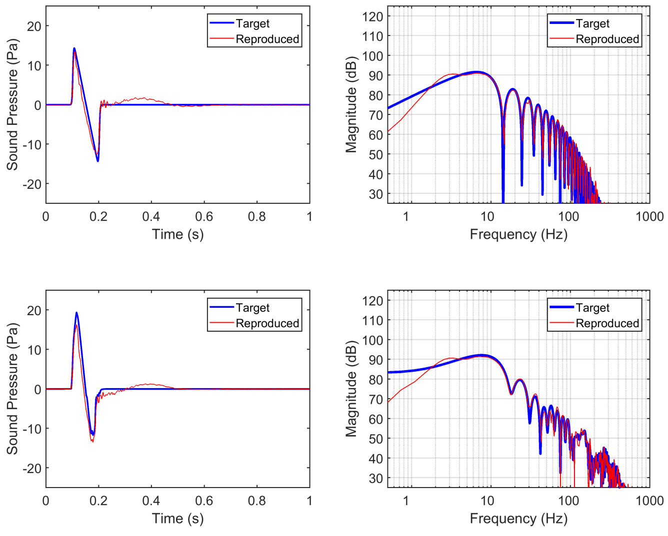

Figure 7: Target signatures (blue) and simulator reproduction (red) in the time domain (left) and spectral domain (right) for two exemplary boom signatures **with** equalization of the playback system.

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