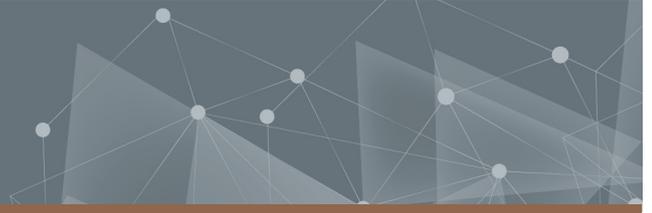




CHALMERS
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A Study in Non-linear Seat Shaker Processors for Enhanced Integration with Full-Range Audio Systems

Master of Science Thesis in Sound and Vibration

Lukas Ghijssels

DEPARTMENT OF APPLIED ACOUSTICS

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2024

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MASTER'S THESIS 2024

**Study in Non-linear Seat Shaker Processors for Enhanced Integration
with Full Range Audio Systems**

In collaboration with Premium Sound Solutions

LUKAS GHIJSELINCK



CHALMERS
UNIVERSITY OF TECHNOLOGY

Department of Applied Acoustics
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LUKAS GHIJSELINCK

Department of Applied Acoustics
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Abstract

This MSc Thesis studies the integration of non-linear seat shaker processors in a full-range audio system, applied in the car environment. The thesis is conducted on behalf of the Research and Development Department of Premium Sound Solutions. The loudspeaker company wants to know more about the scientific implementation and research behind seat shaker processors in cars. Studies have been done on the subjective and objective influence of low-frequency sources, namely subwoofers, on persons. Fewer studies have been done on the haptics and body reaction of low-frequency vibrational sound sources in a car environment.

The transmission of low frequencies in a car has a different modal directivity. The signal affects both the auditory parts with the ear drums as the sensed parts in the rest of the body. It is found that the auditory spectrum has an influence on the perceived vibrations.

Therefore a first experiment is done to retrieve subjective data for the influence of the low-frequency sound source on the body. The data is used to define the shaker positioning with the corresponding threshold of feeling. Secondly, the vibration acceleration levels are measured using accelerometers to retrieve the objective data. Using that objective data, the excited acceleration levels are matched with those of the subwoofer.

A second listening experiment is done in the form of an A/B listening test. The interviewees are asked to quantify the difference of the perceived acceleration between the subwoofer setup and the shaker implementation.

The subwoofer experiment showed that the threshold of sensing the vibrations in the body is frequency-dependent. It is also found that vibrations are sensed in different body parts. The excited body parts are also frequency dependent.

The results of the A/B experiment, where both sound pressure levels and acceleration levels are matched, show that objective measurements and level matching have the potential to be used as a tuning method. However the quality and implementation of the used method can be improved.

Keywords: Shakers, Vehicle Seat Vibration, Vehicle Sound Systems, low-frequency sound sources, subwoofer, personal bass

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I would like to express my deepest appreciation for the people at Premium Sound Solutions Dendermonde, and especially Tom Haelvoet.

They triggered me to develop my knowledge in electroacoustics by providing me access to numerous trainings and literature. I was given many opportunities to learn about commonly used methods with access to all the high-end measurement equipment and programs they have, that are used in the professional field.

I could not wish for a better mentor than Tom. He is a very open-minded person who gives me the freedom to come up with my ideas and guides me where needed. I admire his expertise within the field and it inspires me to develop personally as well. Therefore a very big thank you, Tom.

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I could not say a bigger thank you to my parents and sisters for the many opportunities they have given me over the past two years. It is not self-evident that you give your son the possibility to study in a foreign country for two years. They have always supported me, despite the distance.

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And finally, a big thank you to Chalmers University for providing us students with so many great ways to develop and explore our skills and knowledge.

Lukas Ghijselinck, Gothenburg, June 2024

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis **listed in alphabetical order**:

dBVAL	Vibration Acceleration Level in decibels
PSS	Premium Sound Solutions
SPL	Sound Pressure Levels
VAL	Vibration Acceleration Level

Nomenclature

Below is the nomenclature of indices, sets, parameters, and variables that have been used throughout this thesis.

Indices

Sets

Parameters

P	Power (Watt)
U	Voltage (Volt)
U_{ref}	Reference Voltage
R	Resistance (Ohm)
I	Current (Ampère)
L_p	Sound Pressure Level (dBSPL)
L_{VAL}	Vibration Acceleration Level (dBVAL)
M_m	Motor mass
M_h	Mass of the housing
M_L	Mass of the load

Variables

a_a	Acceleration due to action force
a_r	Acceleration due to reaction force



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1

Introduction

On behalf of the loudspeaker production company Premium Sound Solutions, a research is conducted into Non-linear Seat Shaker Processors for Enhanced Integration with Full Range Audio Systems.

Subwoofers in cars excite a vibration that is physically sensed by the passengers. This MSc Thesis aims to find a method to implement the non-linear Seat Shaker Processors with the full range audio system in the headrest.

A first subjective listening experiment is done to define the body areas where vibration is sensed. For those areas, the threshold of sensing is measured. The threshold represents the minimum sound pressure level where all the excited body areas still experience the vibrations. A panel of fifteen experienced and three inexperienced listeners participated.

The results of the experiment, and additional literature, are then used to define a threshold spectrum that is used to link the somatosensory aspect to the auditory spectrum. The body zone information creates insights to determine the shaker placement.

Additional objective measurements of the vibrational behaviour of the subwoofer driver and the shaker are done using accelerometers to measure the Vibration Acceleration Levels on the dBVAL-scale.

With the purpose of an A/B test, both the Vibration Acceleration Levels and the Sound Pressure Levels of the two setups are matched, using measurement-based equalisation.

In the A/B listening experiment, the interviewees are asked to define the perceived, area-dependent, differences between the subwoofer and the shaker implementation at different sound pressure levels.

Finally, a conclusion is drawn to describe the implementation differences between a subjective and objective approach.

2

Prior Research on Whole Body Vibration

There has been research on the psychoacoustics and objective measurements of vibrational influence on a body. The topic of this MSc Thesis research is more specific. A limited amount of research has been done on vehicle seat vibration, taking the different directions and implementations of the low-frequency source into account.

The description of the following literature should help to indicate the possible methods and outcomes of the measurements.

2.1 Whole-Body Vibration Induced Through Low-Frequency Sound Exposure

The paper about whole-body vibration induced through low-frequency sound exposure,[1], mainly describes the Body Related Transfer Functions for the low frequencies while taking into account the possible correlation of the Body Mass Index. It was found that the BMI correlates with the amount of induced vibration amplitude. The higher the BMI, the lower the induced vibration amplitude.

Figure 2.1 shows the results for the whole-body vibration induced by a low-frequency source. The graph shows averaged resonances at 70 Hz, 116 Hz, and 210 Hz.

It is stated that the shoulders are the most preferable application points since there was a lower variation in acceleration levels at these positions.

The same report describes the sinusoidal perception thresholds as well, as seen in figure 2.2.

The study claims that the body acts as a linear transducer of the vibration energy. The experiment did not take place in a car. Due to the different test environments, one cannot draw the same conclusions.

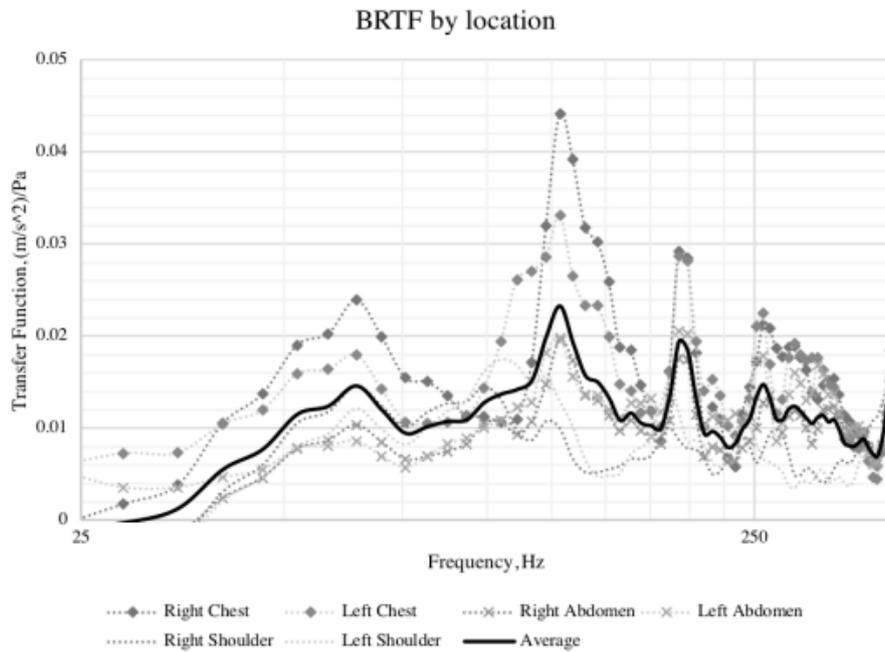


Figure 2.1: The Average BRTF by location [1]

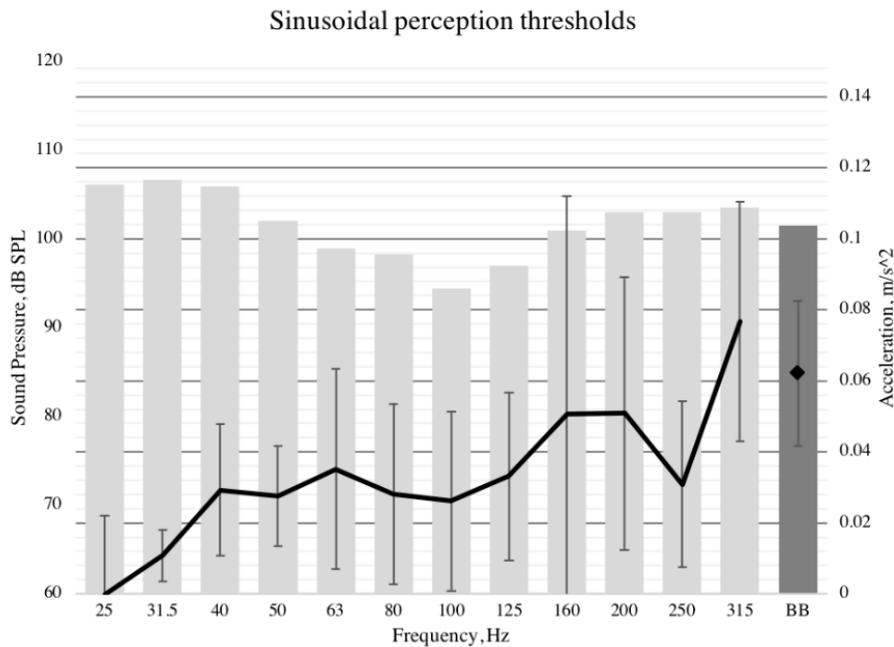


Figure 2.2: Sinusoidal Perception Thresholds [1]

2.2 Influence and Behaviour of Vibrations on the Human Body

Takahashi Y. et al. did several researches on the influence and behaviour of vibrations on the human body [5], [6], [7]. The first research, [5], handled the vibration perceived in the head. That led to the conclusion that the head has a superior

sensitivity at low frequencies with a gap between 40 and 50 Hz.

An additional test with noise-muffling headphones showed that the threshold of sense is higher when the contribution of the auditory part is lower. One can state that the perceived head vibration is also influenced by the pressure change in the ear.

The following paper [6] is about several characteristics of human body surface vibration induced by low-frequency noise expanding the body areas of interest.

The vibration levels were measured at the forehead, abdomen, and chest.

It is found that the vibration acceleration levels of the noise-induced vibrations tend to correlate with body fat percentage at the chest and abdomen, not to be confused with the Body Mass Index.

Their next research on the relationship between vibratory sensation and body surface vibration induced by low-frequency noise leans more toward the research topic of this thesis [7]. A linear relation is found between the Sound Pressure Level and the corresponding Vibration Acceleration Level.

A strong correlation is found between the sensed vibration and the surface acceleration. It will be investigated if there is a difference between the measured and sensed vibration in a car environment.

Research on annoyance and interaction effects of vibration on persons has been done, [8]. The research discusses how the annoyance of vibrational sensing increases with higher SPL's. In this study, it is thus interesting to evaluate if the threshold of the shaker plus the headrest is similar to the one of the subwoofer.

The research also confirms the linear relation between Sound Pressure Level and Vibration Acceleration Level.

2.3 Standards

ISO standards have been written to evaluate and discuss the influence of vibration on humans or seats.

The more general ISO Standard 2631-1 describes the evaluation of human exposure to whole-body vibration [9].

For this thesis research, it is more relevant to take the ISO 10326-1 standard as a guideline. It describes the methods for measuring mechanical vibration, more precisely for vehicle seat vibration [4].

3

Theory

This chapter describes the relevant theory about shakers and the full-range audio headrest to understand the principles of the systems and speakers that are handled in the thesis.

3.1 Subwoofer

A premium audio system in a car includes a subwoofer and a woofer driver. Combined, the target frequency range is 20 Hz - 200 Hz.

In figures 3.1 and 3.2 a driver is shown. One can notice the differences between a loudspeaker driver and a shaker processor.

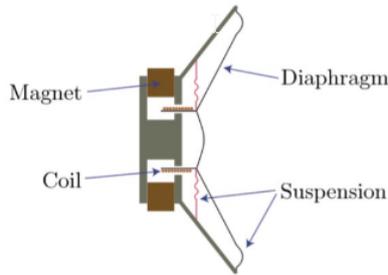


Figure 3.1: Schematic Drawing of Driver [2]

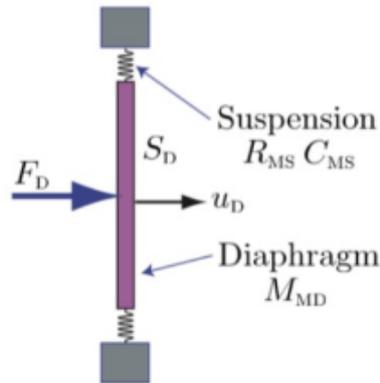


Figure 3.2: Simplified Mechanical Model [2]

$$\text{where } \begin{cases} M_{MD} & = \text{Mass of diaphragm} + \text{air} \\ C_{MS} & = \text{Compliance of suspension} \\ R_{MS} & = \text{Resistance (damping) of suspension} \end{cases}$$

Subwoofers are usually mounted in the trunk of the car.

A car has structural resonance frequencies. A subwoofer in the trunk potentially emits those frequencies which leads to higher amounts of structural vibrations. The combination of structural and airborne sound transmission introduces the vibrations that can be experienced in the seats of the car.

The structural vibration is not always wanted since both the seats and the rest of the car structure vibrate. Regarding the noise levels of a car for the surroundings, those vibrations are unwanted.

The vibrations introduced to seats, on the other hand, can enhance the listening experience of the person.

Shakers are therefore introduced, as explained in the next section 3.2.

3.2 Shakers and exciters

Shakers and exciters are force-driven processors to generate vibrations.

A shaker typically has a target frequency range of 32 Hz - 200 Hz.

Shakers are used for multiple applications ranging from complete seat structure vibration to massage purposes. The company Premium Sound Solutions is working on several implementations to create and optimise the personal listening experience in a car by using shakers in combination with the full-range speakers in the headrest. Therefore in this research, the shakers are used to enhance and emulate the sub-woofer behaviour in a seat.

The shaker consists of two major parts, the moving motor and the moving frame. The moving frame becomes part of the load when the device is coupled to its load. The physical principle is described according to Newton's First Law:

$$F = (M_L + M_h) \cdot a_r = M_m \cdot a_a \text{ (Newton)}$$

and thus

$$a_r = \frac{M_m a_a}{M_L + M_h} \left(\frac{m}{s^2} \right) \tag{3.1}$$

$$\text{where } \begin{cases} a_a & = \text{acceleration due to action force} \\ M_m & = \text{Motor mass} \\ a_r & = \text{acceleration due to reaction force} \\ M_h & = \text{Mass of the housing} \\ M_L & = \text{Mass of the load} \end{cases}$$

An exciter and a shaker are constructed in the same way but mounted differently. For an exciter, the voice coil is directly coupled to a sound-radiating element. It is meant to produce sound up to high frequencies. It has a hi-pass sound characteristic.

A shaker uses the inertia of the motor system to transmit vibration on the coupled element instead of sound reproduction. In this case, the voice coil will not be coupled to the radiating load. Loss at high frequencies occurs. This application shows more band-pass behaviour for the sound characteristic.

The coupling conditions and load are thus different for both applications. Both applications are force-driven, thus Newton, and generate an acceleration on the output.

3.3 full-range audio headrest

The full-range audio headrest is developed to create and enhance the personal listening experience.

The headrest does not emit the same amount of structural vibration on the seats as the subwoofer for the same sound pressure levels. Therefore shakers are used to contribute to the personal subwoofer experience.

The headrest contains two different speaker elements. Low-frequency drivers and mid-high drivers.

The patented low-frequency technology, described in detail in the patent publication [10], uses the nearfield dipole application to create a high contrast between near- and far-field. The proximity effect introduces higher sound pressure levels at low frequencies, which is beneficial for the purpose.

The contribution from the room to the distortion is minimized due to the nearfield application.

The polar pattern in figure 3.3 indicates the figure of eight behaviour of the headrest. The person in the front passenger seat does not experience as much interference from the driver's seat because of the nearfield behaviour.

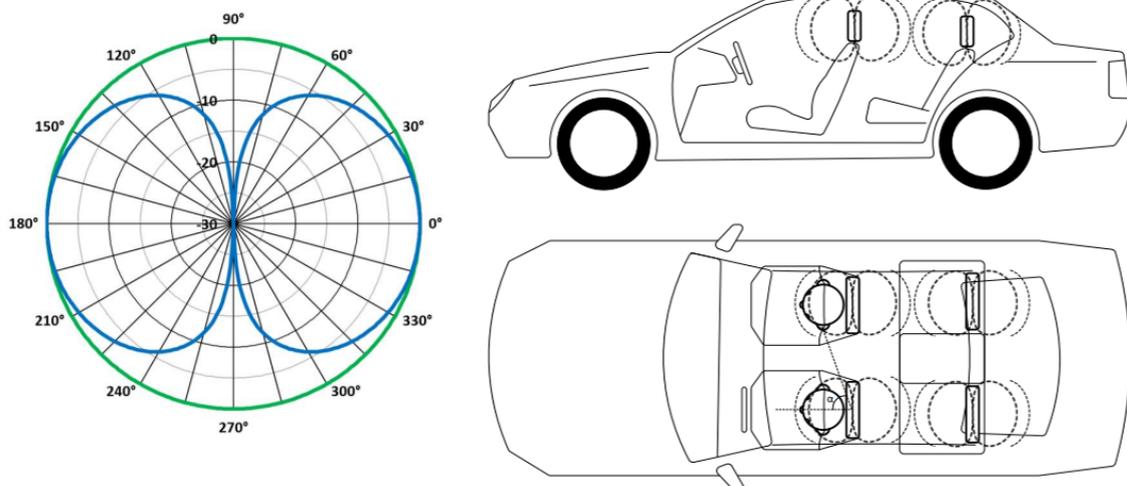


Figure 3.3: Polar Pattern and Behaviour of Headrest in Car Environment

4

The Sensory Impact: Subwoofer Vibrations on Specific Body Zones

This chapter describes the first experiment where the psychoacoustical and sensory impacts of a subwoofer on a person are investigated. The chapter consists of the description and purpose of the test, the setup, and the corresponding outcome of the test.

4.1 Experiment Description and Setup

The experiment aims to find a method to evaluate the behaviour of a subwoofer in a car to then emulate and enhance the bass response by introducing seat shakers.

It is the first experiment's purpose to define which low frequencies in third-octave bands, as shown in table 4.1, are felt in which part of the body. The results are used to investigate optimal shaker placement in the further stadium of the research topic.

Side note: Initially the third octave bands contain 12.5 Hz and 31.5 Hz. At both frequencies, a clear pop occurs when the frequency is adjusted in the MATLAB App. The artifact is unwanted in the experiment so that the listeners are not bothered during the listening test.

The cause was that these frequencies are not integer multiples of the fundamental frequency and that they cannot be perfectly given by the Discrete Fourier Transform. Therefore round, integer, frequencies were used instead.

Frequency (Hz)												
13	16	20	25	32	40	50	63	80	100	125	160	200

Table 4.1: Third-octave band frequency values in Hz

For the test, the interviewees take place in the driver's seat of the AUDI A8 Car, Model year 2000, that was available at the company. A subwoofer is mounted horizontally in the trunk of the car following the setup that is given in figure 4.1

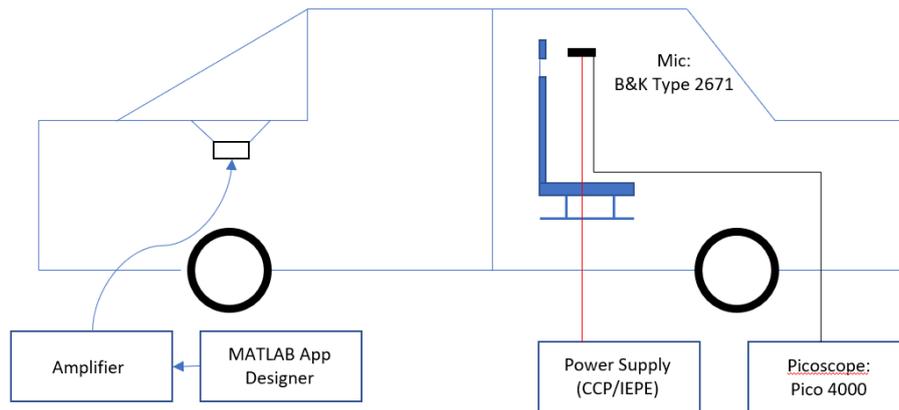


Figure 4.1: Subwoofer Testing: Car Setup

Once seated, the interviewee is asked to use a MATLAB GUI where they can switch frequencies, signal types and adjust the level of the signal, as shown in figure 4.2. The level is an index between 0 and 30 where the value corresponds to a digital amplitude between 0 and 1 in step sizes of $\frac{1}{30}$. The total output, both in volts as in dB SPL, of the signal depends on the amplifier gain and used signal. The calculations for these values are discussed in the methodical test setup section 4.2.

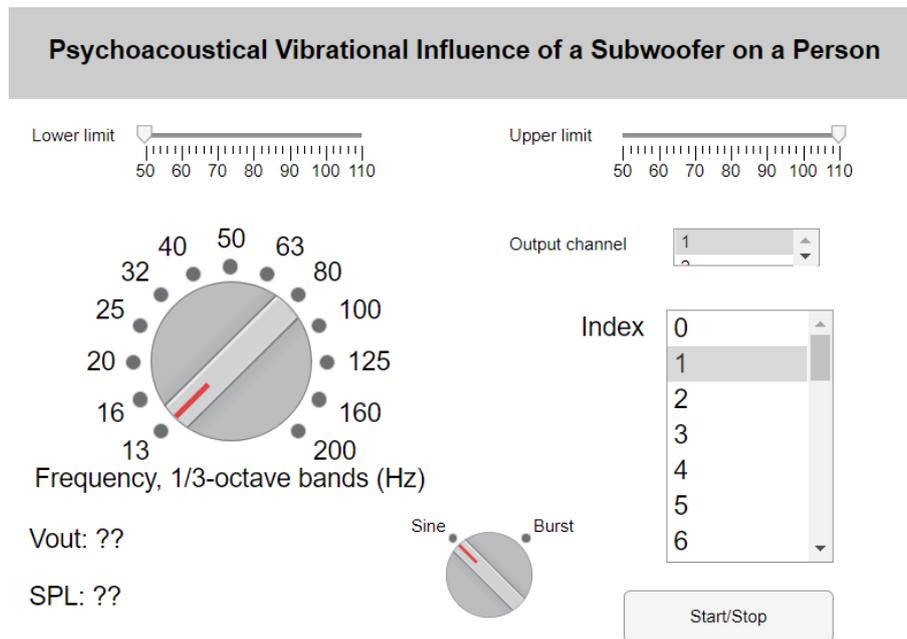


Figure 4.2: Subwoofer Testing: App User Interface

The interviewee is asked to open the accompanying Excel Form, an example question is given in figure 4.3, in which they need to define the body parts where body vibration is sensed. Multiple answers are possible. That way it is interesting for further processing if multiple shakers need to be used with the corresponding amount of excitation per frequency.

4. The Sensory Impact: Subwoofer Vibrations on Specific Body Zones

In the second part of that form, the interviewee is asked to define the threshold at what point all previously sensed vibrations are still present. It is for example possible that at 100 dBSPL the legs, upper back, and lower back sense vibration. But at 98 dBSPL vibrations are only sensed in the legs and the lower back. In that case, 100 dBSPL is defined as the threshold.

With those thresholds, a spectrum is found that is introduced in further filtering and equalisation.

One could critically think about taking a general threshold for multiple body parts. Using body area-dependent thresholds would be too time-consuming for the interviewee, therefore this simplified method was applied. The interviewee is asked to review thirteen frequencies with each at least eight possible body areas. It took the average interviewee to execute the experiment in 35 minutes.

2. 13 Hz: Where does this frequency affect you? *

- Feet
- Legs
- Seating cushion
- Lower back
- Center of the back
- Ribs / Side of the body
- Chest
- Neck and/or head
- Other

3. What was the dBSPL when you felt it? (use dot notation method as in e.g. : **95.12**) *

The value must be a number

Figure 4.3: Excel Form Questionnaire

4.2 Methodical Test Setup

This section describes the method used to create the MATLAB interface, concerning the standards and algorithms.

Subwoofer excitation can be measured using the standard test signals defined in the CEA-2010 (ANSI) Test Procedure ([11]).

According to the standards [11], an ANSI-burst signal is calculated by:

$$f(t) = \begin{cases} (1 - \cos\left(\frac{2\pi f_0 t}{6.5}\right)) \cdot \frac{\sin\left(\frac{2\pi f_0 t}{2}\right)}{2}, & \text{for } 0 \leq t \leq 6.5 \\ 0, & \text{elsewhere} \end{cases} \quad (4.1)$$

where $\begin{cases} f_0 & = \text{Fundamental frequency} \\ t & = \text{Time} \end{cases}$

ANSI-burst signals are Hann-windowed sine waves and can be graphically shown as 4.4.

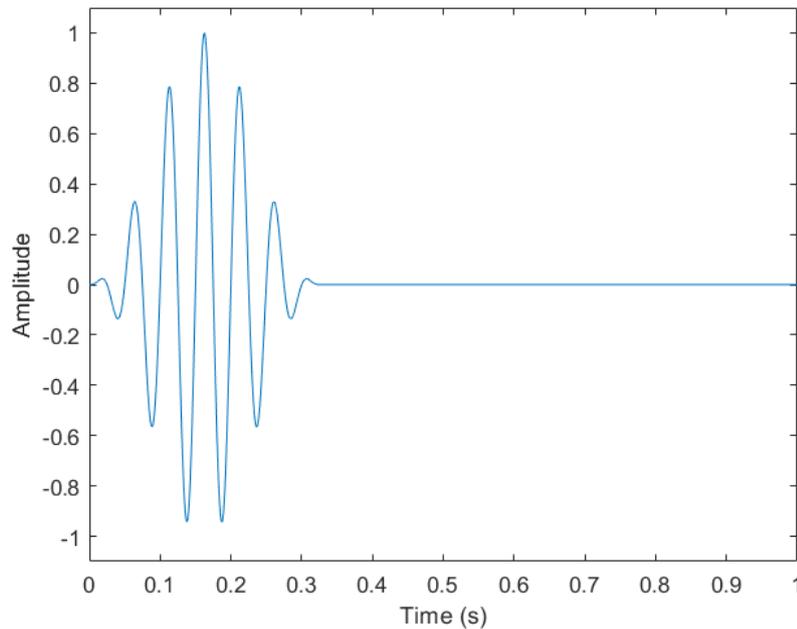


Figure 4.4: Waveform of a 6.5 cycles 20 Hz hann-burst signal

In the MATLAB App, it is possible to choose the ANSI-Burst signal or a pure sine tone.

Some interviewees find it easier to define the excited body parts if a sine tone is used since more time is given to experience and evaluate the sensed vibrations.

The generated sine or burst signal is sent to an amplifier which is connected to the subwoofer. The amplifier plus subwoofer setup does not correspond to a perfectly

flat response, with coil saturation, used analog components, tolerances, circuit design, etc. as possible causes.

The system needs to be calibrated in a way that the set level index on the GUI corresponds to the correct output voltage and thus SPL at the driver's seat.

The calibration is done by using a fixed voltage that corresponds to 1 Watt on the output of the subwoofer. For an 8 Ohm speaker 1 Watt output is calculated as: (4.2)

$$\begin{aligned}
 P &= U \cdot I \\
 P &= \frac{U^2}{R} \\
 U &= \sqrt{P \cdot R} \\
 U &= \sqrt{1 \text{ W} \cdot 8 \Omega} = 2.83 \text{ V}
 \end{aligned} \tag{4.2}$$

The sound pressure level is measured in the driver's seat at headrest height, 10 cm from the middle of the headrest with the seat aligned at a fixed position. The sound pressure level was measured for 1 Watt, thus 2.83 Volts for this setup. The difference with the desired sound pressure level is then calculated to derive the needed correction factor that needs to be applied so that the desired sound pressure level is achieved.

The sound pressure is measured with the Brüel and Kjaer microphone for the third-octave bands and then compared with the theoretical P_{ref} . The difference is then converted to a factor that is applied to the input so that the input level matches the output level. As shown in equation (4.3)

$$\begin{aligned}
 L_{p,\text{measured}}(f) &= [L_{p,13 \text{ Hz}} : L_{p,200 \text{ Hz}}] \text{ dBSPL} \\
 L_{p,\text{desired}} &= \text{e.g. } 94 \text{ dBSPL} \\
 \Delta L_p &= L_{p,\text{desired}} - L_{p,\text{measured}} \\
 \text{correction factor} &= 10^{(\Delta L_p/20)}
 \end{aligned} \tag{4.3}$$

The correction factor is multiplied with the V_{ref} . This corresponds with the needed voltage to have 94 dBSPL on the output. The output is limited to U_{rms} due to the specifications of the amplifier. For some frequencies the wanted L_p might not be achieved due to those voltage limitations.

The actual, possibly limited V_{output} is then converted to an amplitude expressed in digital Full Scale, as shown in figure 4.5 and equation (4.4). The amplitude setting is a value between 0 and 1, with 30 steps in between. The rms-value and the full scale that can be used, [-1,1] are known. With this, the maximum peak value of the system is calculated in volt, after taking the amp gain and limiting into account. Depending on the full-scale setting and chosen amplitude, the conversion to the digital factor is calculated.

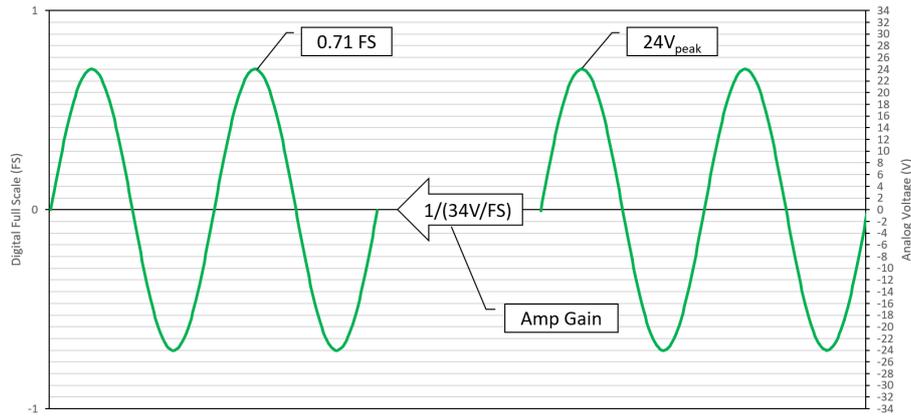


Figure 4.5: Conversion Voltage to Digital Amplitude

$$\begin{aligned}
 U_{ref} &= 2.83V \cdot \text{correction factor} \\
 L_{p,calibrated} &= 20\log_{10}\left(\frac{U_{out}}{U_{ref}}\right) + 94 \text{ (dBSPL)} \\
 U_{rms} &= \sqrt{P \cdot R_{speaker}} \text{ (V)} \\
 U_{output} &= U_{rms,limited} \cdot \text{amplitude setting (V)} \\
 U_{\text{digital factor}} &= \frac{\frac{U_{peak}}{\sqrt{2}}}{\text{amp gain}} \text{ (Full Scale)} \\
 \text{with } U_{peak} &= \sqrt{2} \cdot U_{rms} \\
 U_{\text{digital amplitude}} &= \frac{\frac{U_{rms,limited}}{\sqrt{0.5}}}{\text{amp gain}} \text{ (Full Scale)}
 \end{aligned} \tag{4.4}$$

4.3 Results of Subwoofer Experiment

Eighteen persons, of which fifteen trained acoustical engineers and listeners, participated in the listening experiment. Different interesting insights are retrieved from the subwoofer experiment.

The body zone ratio amplitudes show the normalised amplitude per frequency. If e.g. the lower back was sensed ten times and the center of the back only four times, then the amplitudes are 1 and 0.4. If for another frequency the maximum was seven times and another option was five times, then seven corresponds with an amplitude of 1.

It is found that the sensed body vibration is frequency-dependent. As seen in figures 4.6 and 4.7.

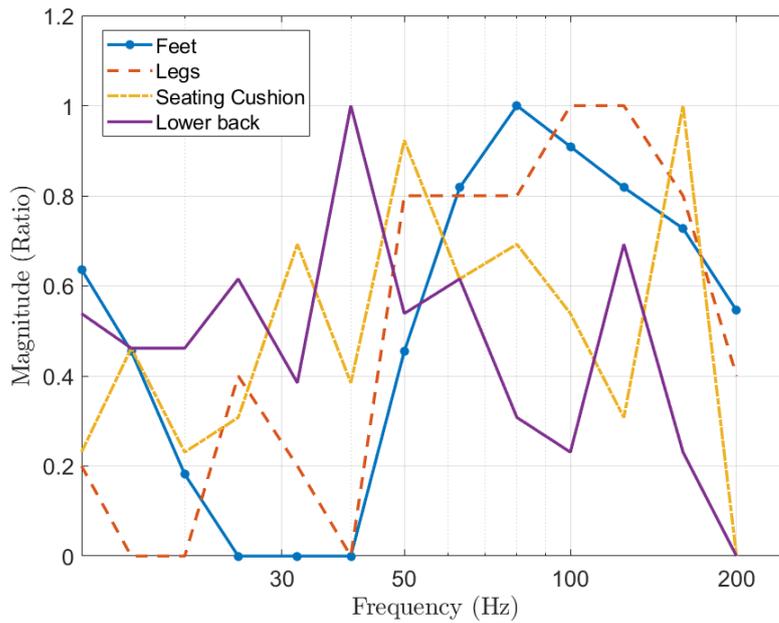


Figure 4.6: Body zones ratio, lower body

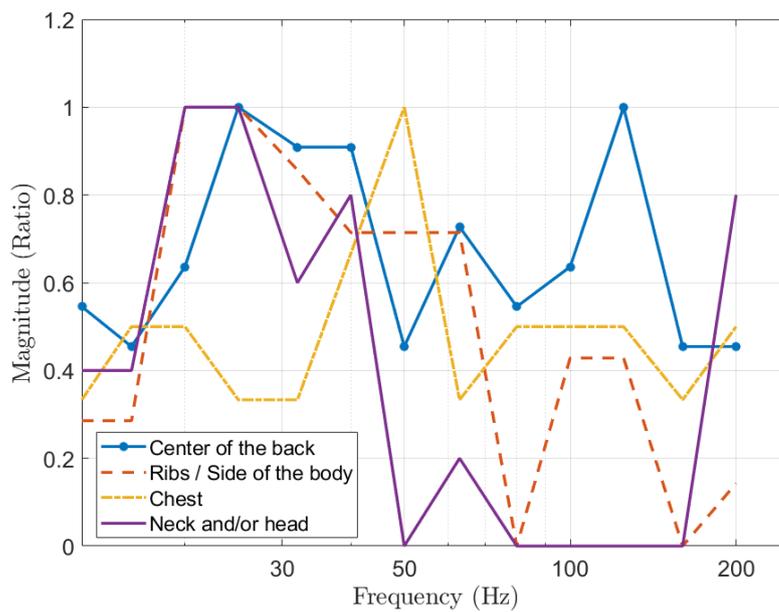


Figure 4.7: Body zones ratio, upper body

From the results, one can notice that the feet, seating cushion, legs, center of the back, and lower back are the most prominent areas where vibration is sensed. The neck and/or head still have a significant influence on the results. It is not possible to implement shakers in the headrest or the neck area.

With that conclusion, four shakers seem to be a realistic and accurate amount of shakers to implement in the seats.

In the backrest we mount:

- Shaker 1: Central x-position, higher y-position in the seat.
- Shaker 2: Central x-position, lower back as y-position

In the seating cushion and foot area we mount

- Shaker 3: Central x-position, y-position is closer to backrest.
- Shaker 4: Central x- and y-position of the feet area placed under the rug.

There is also a significant difference between the four positions. One can notice for example a peak at the lower back at 40 Hz whereas only 40 % of the interviewees sensed vibration on the seating cushion at 40 Hz.

Secondly, the minimum threshold of total vibration was asked. It is found that the threshold of sensing is frequency dependent as well, graphically shown in figure 4.8. Comparing these results to the study [1] it is noticed that there are some significant differences in the perceptual threshold. Overall the threshold in a car is lower. The peaks do not occur at the same frequencies. It is stated that the different testing environments have a significant influence on the results.

The threshold response is used to define an amplitude spectrum that is applied on the output signal to the subwoofer for a representative emulation, using the shakers and the headrest.

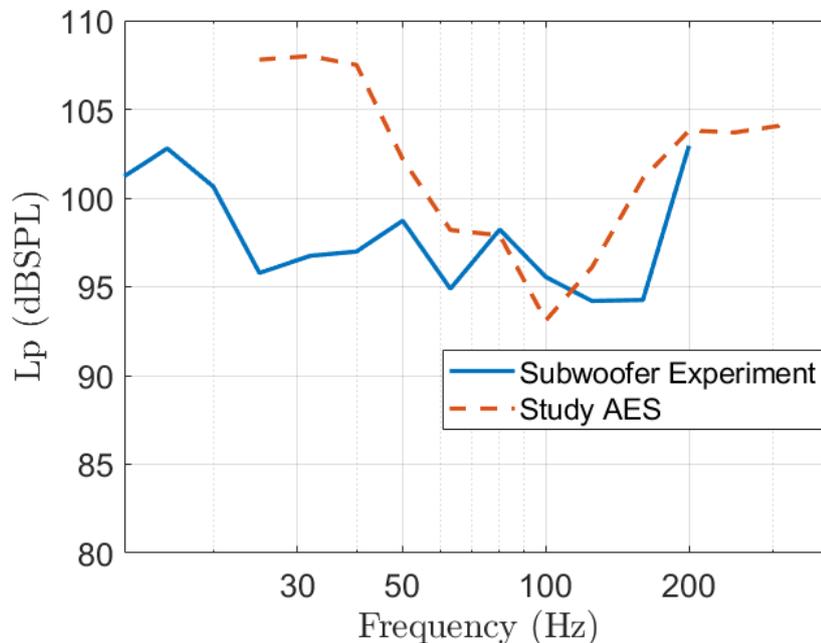


Figure 4.8: Mean SPL of threshold for sensing vibrations (dBSPL)

We now have four shakers that each have different frequency responses. With the threshold, the overall frequency-dependent amplitudes and levels are defined.

5

Shaker Placement and Implementation of the Sensory Impact Results

The four shaker positions are defined from the results of the subjective test. The subjective testing showed interesting insights. For further implementation it also needed, and interesting, to conduct objective measurements of the vibrations.

The objective data is used to convert the excitation of the subwoofer to the actual needed excitation of the shakers.

Secondly, the results are used to analyse the differences between objective and subjective testing of the vibration.

Shakers are force-driven transducers, as explained in the theoretical description of a shaker. The excitation can therefore not be measured with microphones since it is not the purpose to generate acoustic sound pressure.

The accelerations on the seats are measured using accelerometers.

5.1 Measurements of the Vibration Acceleration Levels

Vibration Acceleration Levels are used to express the amount of vibration measured on an object.

The quantity follows the decibel scale with dBVAL as the unit of the Vibration Acceleration Level. Where 115 dBVAL is the reference for the vibrations and 94 dB SPL is the reference for the sound pressure level.

Vibration Acceleration Levels in the decibel scale use a 10-base logarithmic scale with $2 \cdot 10e - 6$ as the reference.

ADAFRUIT ADXL326 accelerometers are used to read three-axis, (x, y, z) , acceleration values. The sensors are connected to the Audio Precision 586 multichannel audio analyzer that reads and converts the voltage output of the accelerometers to the relevant dBVAL-scale.

The accelerometers are mounted at the position where the shakers are implemented. The mounting follows the ISO standard for vehicle seat vibration [4] and the addi-

5. Shaker Placement and Implementation of the Sensory Impact Results

tional positioning of the shakers.

The sensors are kept in place by using medical bandages to ensure that the person does not experience disturbing edges of the sensor on the body.

The setup to measure the vibration acceleration levels is shown in figures 5.1 and 5.2.

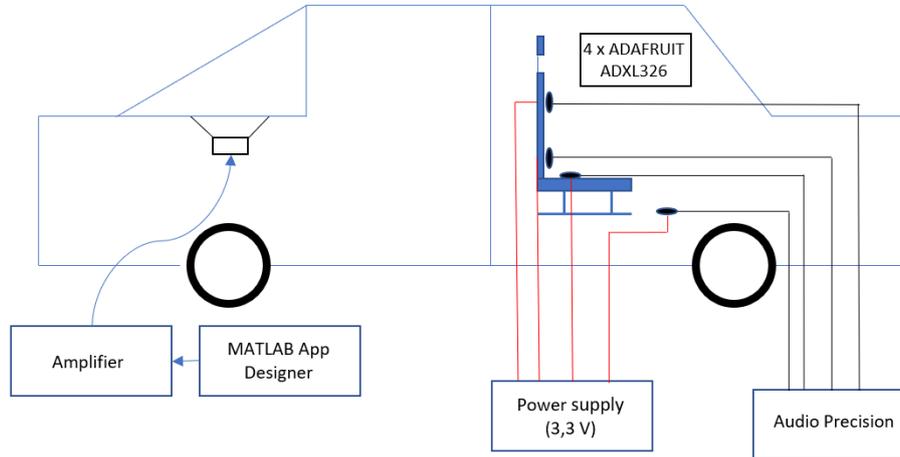


Figure 5.1: Setup Acceleration on the Seats

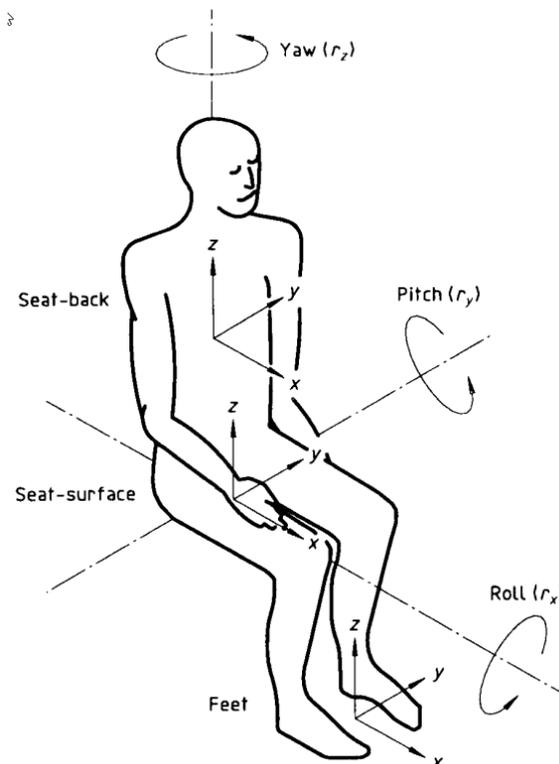


Figure 5.2: Seated Person as given in ISO Standard [3]

The calibration of the accelerometers is done by using a fixed metal jig in which a shaker, with a known frequency response, is excited by a pure sine tone of 100 Hz

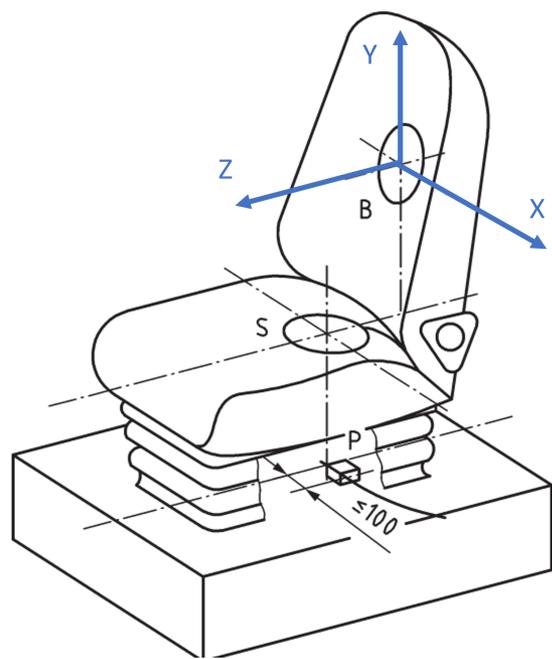


Figure 5.3: Accelerometer Integration in Seat [4]

and 1 Volt input.

That value corresponds to 115 dBVAL at 100 Hz and is used as the reference for the accelerometers. A standard accelerometer calibrator could not be used because of the dimensions of the excitation point of the calibrator. Accelerometers like the PCB Piezotronic are usually magnetic. That way the accelerometer can be rigidly mounted on the calibrator.

The ADAFRUIT accelerometers are not magnetic and have a square shape that does not fit on a standard calibrator.

A designated mounting piece is made so that the sensor can be rigidly mounted and measured in the three axes as it is presented in figure 5.4.

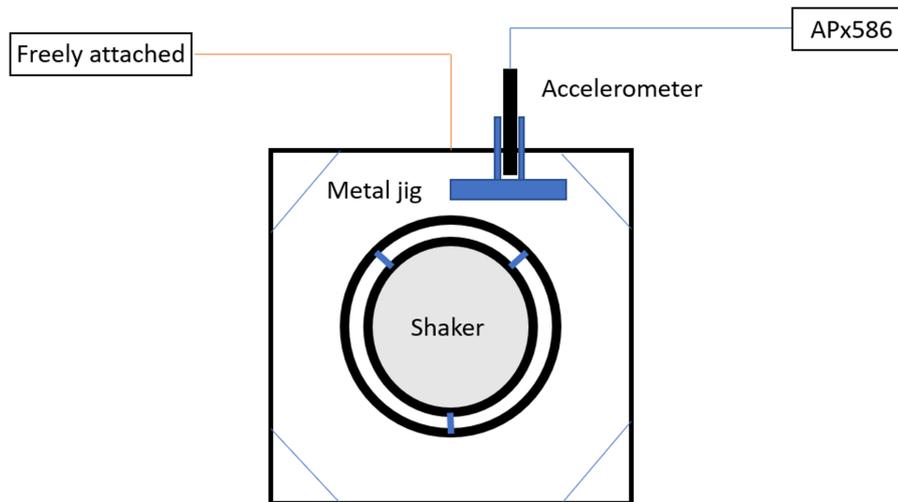


Figure 5.4: Accelerometer Calibration Setup

Standard accelerometer calibrators take 1 g , thus 9.81 m/s^2 , as a reference value and that corresponds to 140 dBVAL with $L_{ref,dBVAL} = 2 \cdot 10^{-6}\text{ m/s}^2$. The dB SPL and dB VAL scale are thus the same. The scale makes it useful to compare the excitation experienced in the sound both in the auditory acoustic domain and in the somatosensory and mechanical vibration domain. This should not be confused with the non-linear volume index behaviour of the shaker.

5.2 Results of Acceleration Levels

5.2.1 Subwoofer

The Vibration Acceleration Levels are measured for the subwoofer with an SPL of 104 dB SPL. 104 dB SPL is a level where it is known that the excitation is sensed by all interviewees.

As shown in figures 5.6, 5.5 and 5.7, it is found that there is a significant amount of acceleration in the y-direction and the z-direction for the seat measurement positions. The axes are defined in figure 5.3. The subwoofer is mounted in the y-direction. That might indicate the high amount of acceleration in that axis.

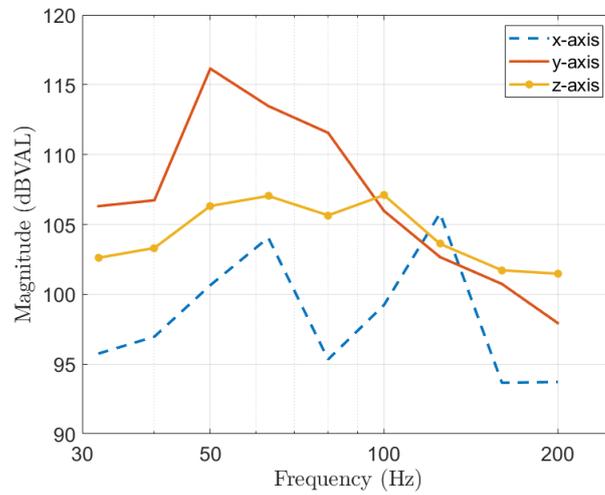


Figure 5.5: dBVAL Measurement at Upper Back Position, Lp = 104 dB SPL

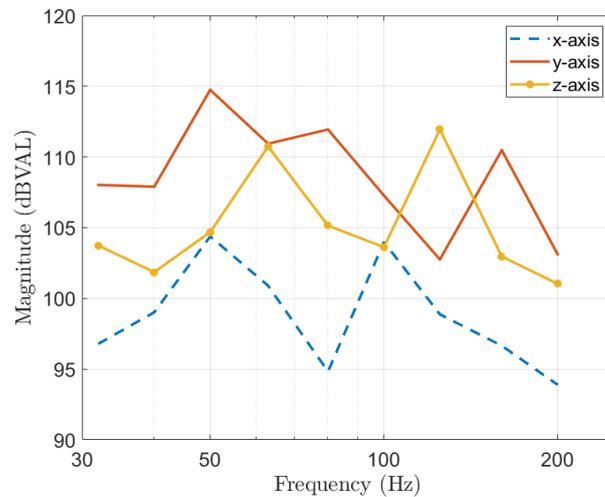


Figure 5.6: dBVAL Measurement at Lower Back Position, Lp = 104 dB SPL

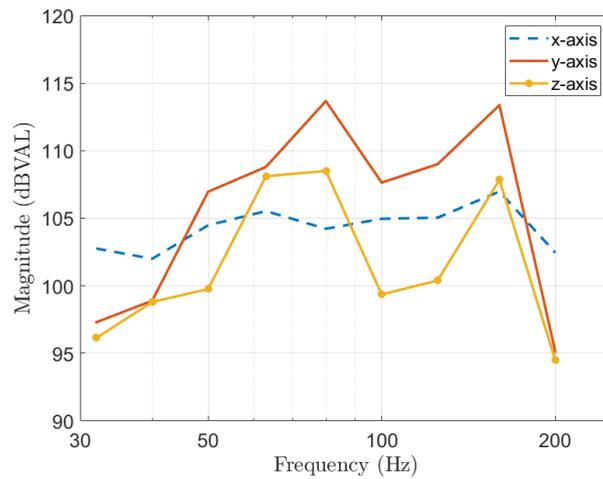


Figure 5.7: dBVAL Measurement at Seating Cushion, $L_p = 104$ dB SPL

5.2.2 Shakers

As with the calibration of the subwoofer, 1 Watt is used for the reference value. The Vibration Acceleration Levels are measured at the four shaker positions.

The results of the Acceleration Levels comply with the hypothesis. The highest acceleration levels are measured in the z-axis for the two shakers in the backrest and the y-axis for the seating cushion and the foot area. Which corresponds to the direction of excitation of the shakers.

The behaviour of the shaker as shown in figures, 5.8, 5.9 and 5.10 is now used to compare the behaviour of the subwoofer at a fixed sound pressure level of the subwoofer.

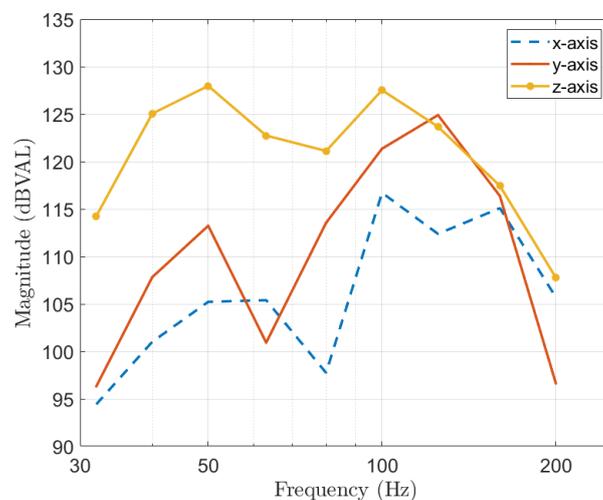


Figure 5.8: dBVAL Measurement at Upper Back Position, 1 Watt on Shaker

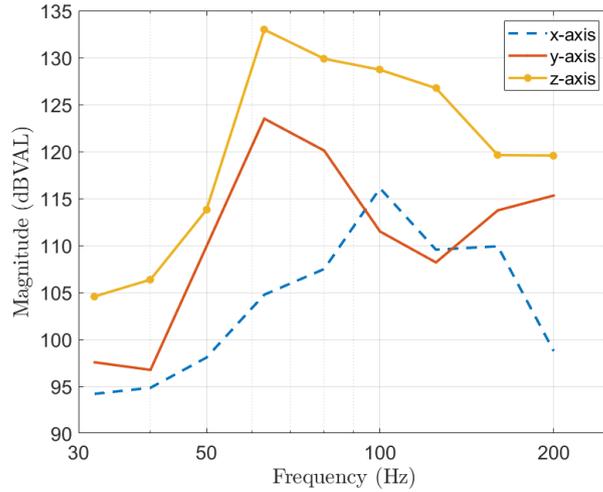


Figure 5.9: dBVAL Measurement at Lower Back Position, , 1 Watt on Shaker

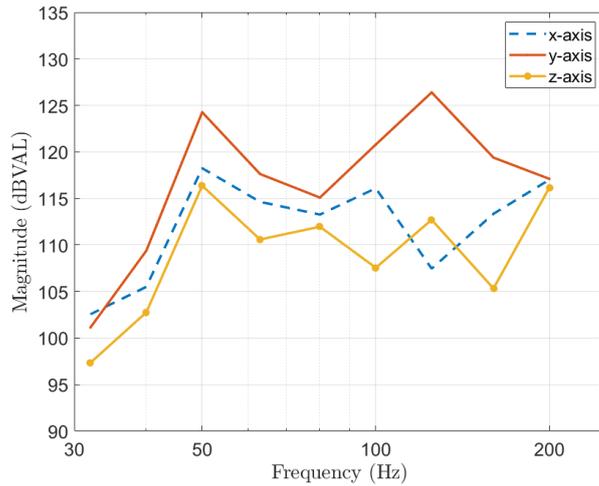


Figure 5.10: dBVAL Measurement at Seating Position, , 1 Watt on Shaker

5.3 Comparison Objective and Subjective Results

This first measurement round of the vibration acceleration levels aimed to understand the behaviour of the subwoofer and shaker under arbitrary conditions. The actual matching of the vibrations is done in the next part, described in chapter 6.

It is found that there are fewer similarities between the subjective and objective results of the lower back than the other three positions. The measurements show magnitude peaks at 63 Hz and 125 Hz. The subjective test results show peaks at [63, 80, 100, 200] Hz. Besides the common 63 Hz behaviour, the results differ.

For the upper body peaks occur at [25, 63, 100, 125, 200] Hz for the subjective tests. Whereas the dBVAL measurements only show relatively high levels between 50 Hz

and 80 Hz. A significant dip occurs in the subjective results at 50 Hz, even though high acceleration occurs at that frequency.

For the seating cushion, both test results show similar behaviour with peaks at 63 Hz and 160 Hz for the subjective test and 80 Hz and 160 Hz for the dBVAL measurements.

As shown in figure 2.1 on average bodies show resonance peaks at [70, 116, 210] Hz. The subjective and objective results don't necessarily confirm the peaks in terms of somatosensory behaviour.

The paper from Takashi about human body surface vibration claims that the head shows resonant behaviour between 31.5 Hz and 40 Hz [6]. That can only be confirmed using the subjective data. No accelerometer was connected in this position. Therefore no dBVAL data is available to compare to. Though approximately forty percent claimed to experience vibration in the head and neck area between 32 Hz and 40 Hz.

Germain Simon, Sean E. Olive, and Todd Welti investigated The Effect of Whole-body Vibrations on Preferred Bass Equalization of Automotive Audio Systems [1]. As in this thesis, they measured the acceleration levels excited on the seat for low frequencies. Their measurements indicate that the majority of the vibrations occur below 100 Hz.

The results of the measurements conducted in this report show similarities, though they are not completely similar. Still, a significant amount of vibration was measured at the lower back and on the seating cushion for frequencies above 100 Hz. At the upper back, the amount of vibration acceleration indeed decreases.

6

Shaker Implementation Testing and Validation

The subwoofer emits a sound pressure that is uniformly distributed in the car. A shaker emits the vibration locally. It is therefore important to verify if the objective level matching corresponds to valid matching results for the subjective experience of the interviewees.

The audio headrest is implemented in the seat. Since this contributes to the auditory aspect of the shaker implementation.

6.1 Implementation Validation

It is the purpose to define filtering so that for a chosen setting and sound pressure level the dBVAL, measured on the seat, is the same for both the subwoofer and the shakers. In the first evaluation round, the values are matched for a sine wave at the third-octave band frequencies. The $L_p = 104$ dB SPL and the needed adjustment is expressed using the equation (6.1).

$$\Delta_{adjustment} = dBVAL_{subwoofer} - dBVAL_{shaker,1Watt} \quad (6.1)$$

Matching the A/B Setup using a sine wave, led to insights that are used to re-evaluate the implementation.

For the A/B listening experiment, it is needed that the whole frequency spectrum matches. One needs to apply tuning and equalisation of the setup in the car.

A sound pressure level of +65 dB SPL at setting 20/30 of the level index is taken as the reference. As explained earlier, the index influences the output amplitude given from 0 to 1 with a step size of $\frac{1}{30}$. These data settings in the car correspond to a pink noise signal with a third-octave spectrum where each octave band has a sound pressure level of 65 dB SPL.

For the A setup, four different drivers are used, A subwoofer, a woofer, a mid-range driver, and a tweeter.

The crossover frequencies are 80 Hz, 200 Hz, 1 kHz.

A commonly used frequency curve is used as a guideline for the tuning. The frequency spectrum, shown in figure 6.1 needs to be measured to do this tuning.

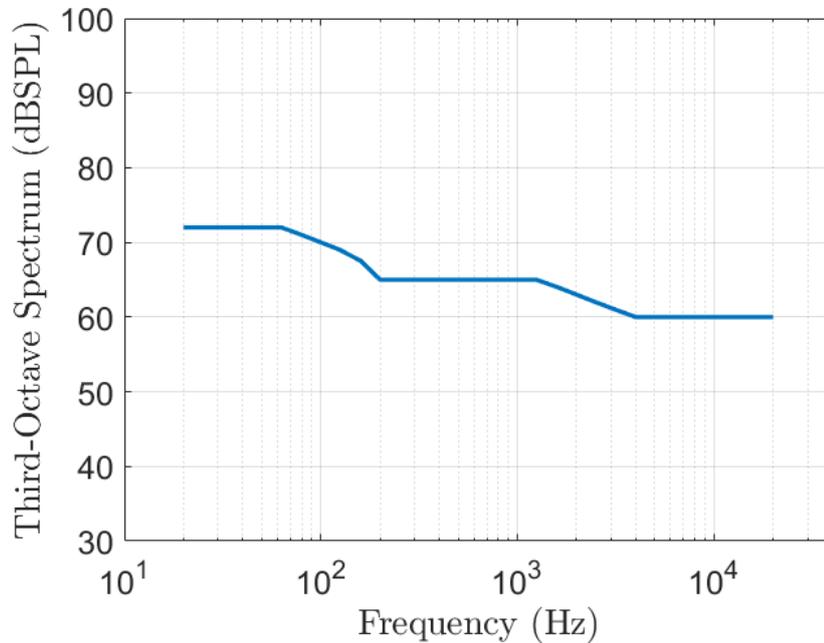


Figure 6.1: Reference Curve for Equalisation

A new measurement is thus introduced. The setup contains four microphones placed in a rectangular shape as shown in figures 6.2 and 6.3. A pink noise signal, (correlated -22 dB), is sent to the drivers. The Fast Fourier Transform of the octave spectrum is measured in the Audio Precision software. Then the arithmetic mean of the four microphones is calculated to derive a single-value frequency response.



Figure 6.2: 4 Microphones Setup Front View



Figure 6.3: 4 Microphones Setup Right Side View

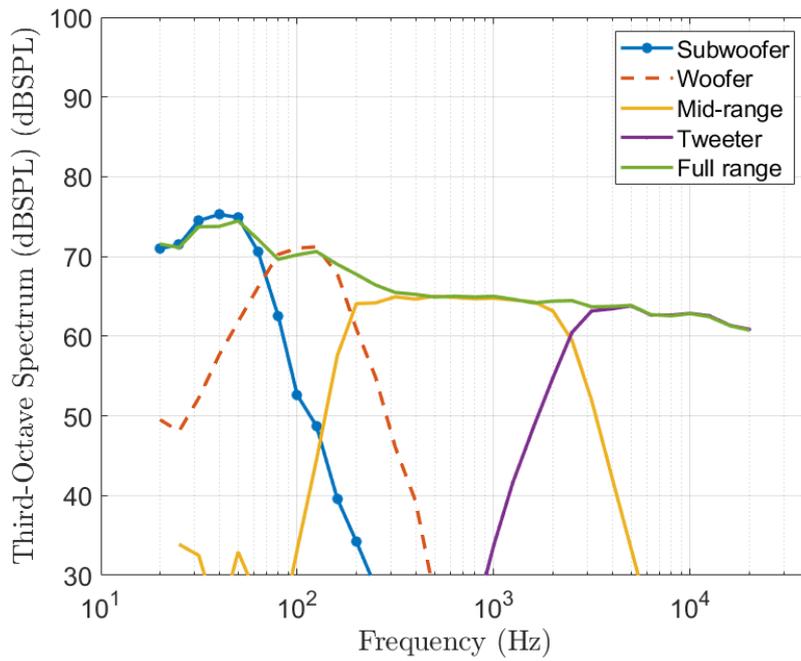


Figure 6.4: Frequency Response Setup A

Setup B needs to have the same frequency response so that the only difference is the vibration acceleration levels.

The frequency response is shown in figure 6.5

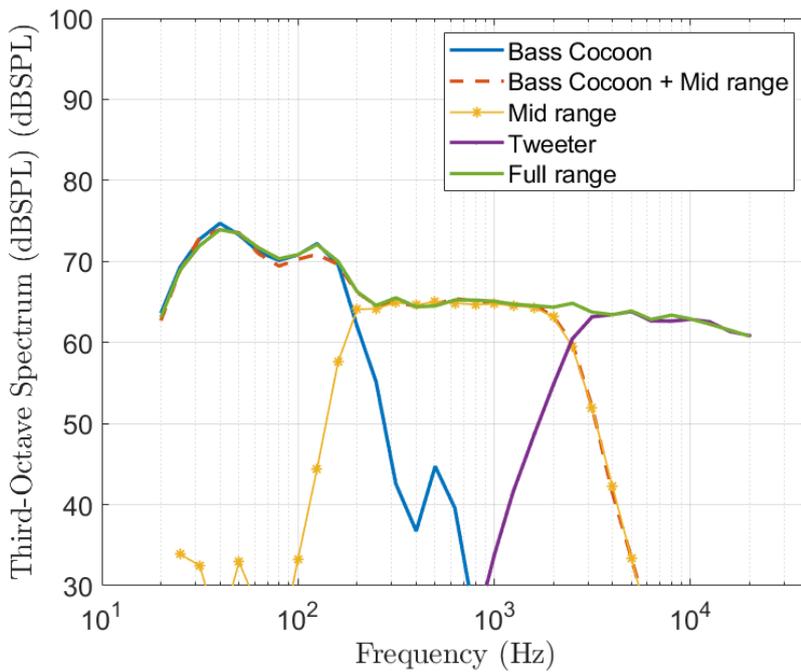


Figure 6.5: Frequency Response Low-Frequency Driver

The systems are aligned differently. The low-frequency drivers of the headrest are aligned closer to the ears than the subwoofer. Therefore time alignment is needed. This is done by using the distances from the speakers to the ear. The speed of sound in a car is taken as $c = 345$ m/s. Because sound travels faster in higher temperatures. According to the formula (6.2) from [12] we know that for a room temperature of $T = 25$ degrees celcius, $v_{in\ car} = 345 \frac{m}{s}$

$$v = 331 \frac{m}{s} + 0.6 \frac{m/s}{c} \cdot T \quad (6.2)$$

The driver dependent adjustments are shown in tables 6.1 and 6.2.

	Tweeter L	Tweeter R	Mid-range L	Mid-range R
distance (m)	0.82	1.27	0.79	1.3
time (ms)	2.38	3.68	2.29	3.77
needed delay (ms)	1.68	0.38	1.77	0.29
delay (samples)	49.39		44.39	

Table 6.1: Time alignment mid and high frequencies

	Woofers L	Woofers R	Subwoofer	Bass cocoon
distance (m)	1.24	1.24	1.4	0.07
time (ms)	3.58	3.58	4.06	0.2
needed delay (ms)	0.48	0.48	0	3.86
delay (samples)	22.96		0	185

Table 6.2: Time alignment mid and high frequencies

The Haas effect discusses the influence of time alignment on the perception of the location of the sound [13]. The effect is taken into account while adding delay. The subwoofer has no time delay since the distance to the subwoofer is the longest. The subwoofer is thus taken as the reference.

Because of the tuning, the behaviour of the subwoofer needs to be re-measured so that the shakers can be matched with the subwoofer.

The vibration acceleration is measured using the same accelerometers that are described in chapter 5. A pure sine tone is used as the test signal.

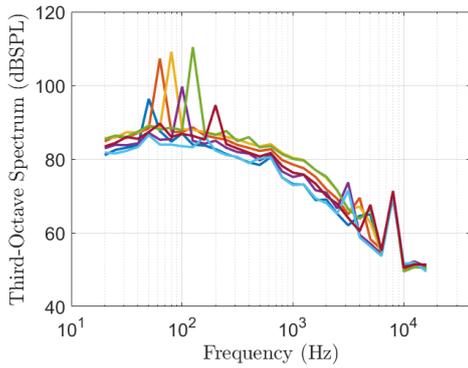


Figure 6.6: dBVAL of Tuned Subwoofer: Floor

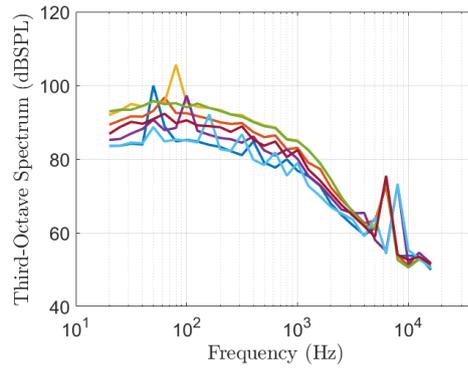


Figure 6.7: dBVAL of Tuned Subwoofer: Seating Cushion

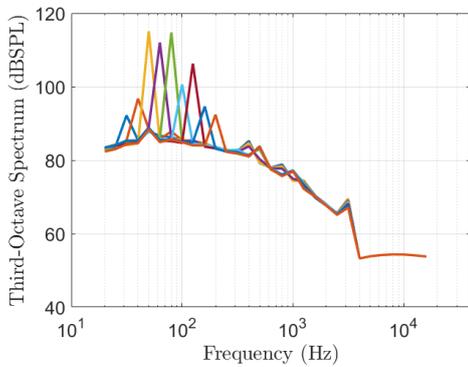


Figure 6.8: dBVAL of Tuned Subwoofer: Lower Back

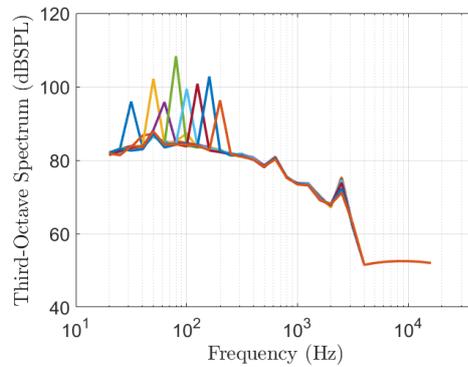


Figure 6.9: dBVAL of tuned Subwoofer: Upper Back

As with the tuning of the low-frequency drivers, these curves and values are taken as the reference to tune the shakers.

The tuning is done for all four shakers, while the whole setup is active. That way the structural vibration influence from the other shakers is considered in the complete tuning.

The measurement curves of the tuned shakers are given in figures 6.10, 6.11, 6.12 and 6.13. 50 Hz is taken as the lower limit due to necessary low-shelf filtering. The target frequency, and thus quality, of the shakers and low-frequency drivers do not reach the lower frequencies properly.

It is noticeable that the peaks of the subwoofer compared to the shaker do not match perfectly at some frequencies. It is hard to match the acceleration levels of the shakers at some frequencies due to the influence of the neighbouring shakers and the significant differences between the magnitudes of the peaks.

The equalisation is done per third-octave frequency. A maximum $Q = 4$ is used since a third-octave filter has a Q -factor around four, where Q is the ratio of the

center frequency and the bandwidth. Filtering with bands that are narrower than the measurement accuracy needs to be avoided. Some frequencies needed attenuation of 20 dB whereas the neighbouring octave band needed a boost of 2 dB. These different gain factors influence each other due to the limited Q factor. A compromise between attenuation and Q factor needs to be made.

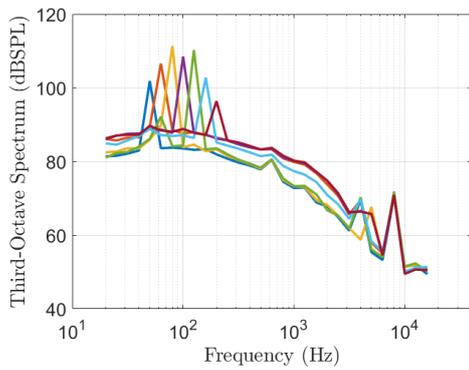


Figure 6.10: dBVAL of Tuned Shaker: Floor

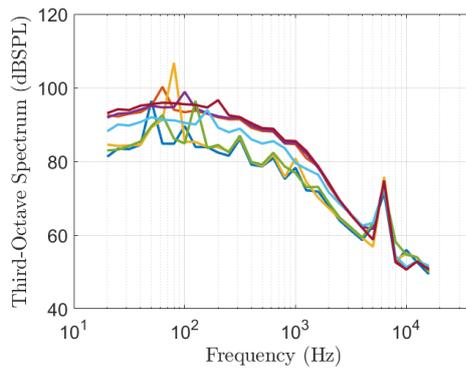


Figure 6.11: dBVAL of Tuned Shaker: Seating Cushion

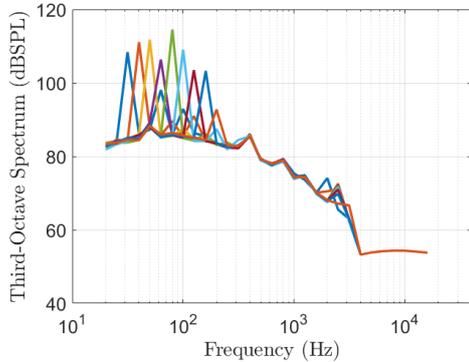


Figure 6.12: dBVAL of Tuned Shaker: Lower Back

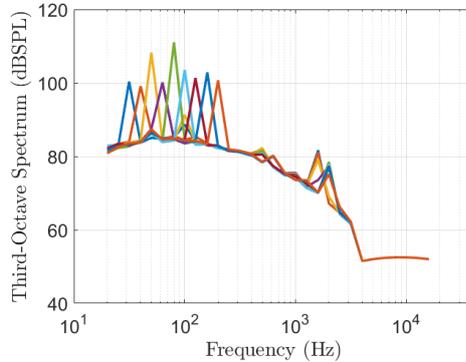


Figure 6.13: dBVAL of tuned Shaker: Upper Back

6.2 A/B Listening Test Description and Setup

The implementation needs to be subjectively evaluated as with the first subwoofer experiment. Therefore an additional listening test is conducted.

The flowcharts of the A/B listening setup are shown in figures 6.14 and 6.15.

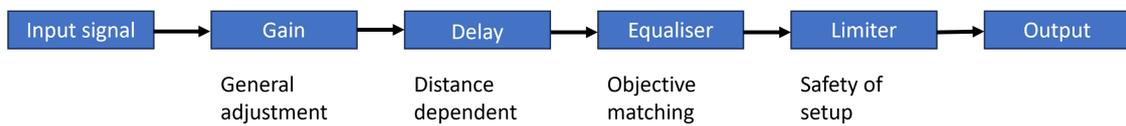


Figure 6.14: Flowchart Simulink

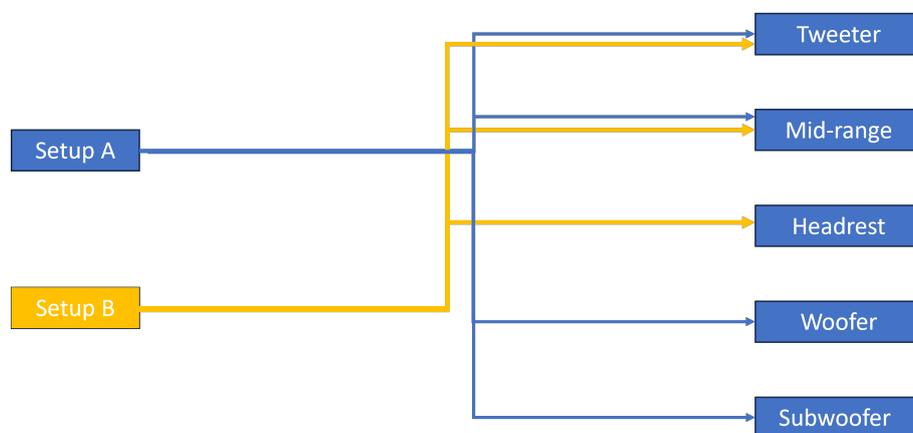


Figure 6.15: Flowchart A/B Setups

6. Shaker Implementation Testing and Validation

A/B Comparison: Level index 15

Please select the relevant number

Setting 5: A and B have the same amount of vibration

Setting 1: A has significant higher amount of vibration

Setting 9: B has significant higher amount of vibration

The figure shows a digital form for an A/B listening test. It consists of two main sections, each with a title, a level setting, and a 9-point scale. The first section is titled '1. Overall Feeling: Level setting 15 *'. Below the title is a row of nine buttons labeled 1 through 9. Below the buttons, there are two text labels: 'A has a significant higher amount of vibrations' on the left and 'B has a significant higher amount of vibrations' on the right. The second section is titled '2. Floor shaker: Level setting 15 *'. It also has a row of nine buttons labeled 1 through 9, and the same two text labels below it. The form is presented in a light gray background with a white border.

Figure 6.16: A/B Listening Test Form

The interviews take place in the driver's seat where the shakers and headrest for the audio headrest are implemented.

The interviewees listen to an A/B setup with:

- A: Subwoofers + Woofers + Mid-ranges + Tweeters
- B: Shakers + Audio Headrest + Mid-ranges + Tweeters

The A/B test is done at multiple Sound Pressure Levels.

For each Sound Pressure Level, the interviewee is asked to describe the difference in perceived vibration between setups A and B. This is done per shaker location, as shown in the figure 6.16.

6.3 A/B Listening Test Results

The A/B test led to interesting and diverse answers. From the thirteen results, it is clear that the sensed vibration is still a subjective matter.

The overall feeling at level index fifteen is according to the interviewees more present for setup A, histogram 6.17. Whereas this is more spread out at level twenty in figure 6.22.

The majority indicated a similar amount of vibration of setups A and B on the floor at level fifteen, figure 6.18. Though 38 percent sensed higher vibration in situation A. The woofer is placed in the door, at leg height. Sound pressure from the side is thus emitted. This introduces sensed vibration that is rather uniformly distributed. The floor shaker on the other hand has a fixed position. The dBVAL-measurements were taken right above the shaker. A slightly different position of the feet may result in a significant difference in sensed vibration. Histogram 6.23 shows more equally distributed answers on the A/B test.

For the seating cushion at level fifteen, the answers are rather equally distributed with a small shift towards the right looking at graph 6.19. This indicates that setup B leads to a slightly higher perceived amount of vibration.

For level twenty in figure 6.24, no apparent conclusion can be taken. Percentage-wise, the majority indicates an equal or lower amount of sensed vibration with the shaker setup. On the other hand, the answers are more extreme for those who claimed to sense a higher amount of vibration in setup B.

The answers for the sensed vibration at the lower back differ for the two-level indices. At level index fifteen, figure 6.20, 69 percent sense an equal or higher amount of vibration in the shaker setup. Whereas this changes to 69 percent find setup A to vibrate equal to or more than setup B at level index twenty, figure 6.25.

For the upper back at both index levels shown in histograms 6.21 and 6.26, the interviewees find the shaker setup to vibrate more. It is a possibility that the sensed vibrations are influenced by the behaviour of the headrest.

At very low frequencies, the headrest behaves as a shaker that excites the head the most to be specific.

However, due to the structural vibration of the metal connectors of the headrest into the seat, additional vibrations may be sensed at the upper back.

The distance from the head to the headrest plays a big role in the sensed amount of vibration in the upper back and head area.

In general, it is concluded that the perception of vibration in different body zones is not as uniformly distributed as expected. One can state that the implementation of shakers in a seat leads to a very subjective amount of perceived vibration.

Besides personal preference, weight, height, etc. could play a role. Since the shakers

are force-driven transducers that need a counter-force to emit the right amount of vibration.

The vibration acceleration level measurements were done using a person weighing 90 kg as the reference weight. From experimental measurements, it became clear that an unloaded versus a loaded seat leads to significantly different vibration acceleration levels.

Both the amount of vibration and the most prominent direction of vibration differ. Using this information, the weight difference of the interviewees is a possible cause of the rather extreme answers in the A/B listening experiment.

An extra comment section was provided so that the listeners could give feedback on the implementation.

The feedback can be separated into different groups, as given below.

Small differences:

- "Close match, differences are more in the 2D vibration pattern rather than the magnitudes of the different zones."
- "Slightly more perceptible vibrations in A but differences are small"
- "Difficult exercise"
- "Nice"

As discussed earlier, the acceleration levels were not completely matched for every direction. The comment on this directional behaviour can thus be confirmed by looking at the results of the vibration acceleration levels.

The shaker setup is perceived as a higher amount of vibration:

- "In general very pleasant feeling, setup B is a little too much, setting between A and B would be ideal."
- "A bit too much punch from lower back shakers: resulting in higher vibration level, but could have been boosted lower in frequency."
- "Upper back shakers should be more subtle in my opinion."
- "I prefer less vibration in the upper seat. Lower back and feet can have a bit more. Setting A suits me best."

These comments are consistent with the outcome that was expected before the interview. Firstly it was known that the headrest had an influence on the upper back vibrations at the low frequencies. Secondly, the weight of the listener could influence the sensed amount of vibration. Thirdly, the positioning of the feet is an important factor in terms of similar sensed vibrations. The interviewees who claimed to sense even the small differences can be supported by the fact that the tuning and level matching of the shakers was not absolute.

Though the results and feedback are not the most desirable outcome of the project, interesting insights have been acquired.

The fact that the majority of comments and results of the interview can be confirmed by the objective measurements and analysis leaves the project with positive room for improvement.

It is claimed that with optimisation of the objective measurement method, e.g. using high-end sensors, and precise adjustments of the vibration acceleration level measurements a useful tool is developed to objectively implement shakers in seats in combination with the full range audio headrest.

Additionally, a feedback loop could be introduced so that weight differences are taken into account and the amount of excited vibration is adjusted accordingly to the counter mass.

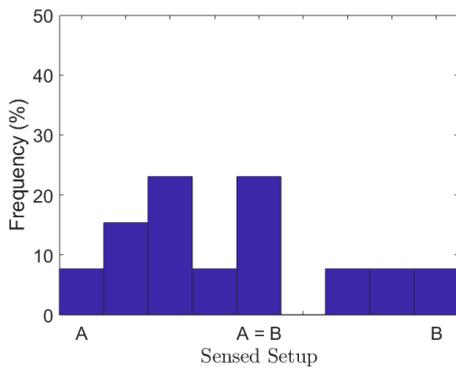


Figure 6.17: Histogram Overall Feeling at Level 15

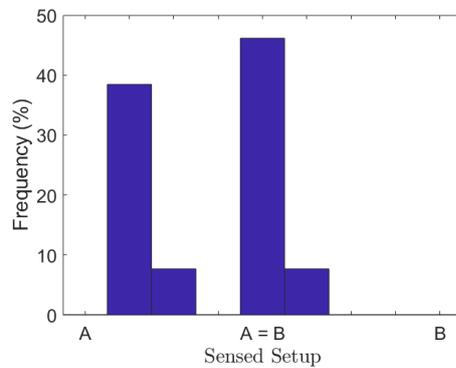


Figure 6.18: Histogram Floor Vibrations at Level 15

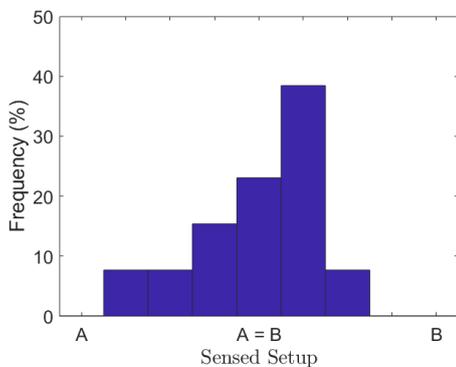


Figure 6.19: Histogram Seating Cushion at Level 15

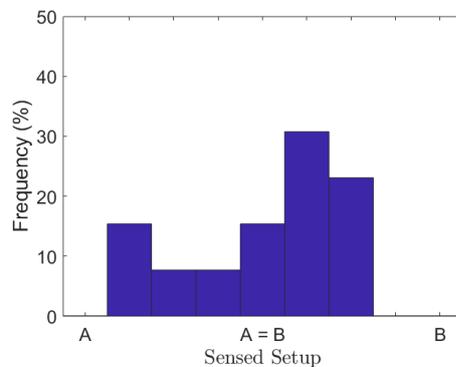


Figure 6.20: Histogram Lower Back at Level 15

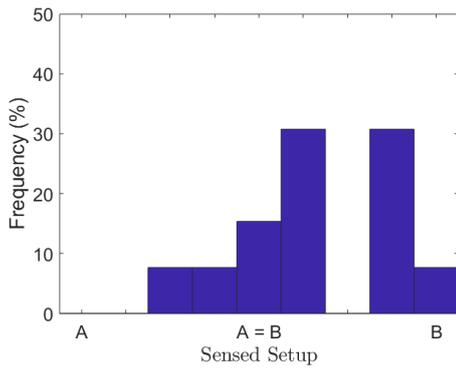


Figure 6.21: Histogram Upper Back at Level 15

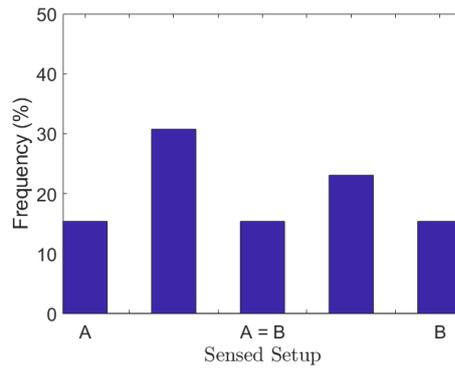


Figure 6.22: Histogram Overall Feeling at Level 20

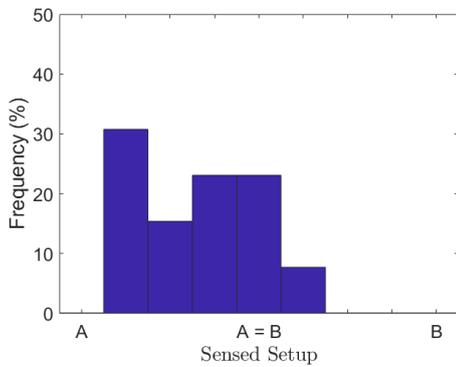


Figure 6.23: Histogram Floor at Level 20

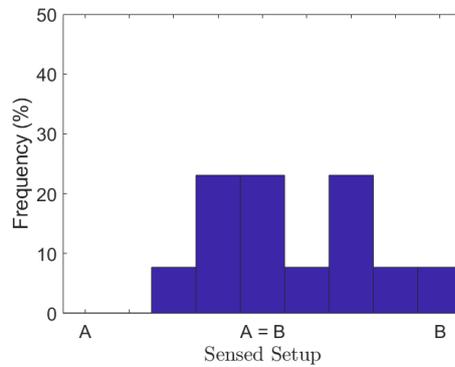


Figure 6.24: Histogram Seating Cushion at Level 20

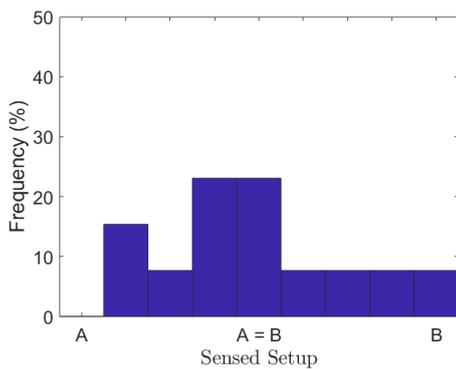


Figure 6.25: Histogram Lower Back at Level 20

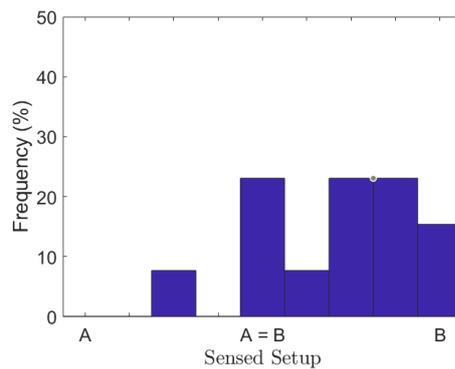


Figure 6.26: Histogram Upper Back at Level 20

7

Discussion

7.1 Subjective Subwoofer Experiment

A subjective test, with eighteen participants, was conducted to investigate the body zones where the vibration of a low-frequency subwoofer is sensed. With third octave frequencies from 13 Hz - 200 Hz.

The body zones per frequency are shown in the figures. 4.6 and 4.7.

It is noticed that the different body zones are excited differently over frequency. From these results, it is defined that four shakers are used. Namely one shaker in the seating cushion. Two shakers in the backrest, one positioned at the lower back and one at the upper back.

A significant amount of participants indicated sensed vibration at the feet. The additional fourth shaker is therefore added under the rug of the car.

Though the participants found the head and neck to be excited, it was chosen to implement shakers in the neck and or head since those vibrations do not correspond with an actual enjoyable experience.

The second part of the subwoofer experiment handled the threshold where all possible zones were still excited, as shown in figure 4.8.

As with the body area influence, the threshold of sensing vibration is frequency-dependent.

7.2 Objective Measurements

The four shaker positions are defined by concluding the results of the subwoofer experiment. Additionally, objective measurements were done to define both the differences and similarities between objective measurements and the subjective subwoofer experiment.

The results of the acceleration level measurements, using the accelerometers measured in dBVAL, were used in the further development of the shaker implementation to match the vibrations of the subwoofer and shaker. It is found that there are similarities but also differences between the perception and the objective measurements of frequency-dependent vibrations.

From the acceleration measurements, it is noticed that the subwoofer emits a significant amount of vibration in the x- and y-direction. For future research, it could be interesting to investigate a method to excite frequency-dependent vibrations in

these directions. As well as the influence of the mounting direction of the subwoofer.

It was chosen to adjust the working method by matching the vibration levels based on the objective data of the subwoofer instead of the subjective data. The dBVAL measurements at 104 dB SPL for the subwoofer and 1 Watt for the shaker seemed interesting but were not completely useful for further level matching. By doing the A/B test with objective equalisation, it is possible to verify if filtering can be done based on measurements instead of subjective tuning.

7.3 Implementation of the Shakers and Headrest

The sound pressure levels of setups A and B are matched using equalisation tuning and filtering in Simulink. Where A uses the subwoofer, woofer, mid-range, and tweeters and B uses the shakers, low-frequency headrest drivers, mid-range, and tweeters. The subwoofer setup, A, and the shaker setup, B, are tweaked so that they have the same frequency response.

Besides the pressure level tuning, the vibration acceleration levels were matched. The re-measuring of the subwoofer dBVAL showed significant differences between body areas and frequencies. It is also noticed that acceleration level matching is not absolute, due to the limits of the Q factor and different gain factors per third-octave band.

With these measurements and adjustments, the A/B test was set up.

7.4 A/B Test

For the A/B test, it is known that both systems have a matched frequency response. This is important to isolate the influence of the auditory aspect of the experiment. It was the main purpose to verify the differences in perceived vibration instead of the perceived auditory difference.

The results of the interview led to divided histograms. The results show a level-dependent difference for the different body areas where for some areas a majority of the interviewees perceived a higher amount of vibration with the shaker implementation and at other body parts, or level indices, it was the other way around.

Clear Gaussian curve behaviour did not appear for every question, which ideally would have been the case. A higher number of interviewees could improve the quality of the histogram results.

8

Conclusion

The loudspeaker company Premium Sound Solutions requested to research the implementation of non-linear seat shaker processors for enhanced integration with the full-range audio systems in the car. It was the purpose to develop a method to evaluate and implement the technology so that an optimal personal listening experience, using the shaker transducers, was achieved.

The research was split into three main segments.

Firstly, preliminary researches were conducted to investigate possible research methods that are relevant within this field of electroacoustics.

Secondly, a subwoofer experiment was created to evaluate the influence of a subwoofer on the vibration experienced by a person sitting in a car.

Thirdly the shaker implementation was evaluated by doing an A/B listening test with setup A being the subwoofer and woofer plus mid-range and tweeters and setup B being the shakers and bass cocoon plus mid-range and tweeters.

For the subwoofer experiment, the listener needed to specify the body areas where vibration was sensed per third-octave band from 13 Hz - 200 Hz.

The interviewees determined the threshold at the point where the most amount of body areas still experienced vibrations.

The data is used to define the four positions where the shakers are placed in the car seat, namely the upper back, the lower back, the seating cushion, and under the rug.

A first round of objective measurements was done at the highest measured threshold of $L_p = 104$ dBSPL. It is found that there are similarities but also differences between the subjective and objective measurements of the vibration introduced on the seat.

Thirdly the shakers and headrest are implemented in the seat. Two full-range audio systems are set up with the purpose of an A/B test.

Both setups need to be tuned so that they have matching sound pressure levels and vibration acceleration levels. The subwoofer is taken as the reference for the matching.

The subwoofer setup was tuned to the point where it followed the reference curve that is commonly used in the tuning of audio systems in a car.

The acceleration levels are objectively measured and used as the reference data.

Then the shakers are tweaked so that the acceleration levels of the shakers and the subwoofer are as similar as possible. It is found that this is not absolute due to the limitations of tuning at specific neighbouring frequencies.

An A/B test is conducted where the thirteen trained listeners define the sensed difference per shaker position at different level index settings.

Useful insights and takeaways are acquired from the results.

The differences between the subwoofer setup and the shaker setup are area and level-dependent.

The results and feedback are in line with the objective measurements and their corresponding limitations.

Though the interviewees were trained listeners, thirteen people is still a small amount of data that is used for the analysis. In the future listening tests with more interviewees are favorable to improve the data and thus confirmation of the working method of this thesis project.

The outcome of this project shows that the used method has potential but that it is not yet optimal and perfect. Multiple factors can be improved. For example, interviewing more trained listeners, using high-end accelerometers so that the objective measurements of the vibration acceleration levels at different areas in the seat are more accurate. The matching of the vibration acceleration of the shakers to the subwoofer behaviour can be optimized using the full range octave spectrum rather than third-octave bands. The researches that were done on whole body vibration have shown interesting working methods to define the behaviour for the full spectrum. A link with this method to measure the FRF and transfer function might be interesting.

Overall, a positive yet critical conclusion is made for the study of non-linear seat shaker processors for enhanced integration with full-range audio systems.

Bibliography

- [1] Adam Ford, Ludovico Ausiello, and Chris Barlow. Characteristics of whole-body vibration induced through low-frequency sound exposure. 2019.
- [2] Per Sjösten. Lecture notes electroacoustics, chap. 3,4.
- [3] International Organization for Standardization (ISO). Preferred reference values for acoustical and vibratory levels. Standard ISO 1683, ISO, Geneva, Switzerland, May 2015.
- [4] International Organization for Standardization (ISO). Laboratory method for evaluating vehicle seat vibration. Standard ISO10326-1:2016, ISO, Geneva, Switzerland, November 2016.
- [5] Yukio Takahashi. Vibratory sensation induced by low-frequency noise: The threshold for “vibration perceived in the head” in normal-hearing subjects. *Human Engineering and Risk Management Research Group, National Institute of Occupational Safety and Health, Japan*, 2001.
- [6] Yukio Takahashi, Kazuo Kanada, and Yoshiharu Yonekawa. Some characteristics of human body surface vibration induced by low frequency noise. *National Institute of Industrial Health*, 2002.
- [7] Yukio Takahashi, Kazuo Kanada, and Yoshiharu Yonekawa. The relationship between vibratory sensation and body surface vibration induced by low-frequency noise. *National Institute of Industrial Health*, 2002.
- [8] Altinsoy E. Maravich M.M. Influence of seat vibration frequency on total annoyance and interaction effects caused by simultaneous noise and seat vibrations in commercial vehicles. 2022.
- [9] International Organization for Standardization (ISO). Vibration and shock – evaluation of human exposure to whole-body vibration – part 1: General requirements. Standard ISO2631-1, ISO, Geneva, Switzerland, May 1997.
- [10] David Corynen. Dipole loudspeaker for producing sound at bass frequencies, EP Patent EP3729822B1, Oct. 2023.
- [11] Daniele Ponteggia. Application note: Measuring maximum subwoofer output according ansi/cea-2010 standard. *AN-007 Application Note*, 2010.
- [12] Iowa State University. Temperature and the speed of sound.
- [13] Michael Pastore and Jonas Braasch. The haas effect - lateral extent and perceptual weighting of localization cues. *The Journal of the Acoustical Society of America*, 133:3512, 05 2013.

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