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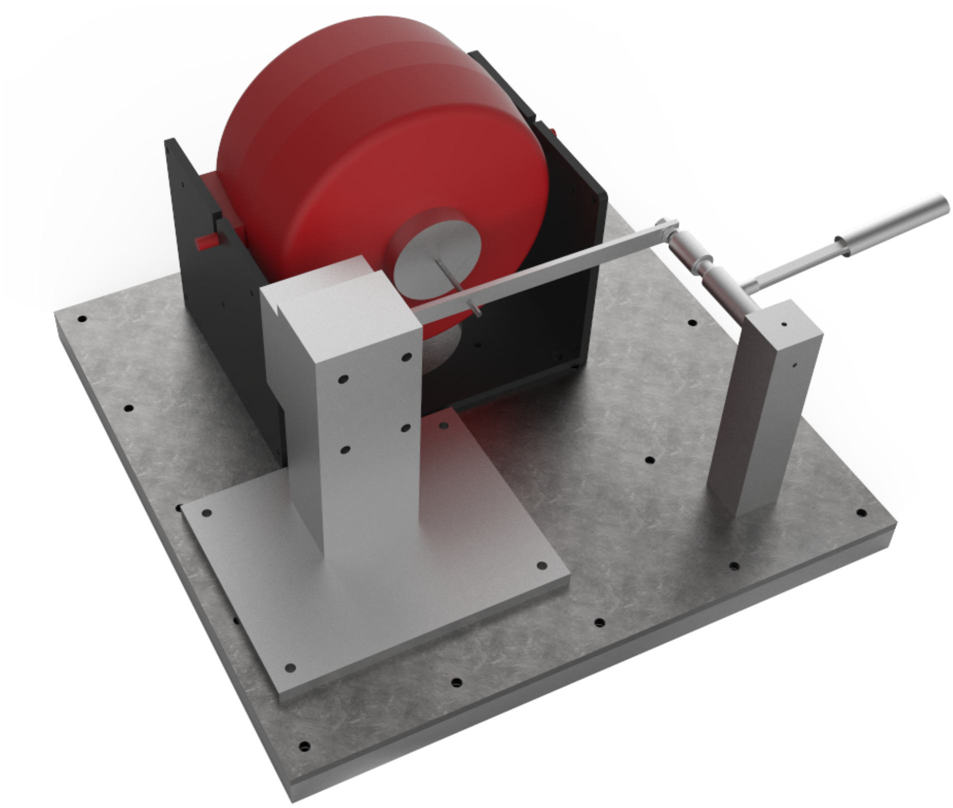

Fundamental Physical Testing of Rattle

Design and Evaluation of a Rattle Producing Test Rig

Master's thesis in Applied Mechanics

JONATHAN HASSELSTRÖM
AXEL SVENSSON

Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017

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Supervisor: MOHSEN BAYANI KHAKNEJAD, Volvo Car Corporation
Examiner: MIKAEL ENELUND, Applied Mechanics

Master's Thesis 2017:22
Department of Applied Mechanics
Division of Dynamics
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Rendered Coumputer Aided Design (CAD) assembly of Test Rig

Typeset in LaTeX
Printed by department of Applied Mechanics, Chalmers University of Technology
Gothenburg, Sweden 2017

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Abstract

Squeak and rattle is a cause of high warranty costs and a driver behind the production of pre-series cars for subjective evaluation. An important feature for a premium car brand is a high perceived quality and consequently the lack of squeak and rattle issues. To bring down development time and cost while still increasing the squeak and rattle capabilities, the automotive industry is now striving towards better models for virtual evaluation of squeak and rattle.

This master's thesis is a step toward virtual rattle evaluations at Volvo Car Corporation. A test rig for rattle measurement was successfully designed, built, tested and evaluated. An objective rattle metric, based on psychoacoustics theory, was evaluated by comparison of subjective clinical trial results of rattle produced by the test rig. Some features, such as temperature dependency, could be verified through the virtual evaluation of rattle with the objective metric while other features could not, judging from comparisons with the subjective data. The overall congruence between subjective and objective evaluation was inconsistent. More work is needed before any model for virtual evaluation can be used in the development of new car models.

However, all hypotheses set out by the group were confirmed, if considering the mean value trends, both by the objective metric and the subjective listening clinical trials if studying the results of these independently. This means that both of the evaluation methods work well by itself but that the connection between them is yet to be established.

Keywords: Squeak, Rattle, Clinical Trials, Virtual evaluation, Psychoacoustics, Physical Testing

Acknowledgements

This report is submitted to fulfill the requirement of the Master's degree at Chalmers University of Technology, Gothenburg and has been carried out in collaboration with Volvo Car Corporation and Fraunhofer-Chalmers Centre in Gothenburg, Sweden. The work was conducted during the spring semester of 2017.

Many have contributed in this project. The group would like to give special thanks to the supervisor at Volvo Cars Company, Mohsen Bayani, for his helpful insight in the subject and the process of the project. The supervisor at Fraunhofer-Chalmers Centre, Samuel Lorin, has been very helpful when discussing fundamental theory of rattle, a subject previously not studied by the group, and the group is grateful for his support. We would also like to thank Mikael Enelund, examiner at Chalmers, who has, beside his role of being the examiner, been very active and keen about the process of the work and supporting with many tips. Workshop personnel at Chalmers University at Technology, especially Jan Bragee and Reine Nohlborg, were very helpful in the design process of the test rig. Informal supervisors at VCC have also been helpful, especially Anneli Rosell and Penka Dinkova which have contributed a lot in keeping this thesis moving forward by helping out with many practical issues at VCC. Last, but not least, we would like to thank everyone that participated in the listening clinical trials in general and Victor Andersson, Erik Ekstrand and Daniel Eriksson in particular.

Jonathan Hasselström , Gothenburg, May 2017
Axel Svensson, Gothenburg, May 2017

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1
Introduction

Squeak and rattle (S&R) is the audible sound produced by relative motion of adjacent parts. Squeak comes from relative transverse motion between parts and rattle is formed from relative motion between parts with a short loss of contact.

1.1 Background

S&R is consistently ranking among the most important factors for the overall perceived quality of new cars. As Volvo Car Corporation (VCC) is branding itself as a premium car manufacturer the issue of S&R is one of increasing importance. VCC is currently investing heavily in the research of S&R related issues and is striving to become a forerunner in the subject. This thesis work is a part of that effort and is as well a cooperation between several of VCC's partners, including Chalmers University of Technology, Fraunhofer Chalmers Centre and Wingquist Laboratory.

1.2 Purpose

In order to have a full connection between perceived rattle sound and computer simulation the parameters that affect rattle sound must be established. A test rig is to be designed where the alteration of such parameters is swift and the corresponding influences can be evaluated in a scientific manner. By a design of experiments (DOE) the overall behaviour and influence of these parameters on the perceived rattle noise are sought to be found.

Repeatability and alignment to simulation are integral parts of the overall performance of the physical test rig. Build quality and robustness are therefore of utter importance towards finding the influence of given parameters in perceived rattle noise. Validation of the physical test rig is to be achieved through a modal analysis using finite element analysis (FEA).

1.3 Clarification of the Issue

By answering the following questions the full scope of the project is covered.

- What fundamental parameters can be identified to affect the perceived rattle noise?
- What connection between subjective rattle evaluation and objective rattle evaluation can be found?

Note that the second question is based on that the group has time to perform the tasks set up as extracurricular. See Section 1.4 below.

1.4 Goals

This thesis work is intended to act as a stepping stone for further research within the S&R field at VCC. The project covers the start up phase towards a fully virtual evaluation of S&R related issues. The goals of the project are to:

- Create a stripped down experimental setup for rattle evaluation
- Identify parameters that are influencing rattle

1.5 Deliverables

Below are the deliverables for this project listed,

- Literature studies on previous experiments on rattle evaluation
- Determine the underlying parameters influential on rattle
- Build physical test rig
- Validate test rig through eigenmode analysis
- Perform rattle measurements

A couple of deliverables was set up as additional tasks for the students to perform if time allowed. These included,

- Calculate objective annoyance value of recorded sounds
- Host listening clinical trials of recorded sounds generated by the test rig

1.6 Limitations

Even though simulation is the core for virtual evaluation there will be no simulation, except the FEM validation, included in the scope of this work. The work is instead focused on finding the fundamental underlying variables to rattle producing noises. Parts such as signal processing and data implementation are left for future studies, as well as the mechanisms of squeak even though it is a close relative to rattle. The rig is to be designed and built in such a manner that it is portable, to enable transportation between climate chambers and quiet testing rooms. The choice of the shaker is implicit since it is provided by VCC. Any tests performed with the test rig is limited to be performed in the temperature span $-10°C$ to $+40°C$, this because of temperature limitations on the components used.

1.7 Hypotheses

With the background of creating a physical test rig by which to measure and evaluate different rattle sounds produced by material and gap combinations, the group has some initial hypotheses about the outcome of the testing.

After elaboration, the groups hypothesis is that there should be a distinct difference in perceived annoyance divided into three material pair categories.

1. Metal - Metal
2. Metal - Plastic
3. Plastic - Plastic

where the annoyance should follow the list in descending order, meaning that the *Metal - Metal* category should be the worst.

The group also hypothesize that the gap should influence the annoyance less with an increasing gap size. The greater the gap, the lesser the force on impact, resulting in a quieter propagated sound. The group is indecisive about how the pre-loaded case would affect the annoyance.

Regarding the temperature the groups hypothesis is that, especially for the plastics, the annoyance will increase with decreasing temperature. The motivation is that the materials should be more brittle at lower temperatures and therefore produce a sharper noise.

2
Theory

The following presents the theoretical foundation on which this master's thesis rely upon. This is to clarify the theoretical parts of the method and results in order to help the reader understand those parts better.

2.1 Previous Studies on Squeak and Rattle

Several studies has been conducted on the area of Squeak and Rattle. Below is a substantial summary on previous work.

Kavarana & Rediers [1] state that there were few studies, at the time of publication, on buzz, squeak and rattle (BSR) and that a common approach towards BSR issues among car manufacturers is the "find-and-fix" approach. The importance on solving BSR issues in a design approach was emphasised, both to improve on the overall perceived quality but also to lower the warranty bills that S&R issues cause. Measures such as Things-Gone-Wrong (TGW) and JD power surveys were also studied through this paper.

Both Shorter et. al, [2] and Choi et. al, [3] use a cantilever beam as a validation model for their process of simulating S&R issues. Different contact materials are explored in [3], however the setup of the test rig is not disclosed. A sound quality metric is also calculated based on parameters such as sound pressure level (SPL), Kurtosis, Zwicker loudness, sharpness and roughness. Auralization, the process of rendering a computed sound field audible, was in this case achieved through the Rayleigh integral method.

Shorter et al. [2] focus on the acoustics of rattle and the development of a computationally efficient numerical method for rattle prediction. Their methodology includes simulation of impact locations, forces on impact and the resulting acoustic radiation. They highlight the fact that only simulating the locations of impact is insufficient. This since both many of these impacts do not radiate a significant amount of noise to the far field and that the resulting acoustic radiation is dependent on parameters such as the material.

Weber et al. [4] exemplify the use of the E-LINE method at VCC. The E-LINE method simulates the relative motion between two adjacent parts along a specified line and evaluates the risk of rattle for cases when the gap between the parts is fully closed. It also evaluates the risk of squeak through the use of VCC database of "stick-slip" tests.

Zwicker & Fastl [5] discuss a more comprehensive audio evaluation than simply using the traditional dBA measurement. They discard dBA measure when it comes to S&R evaluation. Instead, they suggest the psychoacoustic annoyance as a better measurement on the severity of the propagated sound. The psychoacoustic annoyance, P_A, is calculated as:

$$P_\mathrm{A} = N_5 \left(1 + \sqrt{w_\mathrm{S}^2 + w_\mathrm{FR}^2}\right) \tag{2.1}$$

$$w_\mathrm{S} = \begin{cases} 0.25(S_5 - 1.75)\log(N_5 + 10), & \text{if } S_5 > 1.75 \text{ acum} \\ 0, & \text{if } S_5 \leq 1.75 \text{ acum} \end{cases} \tag{2.2}$$

$$w_\mathrm{FR} = \frac{2.18(0.4F_5 + 0.6R_5)}{N_5^{0.4}} \tag{2.3}$$

where N_5 is the loudness, S_5 is the sharpness, F_5 is the fluctuation strength and R_5 is the roughness of the sound. Index 5 above indicates the quantities being in the 95th percentile. Of course, to be able to use this measurement, the audio recording device used must be able to separate all these metrics.

Chen & Trapp [6] mention what they call "the rattle factor" which is a measurement on the severity of rattle. With $E(x)$ corresponding to the expected value of T_b^i, where T_b^i corresponds to the time of every rattle event, the rattle factor is defined as:

$$R = \frac{1}{E[T_\mathrm{b}^\mathrm{i}]} = \frac{1}{\text{expected event time}} \tag{2.4}$$

A small value of R is desired since this corresponds to infrequent and short rattle events.

2.2 Sound Quantities

The sound quantities mentioned in Section 2.1 need to be well understood and defined.

2.2.1 Terms, Measures & Parameters

Terms, perhaps new for the non expert in S&R will be introduced in later sections.

2.2.1.1 Band Width

The band width of a sound is the span of frequencies the propagated sound produces.

2.2.1.2 Critical Bands

The critical band is the frequency band where two tones will interfere with the perception of the sounds, by auditory masking. It is basically the filter created by the hearing system of the individual subjected to the sound [7].

2.2.1.3 FM/AM

Frequency modulated (FM) waves are waves with varying frequency in the time domain. The amplitude and phase of the wave remain constant. For amplitude modulated (AM) waves, the amplitude of the wave is varying in the time domain while the phase and frequency are hold constant [8].

2.2.2 Sharpness

Sharpness is defined using the unit acum, where the reference sound producing 1 acum is a narrow band-width sound, one critical-band wide at a centre frequency of 1 kHz at a sound pressure level of 60 dB. For higher frequencies, the sharpness increases faster than the critical bands, which is why sounds with higher frequencies produce higher sensations of sharpness [5].

2.2.3 Fluctuation Strength

Modulated sounds have two different sound quantities for hearing sensations. For FM waves, with modulations frequencies up to 20 Hz, fluctuation strength is produced, and above that, roughness is produced. For more information on roughness, see Section 2.2.5. There is no abrupt distinction as to when fluctuation strength or roughness is produced. Instead there is a smooth transition around 20 Hz in modulation frequency where both of them are produced. A FM sound reaches its maximum in fluctuation strength at around 4 Hz, then roughness starts to form. The unit for fluctuation strength is vacil, one Vacil is defined as a noise of 60 dB, 1 kHz tone and 100% AM at 4 Hz [5].

2.2.4 Loudness

Loudness belongs to the category of intensity sensations. The loudness function used in Eq. 2.1 is measured in the unit sone. The loudness function is used to evaluate how much louder (or softer) a sound is compared to a standard reference sound. In psychoacoustics the reference sound, or one sone, is defined as the level of a 40 dB sound at a 1 kHz tone, [5].

2.2.5 Roughness

Three parameters are important for determining the roughness of a sound. For amplitude modulated sounds, the important parameters are the degree of modulation and the modulation frequency. For frequency modulated sounds it is the frequency modulation index and the modulation frequency. The unit of roughness is asper, where one asper is defined from a 100% amplitude modulated sound at a 1 kHz tone, a SPL of 60 dB and a modulation frequency of 70 Hz [5].

2.3 Eigenmode Analysis

An eigenmode is the natural vibration shape of a system [9]. Every part of the system is vibrating with the same frequency, called the eigenfrequency. The vibrating system is experiencing nodes and anti-nodes in the deflection space, where the nodes corresponds to the zero-deflection areas of the wave and the anti-nodes corresponds to the areas with maximum deflection, see Figure 2.1

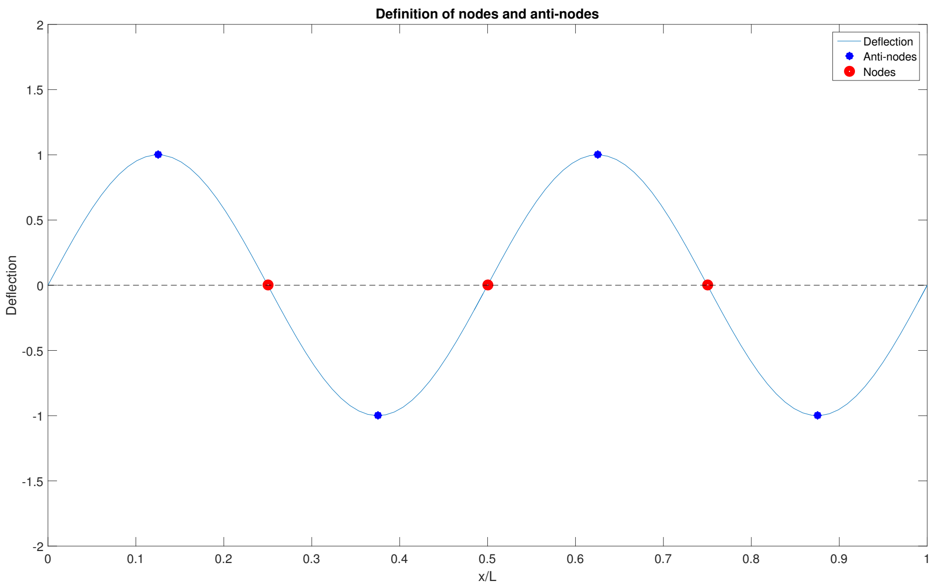

Figure 2.1: Display of theoretical definition of nodes and anti-nodes

The deflection of the system will reach its maximum when excited in its eigenfrequencies. A continuous system has an infinite number of eigenmodes of different frequencies. Figure 2.2 displays the vibration behaviour for a cantilever beam excited in the first two eigenfrequencies.

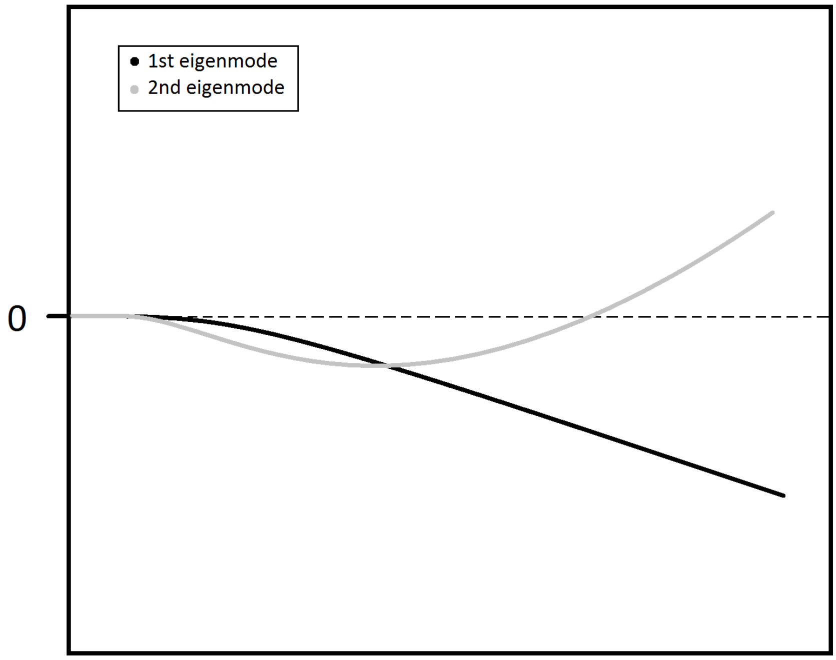

Figure 2.2: The first two eigenmodes of a cantilever beam

2.4 Excitation Signal

The excitation signal is the signal by which the system will be excited. There are several different ways to excite a system. Three types were evaluated, a stochastic signal, sine sweep signal and a semi-stochastic signal. Recommmendations from VCC experts lead to the evaluation of these three signal types.

2.4.1 Stochastic Signal

A stochastic signal, or random signal, is a signal with random amplitudes and random frequencies within a defined span. All eigenfrequencies within the defined span will then be excited.

2.4.2 Sine Sweep Signal

For a sine sweep signal, the amplitude and the frequency range is set, and the response is then left to sweep from one end of the frequency span to the other end. For a visual representation see Figure 2.3.

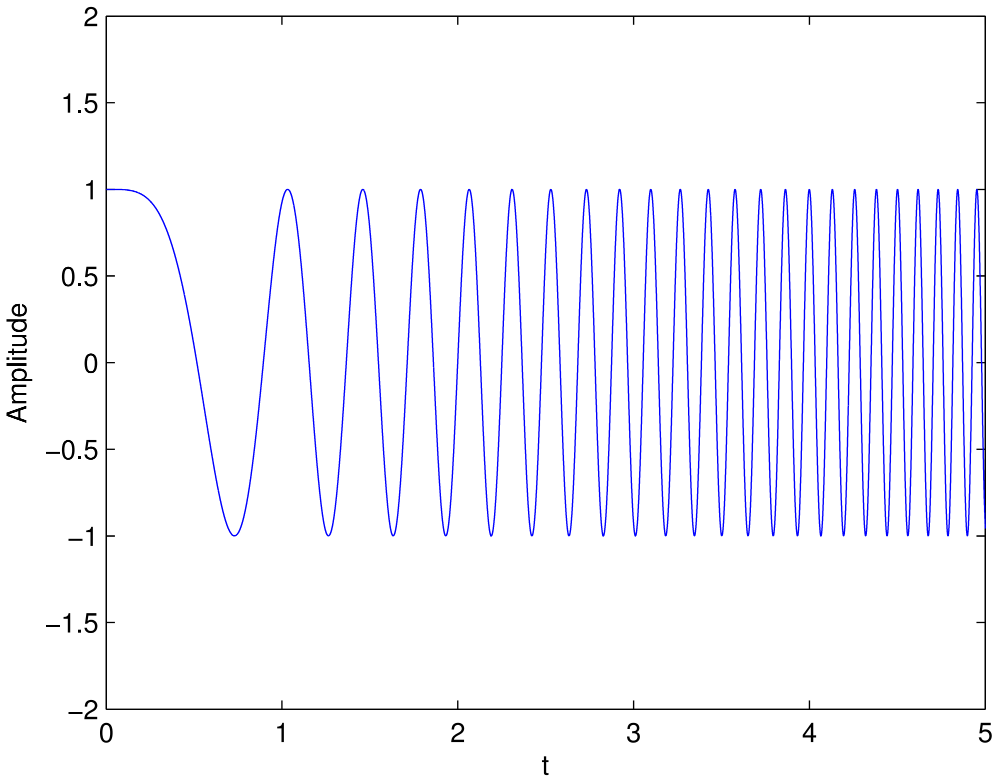

Figure 2.3: Display of theoretical definition of a sine sweep signal with a normalized amplitude

2.4.3 Semi-Stochastic Signal

A semi-stochastic signal is defined as a stochastic signal in Section 2.4.1 but the randomness goes on for a finite time, and then repeats.

2.5 Listening Clinical Trials

In order for the objective measurements to be verified, they are to be compared with subjective measurements. Therefore, listening clinical trials will be conducted. Both S&R experts from Volvo as well as people who have zero experience in S&R issues will participate in these clinical trials.

3
Method

The methodology of this project is developed in close collaboration with experts from VCC and Chalmers. The majority of time was spent at VCC, apart from the literature survey that was conducted at Chalmers. See Appendix C for the project Gantt chart.

3.1 Physical Test Rig

Several designs for the test rig have been evaluated. Proposals such as a simply supported Kirchhoff plate and a cantilever beam with a vibrating load acting on it were evaluated. After discussions with experts from VCC, a cantilever beam was chosen due to factors of simplicity, robustness and repeatability.

Figure 3.1 displays the schematic design of the test rig. The material of the beam is aluminium combined with easily exchangeable inserts of different materials for the contact point of the beam and the tip of the modal hammer. The beam is attached to a shaker exciting with any given input signal, denoted P_0(t) in the figure. A modal hammer is placed with an adjustable gap to the cantilever beam.

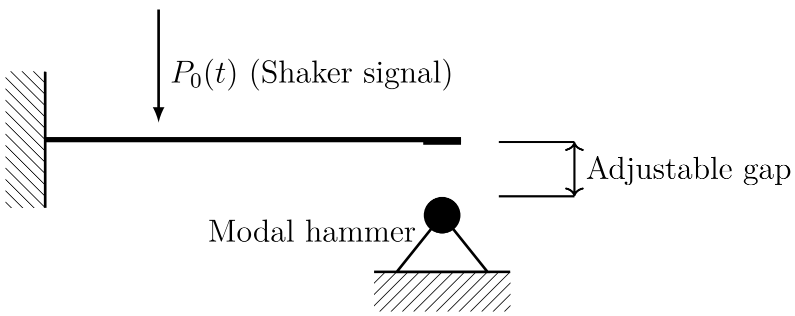

Figure 3.1: Schematic representation of the test rig

3.1.1 Overall Design

The final design of the test rig is shown in Figure 3.2, as can be seen it is similar to the schematic design of Figure 3.1 proposed earlier in the project.

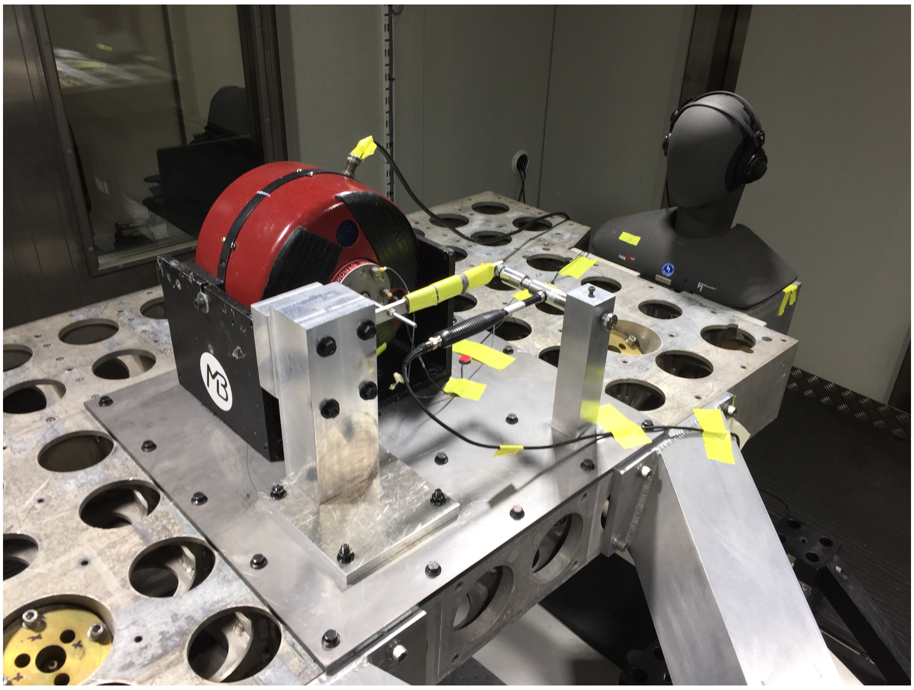

Figure 3.2: Overall design of the test rig

Below will follow more detail of every part of the test rig, with references to each corresponding drawing in Appendix A.

3.1.1.1 Modifications of the Schematic Design

The schematic representation in Figure 3.1 is the most straightforward way to get an overview of the final design of the rig. The only addition to the schematic design is an attached damping material to the beam, in order to remove/reduce the effect of it behaving like a guitar string and produce sounds from its own vibration. The only sound that is interesting is the rattle sound produced from contact between the material inserts. The reader is referred to Figure 3.7 for a zoom in on the damping material.

3.1.2 Cantilever Design

The cantilever beam had to be designed to fulfill a number of requirements. These included, for example, characteristics such as eigenfrequencies, stiffness, ease of manufacturing, assembly rigidity and thermal properties. Mechanical properties such as fatigue life was also taken into consideration during the design process and the beam was designed in a manner such to avoid unnecessary stress concentrations and consequently possible fatigue cracks. Another important factor was to design the beam in conjunction with the fastening elements to assure that a solution as closely representative of an ideal cantilever beam as possible was achieved.

A parameter study for the design of the beam on the first eigenfrequency was performed to get guidance on what dimensions to use, see Section 3.3.1. An iterative

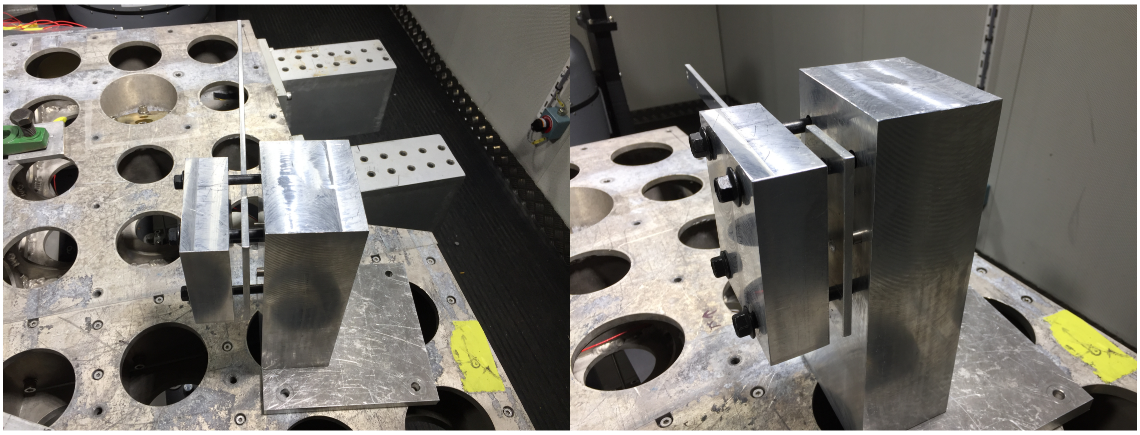

Figure 3.3: Pictures of cantilever beam and fastening modules

process of 3D design and FE analysis was then performed until a satisfactory design was achieved, see Section 3.3 for further details.
For upclose pictures on the final design of the cantilever, see Figure 3.3. There, both the bolted joints to clamp the beam as well as the swivel pins to keep the beam in the right place are noticeable.

3.1.3 Material Inserts

Simplicity, robustness and repeatability of the final setup have been key factors throughout this work. Therefore it was deemed necessary to design the material inserts in such a manner that the swapping of inserts was swift and, most importantly, affected the characteristics of the beam as little as possible. Since the material insert is located at the tip of the beam, even a slight change in mass between two material inserts could have a significant effect to the eigenfrequencies of the beam and consequently the behaviour of the beam under excitation.

The material inserts were sought to be similar geometrically and thus a solution to use modified bolts and glue round sheet samples of the materials to these was developed. Figure 3.4 shows the exchangeable material inserts. As could be seen in the figure, they are similar in shape independent of it being the insert for the modal hammer or the beam. The only difference between the two sides is the length of the bolt, see Appendix A for drawings of the components.

Figure 3.4: A display of different material inserts for both hammer and beam

The inserts for the beam will be mounted with a nut, and the inserts for the hammer will be mounted directly in to the hammer. Figure 3.5 shows a mounted system with PolyPropylene (PP) on the hammer side and aluminium on the beam with 1 mm gap.

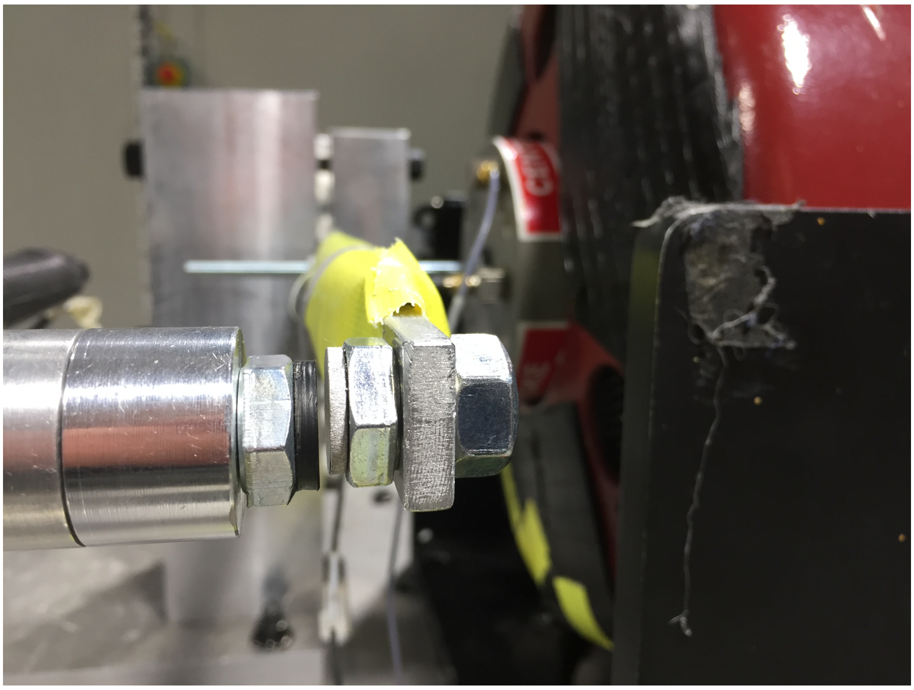

Figure 3.5: A mounted system with 1 mm gap

3.1.4 Gap Control

In order to control the adjustable gap between the modal hammer and the beam, the hammer support is equipped with a mechanical solution for adjustment. It is based on a M6 bolt with a pitch of 1 mm, meaning that one full turn of the wheel transverse the hammer 1 mm. By first adjusting the gap to 0 mm between the modal hammer and the beam then turning the adjustment bolt one round, the gap will either be -0.5 mm (pre-loaded with a force corresponding to 0.5 mm negative offset) or +1 mm. To make this easier, the rotation bolt has been marked with ten lines equally distributed along the circumference. A turning of one line therefore results in a 0.1 mm adjustment of the gap. Figure 3.6 shows the turning wheel with its ten lines representing 0.1 mm each.

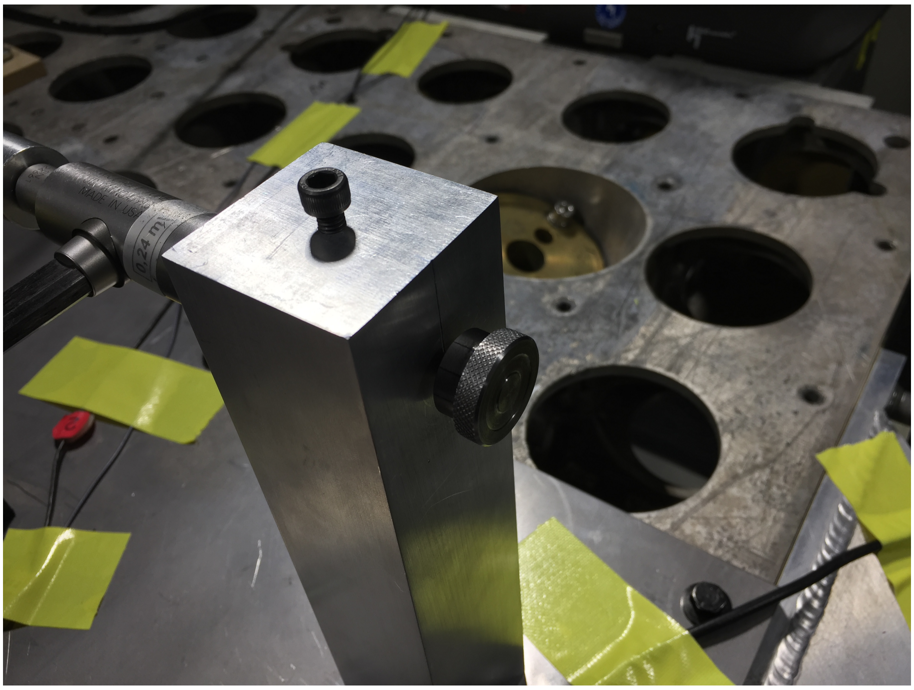

Figure 3.6: Wheel of gap control

3.1.5 Shaker Mount

In accordance with the schematic representation of the rig, the shaker will be mounted to the beam producing any chosen modulation. Figure 3.7 displays the mount between the shaker and the beam.

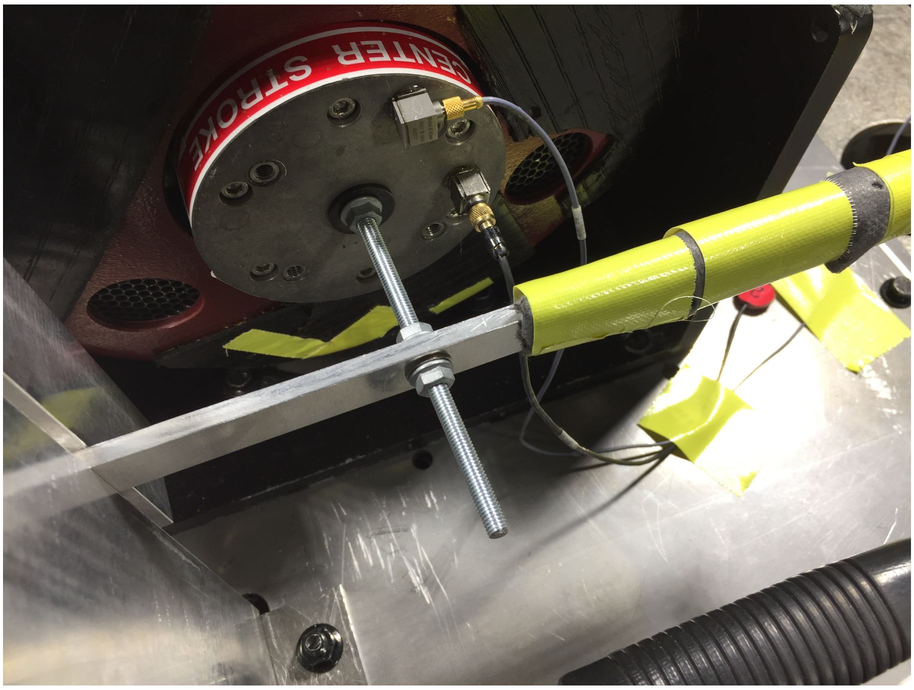

Figure 3.7: Shaker mount

3.2 Manufacturing of Test Rig

As discussed earlier, the simplicity, robustness and repeatability of the setup were crucial factors during the design process. Precision and accuracy were therefore of utter importance during the actual manufacturing of the test rig. To have full control over the design and to sort out in-situ design improvements the team choose to, under the guidance of the workshop personnel at Chalmers, build the test rig themselves. All parts of the test rig were manufactured at the Mechanical engineering workshop at Chalmers, with the exception of the base plate which was ordered to be laser cut to dimension at VCC.

3.3 Eigenmode Analysis

In order to validate the physical test rig to make sure that it behaves as expected, an eigenmode analysis was performed. Not only did this ensure accurate results from the test rig, but it also worked as a mean in the design process to avoid different components interfering with each other by having similar eigenfrequencies. The eigenfrequencies were both solved for analytically and evaluated in ANSYS. In order to meet the requirements of VCC, the first eigenfrequency of the system was recommended to be between 40-50 Hz.

3.3.1 Analytical Solution

To initiate the design towards a desired first eigenfrequency of around 50 Hz, an analytical parameter study was conducted to narrow down the span of the design parameters. The eigenfrequencies of a cantilever beam is obtained from Eq. 3.1.

$$\omega_{\text{eig}} = \alpha\sqrt{\frac{EI}{mL^4}} \tag{3.1}$$

where α is a constant for each eigenmode, E is the Young's modulus of the material, I is the moment of inertia of the cross section of the beam, m is the mass per unit length of the beam and L is the length of the beam.

For a cantilever beam the constant α is, for the first three eigenmodes, [10]

$$\alpha = \begin{bmatrix} 0.560 & 3.51 & 9.82 \end{bmatrix} \tag{3.2}$$

With the moment of inertia for the rectangular cross section of the cantilever beam as $I = bh^3/12$ and the mass of the beam per unit length as $m = \rho bh$, the following is obtained [11]

$$\sqrt{\frac{EI}{mL^4}} = \sqrt{\frac{Ebh^3}{12\rho bhL^4}} = \sqrt{\frac{Eh^2}{12\rho L^4}} \tag{3.3}$$

and the eigenfrequencies of the beam is therefore independent of the width, b, of the beam. This results in an updated Eq. 3.1 as

$$\omega_{\text{eig}} = \alpha\sqrt{\frac{Eh^2}{12\rho L^4}} \tag{3.4}$$

The recommendation from VCC was to have a system with the first eigenmode between 40-50 Hz, giving the following design equation

$$40Hz \leqslant 0.560\sqrt{\frac{Eh^2}{12\rho L^4}} \leqslant 50Hz \tag{3.5}$$

With another recommendation from VCC to not have the beam longer than 500 millimeters, the beam was designed according to the following parameter values

Table 3.1: Beam parameters

Parameter	Value	Acronym
Length	320 mm	L
Sheet thickness	6 mm	h
Width	20 mm	b
First eigenmode	40.32 Hz	ω_{eig}

An eigenfrequency in the lower recommendation range was chosen due to restrictions of the excitation system. A lower eigenfrequency results in lower requirements for the excitation force. The restriction in what force span the system could manage was considered to be of greater importance than for it to be able to hold the frequency range given. An analytical solution is not a perfect solution since it is hard to manufacture an ideal cantilever beam, and the risk of having the first eigenfrequency below 40 Hz was approved by VCC.

3.3.2 Finite Element Analysis

In order to avoid any rattle sounds between adjacent parts, the eigenfrequencies of the parts need to be well separated. In addition to this, if one part experiences its first eigenfrequency much higher than the exciting system, it is unlikely for this part to vibrate significantly.

3.3.2.1 Base Plate

The contact with the highest risk of rattle was determined, after initial testing and elaborations, to be between the base plate and the table, see red box in Figure 3.8.

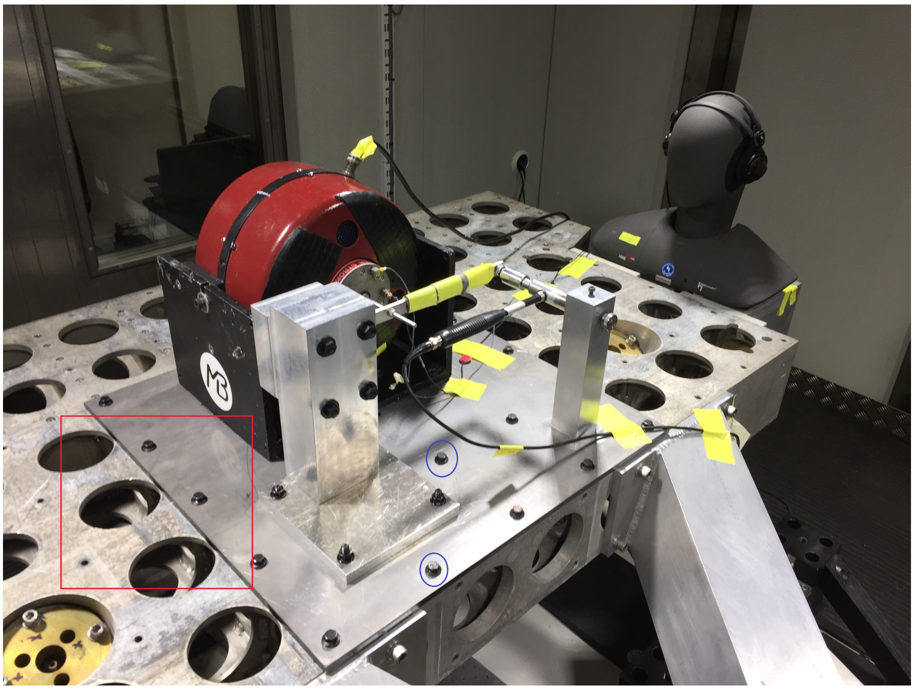

Figure 3.8: High risk contact and bolts for clamping

As can be seen in Figure 3.8 there are several bolts that keep the two parts moving dependently, represented by the blue circles. To model the base plate in a conservative manner in ANSYS [12], bolts were only modelled on the boundary of the plate. This resulted in a weaker structure than the actual system and therefore, if enough separated from the eigenfrequency of the exciter system, it will not vibrate enough to cause any rattle sounds. Figure 3.9 displays the modelled base plate.

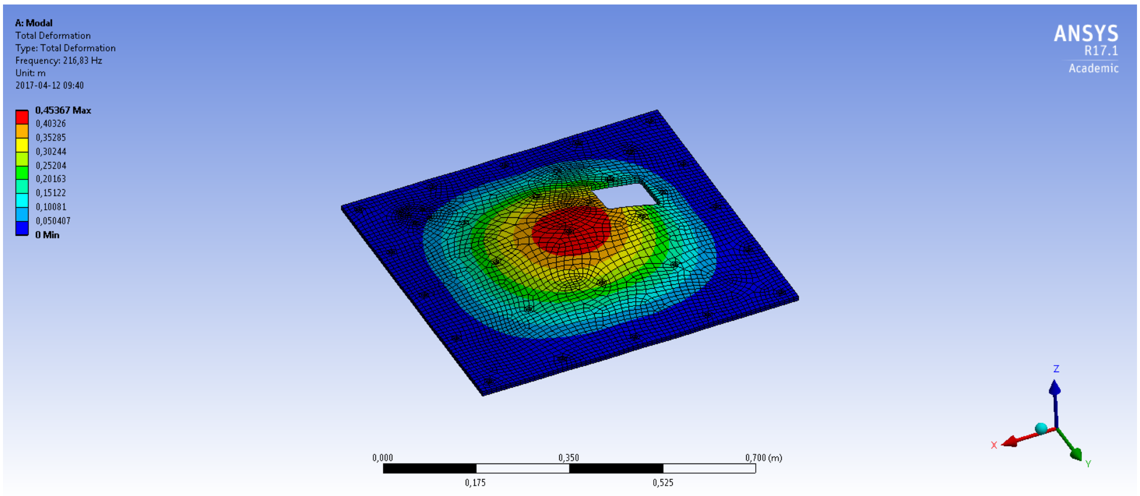

Figure 3.9: Deformation of Base Plate at first eigenfrequency

As can be seen, this models a plate with fixed support on the boundary, producing the first eigenmode with an anti node at the center of the plate. This would not be the case in reality, since there are bolts clamping the base plate to the table at other places than at the boundary. Table 3.2 displays the six first eigenfrequencies for the base plate.

Table 3.2: Eigenfrequencies from ANSYS for the Base Plate

Mode	**Frequency [Hz]**
1	216.83
2	438.07
3	451.09
4	658.06
5	775.50
6	800.67

3.3.2.2 Beam

As discussed in Section 3.3 the beam had a requirement, among others, to have a first eigenfrequency in the span 40-50 Hz. As a verification of the analytical design method discussed in Section 3.3.1 an ANSYS simulation was performed for the beam. An illustration from ANSYS of the first eigenmode simulation can be seen in Figure 3.10

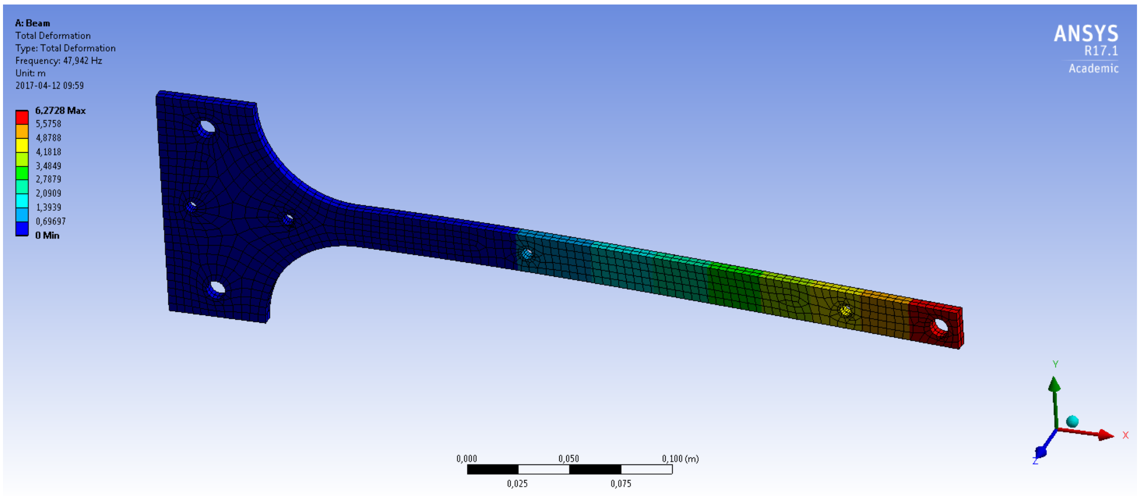

Figure 3.10: Deformation of beam at first eigenfrequency

The following eigenfrequencies were calculated for the beam, by ANSYS.

Table 3.3: Eigenfrequencies from ANSYS for the Beam

Mode	Frequency [Hz]
1	47.94
2	161.56
3	299.37
4	826.14
5	988.55
6	1254.50

If a comparison between Table 3.2 and Table 3.3 is made, it can be seen that the first eigenfrequency of the base plate is well above that of the beam.

3.4 Design of Experiments

In simulation, any arbitrary combination of values for the design variables must be able to be evaluated. The number of measurements that can be done is limited and a clever way of sampling these measurement points must be made. These measurement points together with a response surface should capture the overall behaviour of the outcome metric of rattle noise. This is the idea behind setting up a DOE.

For the test rig setup there are seven parameters to take into consideration, displayed in Table 3.4. The values of these are already reduced to a minimum amount that is needed for a meaningful parameter study. Some of these quantities have been given as constraints from VCC and some of them, such as the number of gaps and shaker signal, have been deduced by the team. To do a full factorial testing of these parameters would be infeasible, see equation below.

$$N = M_{\mathrm{H}} M_{\mathrm{B}} S_{\mathrm{H}} S_{\mathrm{B}} G T P_0 = 2700 \tag{3.6}$$

As 2700 combinations are too many to measure during a master's thesis it was instead decided to split up the combinations in separate studies as a sort of design of experiments. This is not the traditional way to do a design of experiments, but in the case where listening clinical trials are to be set up it was a good approach.

3.4.1 Material Pairing Combinations

First the material pairing was set up so that each material was paired with all of the other materials, however no consideration to which of the contact surfaces that was equipped with what material was taken. This meant, for example, that a measurement of *Steel - Aluminium* was equivalent to a *Aluminium - Steel* measurement and thereby only one of them had to be performed. See Table 3.5 for a visual representation of the material pairings.

Table 3.4: Parameters for test rig setup

Parameter	Value(s)	Acronym
Material hammer insert	5	M_{H}
Material beam insert	5	M_{B}
Shape hammer insert	3	S_{H}
Shape beam insert	3	S_{B}
Gap size	4	G
Temperature	3	T
Shaker signal	1	P_0

By using this approach the number of combinations could be reduced from

$$N = M_{\mathrm{H}} M_{\mathrm{B}} \tag{3.7}$$

to

$$N = \sum_{i=1}^{n} i = (n+1)\frac{n}{2} \tag{3.8}$$

for each of these variables, where n is the number of parameters for a given variable and N is the total number of experiments for a given variable. As for the material pairings for example the number of combinations could be reduced from 25 to 15, as can be seen in Table 3.5.

3.4.2 Shaker Signal

A stochastic signal is the best option for excitation of all eigenmodes and also resembles the excitation experienced during actual driving of a car more than, for example, a sine sweep. A stochastic signal is also very simple in the sense that except for specifying a frequency span and amplitude there are not any parameters to tweak, which in turn makes for less combinations in the DOE. Hence, a stochastic signal was argued to be the most suiting shaker signal to use for listening clinical trials.

3.4.3 Gap Variation

As discussed earlier, in Section 3.1, both gaping and pretension setups were planned to be tested. An initial thought was to have five different gaps; two gaping, one zero gap and two pretension setups. After some initial testing of the setup it was concluded that rattle could be eliminated even at a low pretension and so it was decided to only use one pretension case, 0.5 mm, reducing the number of gap tests to four.

3.4.3.1 Force as a Function of Gap

Even though the gap for the preloaded case is controlled in millimeters, the interesting part of the preloaded case is the force of the preload. A cantilever beam exposed to a transverse force at the tip, will have the following analytical solution for the displacement at the tip ($x = L$)

Table 3.5: Material pairings

Material	Steel	Aluminum	PP	PC/ABS	PA66
Steel	1				
Aluminum	2	6			
PP	3	7	10		
PC/ABS	4	8	11	13	
PA66	5	9	12	14	15

$$w(L) = \frac{2PL^3}{6EI} \tag{3.9}$$

resulting in the expression for the force at tip

$$P = \frac{6EI}{2L^3} w(L) \tag{3.10}$$

where P is the force, E is Young's modulus, I is the moment of inertia of the cross section of the beam, L is the length of the beam and $w(L)$ is the deflection of the beam at the tip.

3.4.4 Temperature Variation

Especially for the plastics it was sought after to explore the influence of the temperature on the resulting sound. However, all material pairings were tested for all temperature setups to get a consistent sampling. Three temperatures were chosen, a room temperature which in this case was approximately 25°C, a cold temperature at -10°C and a warm temperature at 40°C. The full table over the parameters for testing can be seen in Table 3.6.

3.5 Rattle Measurements and Post-Processing

Rattle measurements were performed both objectively, with sensors, and subjectively, by experts from VCC. The post-processing mainly consisted of comparing objective results with subjective results.

3.5.1 Collection of Data

For the initial testing of the rig a laser camera was used to validate the eigenfrequencies of the beam and to record the movement of the beam under the excitation of different input signals, see Section 4.1.1 for these results. The laser rig was only used in the very beginning of the testing and thereafter the *Head Acoustics Squadriga II* [13] was used as the front end. The sensors plugged into the front end can be seen in Table 3.7.

Table 3.6: Parameters for testing

Parameter	**Value**	**Value**	**Value**	**Value**	**Value**
Material	Steel	Aluminum	PP	PC/ABS	PA66
Shape	Flat	Point	Line	NA	NA
Gap Size	1mm	0.5mm	0mm	-0.5mm	NA
Temperature	-10°C	20°C	40°C	NA	NA
Shaker Signal	Stochastic	NA	NA	NA	NA

To replicate the perceived sound as closely as possible to what a human would experience in a car, the *HEAD Acoustics BHS II Binuarual Headset* [14] was mounted on a *HEAD Acoustics HMS IV Dolly* [15] placed at a right angle to the beam. See Figure 3.2 for all components.

The rig was setup in a semi-acoustic climatic chamber allowing for both consistent sound quality and the ability to run tests in different temperatures. Although the testing room was semi-acoustic, some noise from the surroundings, if loud enough, could still be perceived in the recordings. For this reason, and for the reason of statistical certainty, each recording was, about but not less than, 60 seconds long. *Head Acoustics ARTEMIS Suite Data Acquisition* [16], a calibrated software, was used in conjunction with the the *Head Acoustics Squadriga II* to record the signals from the sensors.

3.5.2 Post-Processing

The post-processing of the data was done both in *HEAD Acoustics ARTEMIS Suite* [17], to retrieve the sought after sound quantities on which to calculate an objective measure for the rattle, and in *MATLAB* to process the data and to perform the actual calculations, as well as truncating the signals to be used in the listening clinical trials. The PA measure was calculated both as a mean of the full length signals, as a moving average of five seconds for each signal and as a peak loudness PA value. All three approaches exhibited the same overall behaviour of the PA values, as can be seen in Figure 3.11.

One of the goals with analyzing the signals in MATLAB was to choose five second intervals, which to playback at the listening clinical trials, in a scientific manner. The first approach was to simply calculate the PA value as a mean value over the entire signal, regardless if the signal was exactly 60 seconds or longer. This method did not support a scientific choice of which five second intervals to choose for the listening clinical trials, but it did work as a first indication that the PA measure worked and correlated with the two other PA measures, that was to be calculated.

The second approach was to calculate the moving average PA value. This moving average PA measure was calculated in a five second span were the maximum mean PA value was chosen among these five second intervals to represent the PA value for each signal.

After studying the loudness values of the signals together with the PA measures, see Figure 3.12, already calculated it was deduced that the loudness value of the

Table 3.7: Sensors used during collection of data

Sensor	Unit of Measure	Channel
Sound Recorder	Multiple	1,2
Modal Hammer	N	3
Tri-Ax Accelerometer	m/s^2	4,5,6

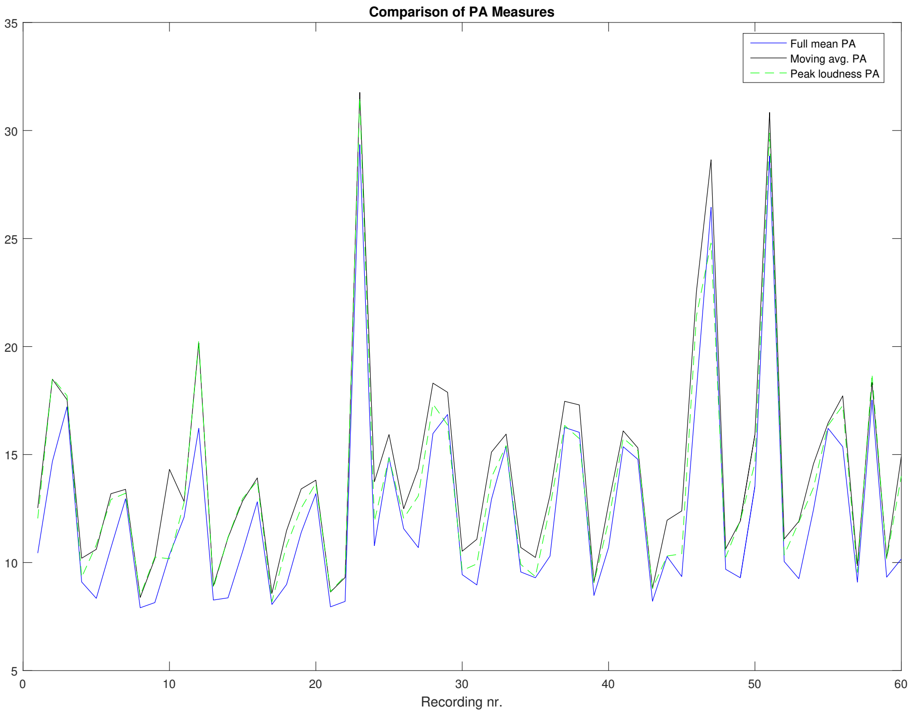

Figure 3.11: Comparison of PA measures, where the green dashed line corresponds to the "peak loudness PA", the black continuous line corresponds to the "moving average PA" and the blue continuous line corresponds to the "full mean PA"

signals followed the PA measures, shape wise. The loudness values were therefore used when finding the third PA measure. The PA measure was found by first finding the maximum loudness of each signal and then taking a five second interval around this peak and calculating the mean PA value of this area. In this case, regard had to be taken to where in the signal the peak loudness value was located, treating it differently if it was close to the beginning or the end of the signal.

Comparing the three measures, and reasoning that the most severe peak in each signal should be what is most concerning for a car passenger, the peak loudness PA measure was chosen as the standard for using when choosing five second intervals for the listening clinical trials. This measure also correlated the best, shape wise, with the mean PA value for the signals.

3.6 Listening Clinical Trials

In order to validate the PA values, subjective listening clinical trials were conducted where participants were to rate annoyance of above explained five second sections, see Section 3.5.2. The total length of the clinical trials should not exceed 30 minutes due to reasons of comfort for the participants. This limit forced some cherry picking

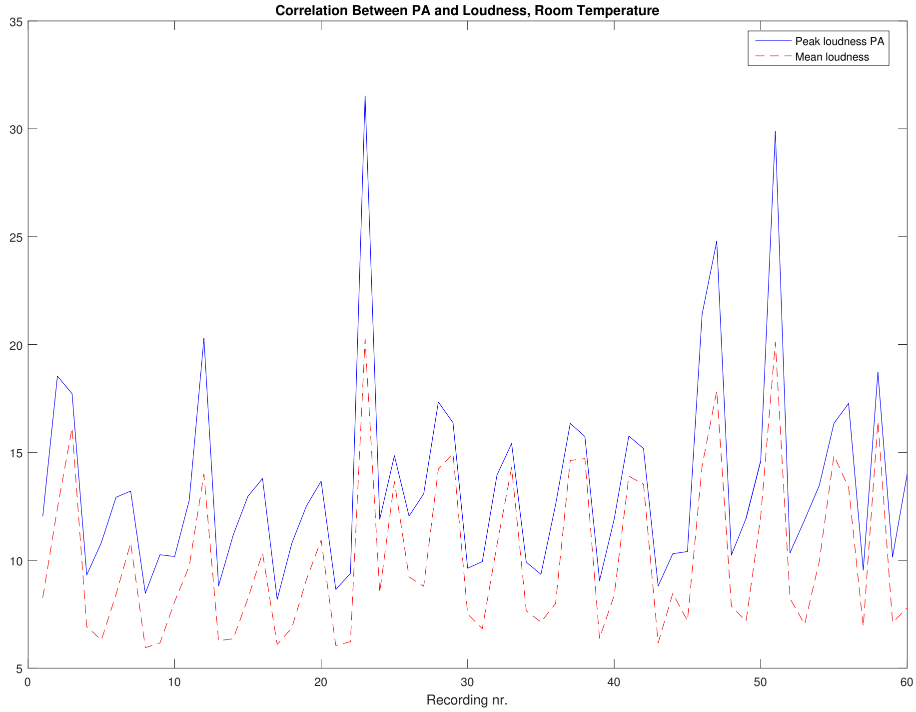

Figure 3.12: Comparison of loudness and peak loudness PA, where the red dashed line corresponds to the mean loudness and the blue continuous line corresponds to the "peak loudness PA"

as to what recordings that were to be used. Room temperature was considered to be the most common, and therefore, most important condition, with the temperated cases being more peripheral. With this in mind, all 60 recordings in room temperature were chosen to be included in the clinical trials, with occasional temperature checks to try to find a pattern as to how temperature increase/decrease changes behaviour of sound propagation.

3.6.1 Sound File Design

A simple pairwise comparison of rattle sounds enables anyone, regardless of previous S&R or listening clinical trial experience, to take part in the listening clinical trial on similar conditions. After the decision of pairwise comparisons had been made the design of the sound files could begin. It was decided that the two sounds in one pair should be separated by a moment of silence to distinguish them and that a longer silence was needed between each pair to have time for the rating of the sounds. A long enough sequence of each sound to get a feeling for severeness, but short enough sequence to keep the listener from starting to think about the sound was desired.

This led to a final design of the sound files with each sequence in a pair being five seconds long, separated by a one second silence. Each pair was then separated by five seconds of silence for the listener to rate the sounds. Totaling to each pair-sequence in the sound file to be 16 seconds long. An extract from the listening clinical trial sound file can be seen in Figure 3.13.

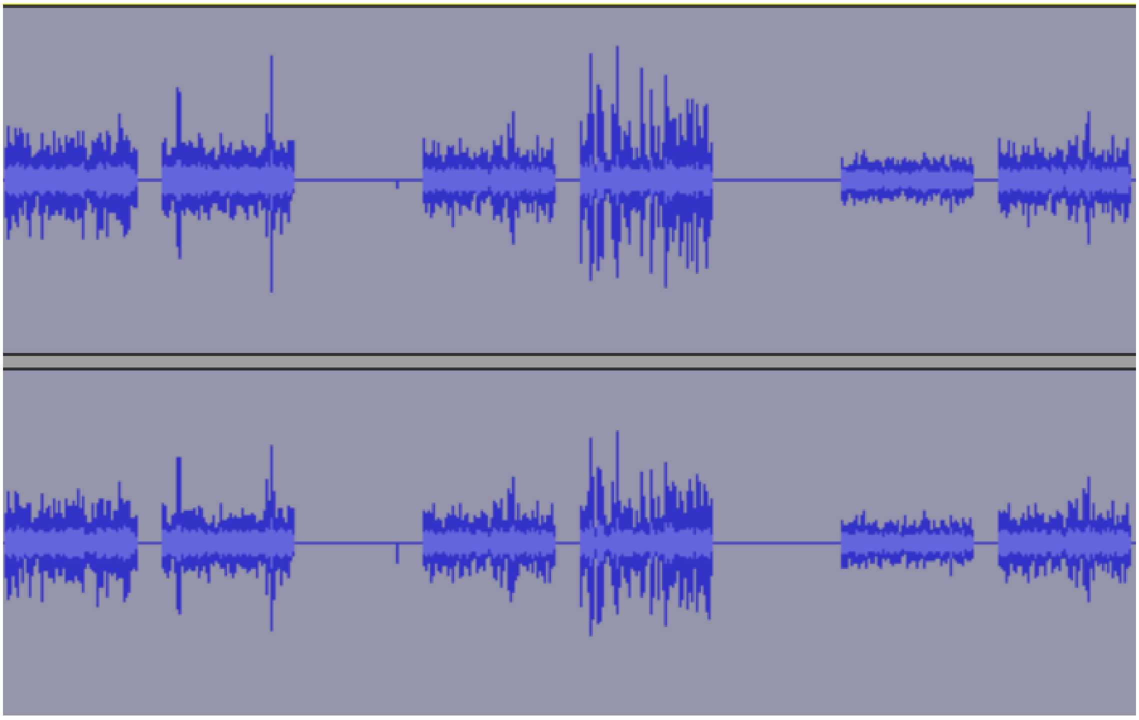

Figure 3.13: Waves of the clinical trial sound file

However, there was more work to go into the design of the sound files before any listening clinics could be performed. It was decided that one reference sound should be picked from each of the material pairing categories *metal-metal*, *metal-plastic* and *plastic-plastic*, leading to the use of three reference sounds. It was decided that the 0.5 mm gap case would be the most representative for the reference sounds judging from initial perceptions during the recording phase of the project. It was also deduced, in a similar manner and by looking at PA values calculated for the different temperature cases, that room temperature should be chosen for the references.

As mentioned before all room temperature recordings were to be included in the listening clinical trials. Thereby sixty pairs were already decided upon. With a maximum time length of each clinical trial set to 30 minutes it was decided that 105 pairs could be used in a clinical trial, see equation below.

$$105 \times 16 \text{ seconds} = 1680 \text{ seconds} = 28 \text{ minutes} \tag{3.11}$$

It was decided that 24 out of the 105 pairs should be reserved for including the other two temperature cases. Once again the experiences from the recording sessions along with initial PA calculations were used to choose these temperature cases.

Another six of the spots were reference comparisons where each of the three references were compared to each other, as well as played twice in a row as a check of the listeners ability to recognize the same sound. The idea behind this was to discover listeners who would rate the same sound inconsistently. As another check for inconsistency, five pairs were dedicated to changing the order of already included sounds. Meaning that if the sequence *Sound A - Sound B* had been played, a sequence with *Sound B - Sound A* would be played to see if it was rated consistently.

Finally ten random sound pairs were added where none of the sounds included would be a previously used reference sound. This enables the comparison *Sound A - Sound B*, *Sound A - Sound C* with *Sound B - Sound C* for these ten pairs.

3.6.1.1 Coding Procedure

Data (loudness, roughness, sharpness, fluctuation strength etc.) for each of the recorded sounds were, together with the corresponding **.wav** files, imported to MATLAB. Using the peak loudness PA measure procedure described in Section 3.5.2, the starting point for truncating the sound files was made. Knowing that the sampling frequency was set to 48kHz during recording, a five second interval could be computed and truncated from the original sound files. The five second sound files were then saved in a structure together with the indexing of the recording as well as the just calculated peak loudness PA measure. The order was then randomized and paired with either of the three reference sounds. The reference sounds were equally distributed to a third of the sounds each.

Once paired the order of what sound to play first in each pair was decided from the calculated peak loudness PA measure, where the sound with a lower PA value was played first. This was the case for all pairs in the listening clinical trials except for the five sounds where the order was changed, as discussed above.

This procedure continued similarly for all sections of the clinical trial sounds. Before writing the data back to the playable **.wav** format the order of the sounds was once again randomized to avoid any sectioned order of the playback. The sound file was also divided into two pieces to allow for a pause for the listeners fourteen minutes in to the listening clinical trial, see Chalmers box [18] for the MATLAB code.

3.6.2 Questionnaire and Rating Procedure

Every sound pair included in the clinical trials should be rated in the same manner. The first sound in each pair will be rated beforehand to a value of 100 and it is the task of each participant to rate the second sound with reference to the first one. This procedure is then repeated throughout the listening clinical trial. Table 3.8 displays how each pair rating looks like for the participants.

Table 3.8: Listening clinical trial questionnaire layout

Pair 25	A	100
	B	?

Thus, if sound B is perceived as being twice as annoying as sound A, the question mark in Table 3.8 should be replaced with 200. The listening clinical trials were conducted in an acoustic room at VCC designated for sound experiments. The room could lodge a maximum of five participants each sit and is equipped with amplifiers and playback software calibrated for the recording device that was used throughout the project, see Figure 3.14 for a picture of the listening room. A short interview of each participant was conducted prior to the start of the listening clinical trial where age, gender, experience in S&R, number of listening clinical trials previously attended, previous experience in psychoacoustics and hearing ability. This in order to be able to separate the participants into different groups. For the complete listening clinical trial questionnaire, see Appendix B.

Figure 3.14: Acoustic room for sound experiments

In the event of any unwanted disturbances a slide show, synchronized to the order of listening pairs, was played on a projector screen durint the listening clinical trials. A quick look at the screen would guide the participants back to the currently playing sound pair. Figure 3.15 displays how this slide show looked like.

3.6.3 Reference conversion

From the total domain of the listening clinical trials, a mean value when the participants compared reference 1 to reference 2 and reference 1 to reference 3 are shown in Table 3.9.

Figure 3.15: Slide show to help participants keep track of the sound pairs

Every sound that is paired with references 2 & 3 can be compared with respect to reference 1 after conversion. For this conversion there will be two cases depending on if the reference is placed first or second in the pair. If the reference is placed first in the pair, Equation 3.12 will convert from reference 2,3 to reference 1.

$$C(R_1) = \frac{C(R_\mathrm{X})R_{\mathrm{X,conv}}}{100} \tag{3.12}$$

where $C(R_1)$ is the converted mean value of the sound rating of sound x, with respect to reference 1, $C(R_\mathrm{X})$ is the mean value of the sound rating of sound x, with respect to its original reference x and $R_{\mathrm{X,conv}}$ is the conversion constant between reference 1 and reference 2, 3, written in bold style in Figure 3.9.

If, instead, the reference is placed as the second sound, Equation 3.13 is used.

$$C(R_1) = \frac{100}{C(R_\mathrm{X})}R_{\mathrm{X,conv}} \tag{3.13}$$

Table 3.10 shows two examples of conversion, one from each case. Studying pair 16, sound 2 is rated, on average, 130.00 with respect to reference 3. Since reference 3 is rated 50.00 with respect to reference 1, see Table 3.9, this implies that sound 2

Table 3.9: Mean values from the reference check

Reference	Reference 1	Reference 2	Reference 3
Reference 1	108.33	**82.08**	**50.00**
Reference 2	NA	100.00	NA
Reference 3	NA	117.5	100.00

in pair 16 will be perceived as less severe than reference 1, hence giving it a lower value than 100, in this case 65.00.

For sound pair 3, reference 2 is rated, on average, 45.83 with respect to sound 2. From the reference check in Table 3.9, reference 2 is rated 82.08 with respect to reference 1, implying that sound 2 in pair 3 is perceived more severe than reference 1, hence giving it the relative value 179.09 with respect to reference 1.

Table 3.10: Examples of reference conversion

Sound pair	Sound 1	Sound 2	Ref nr	Ref pos	Converted value
16	100	130.00	3	first	65.00
3	100	45.83	2	second	179.09

4
Results

The outcomes of this master's thesis can be divided into three categories, the *test rig*, the *objective rattle evaluation* and the *subjective rattle evaluation*.

4.1 Test Rig

The full design of the test rig, including manufacturing, testing and evaluation, is the main deliverable in this project. The results of the test rig are the actual physical build itself and the eigenfrequencies of the rig. Figure 4.1 shows the assembled test rig in an experiment setup.

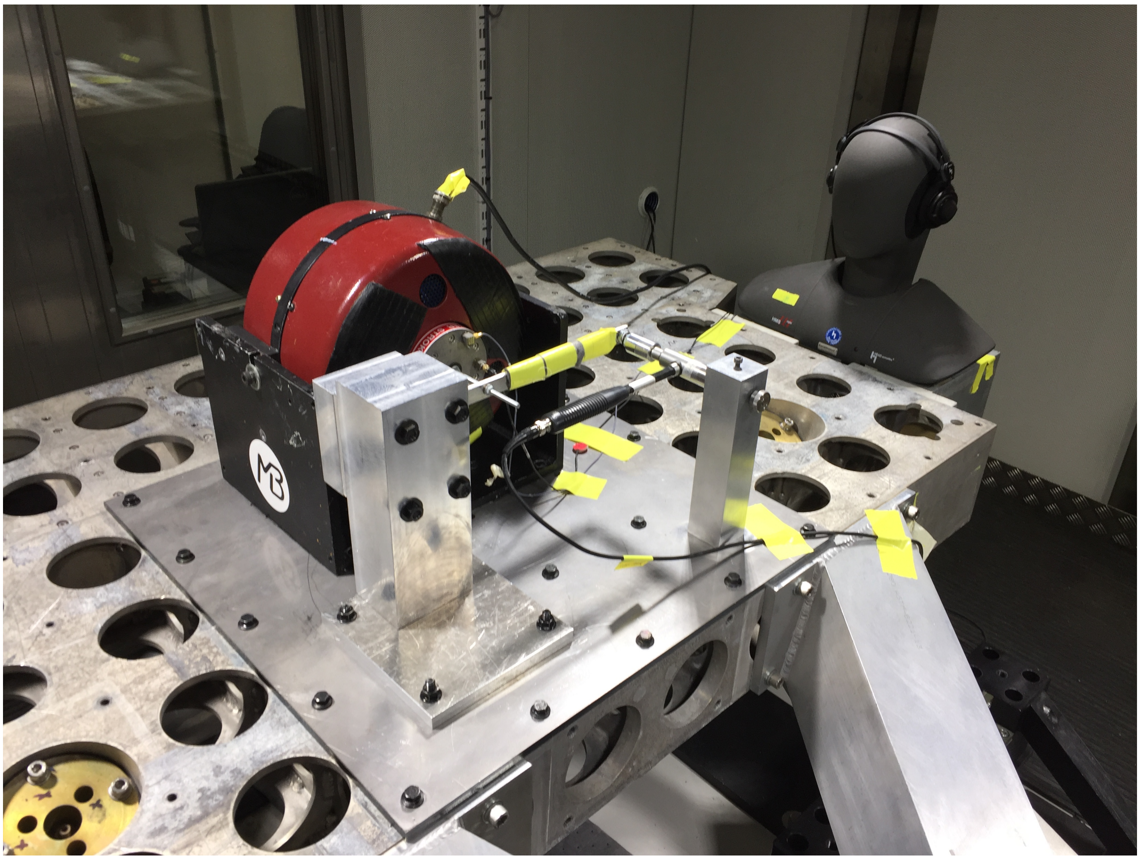

Figure 4.1: Test rig assembled in semi-acoustic chamber

4.1.1 Eigenfrequency Verification

A laser rig was used to verify the eigenfrequencies of the beam. The laser rig comprise many functions and abilities that were not used at this stage of the project, however going forward some of these functions may be used and hence it was interesting to use the laser rig for the verification of the eigenfrequencies. Figure 4.2 displays the overall behaviour of the beam over the frequency span. The first eigenfrequency occured around 40 Hz, making the analytical solution in Section 3.3.1 very close to the actual first eigenfrequency of the beam. A stochastic signal was used to excite the beam during the measurement of the eigenmodes.

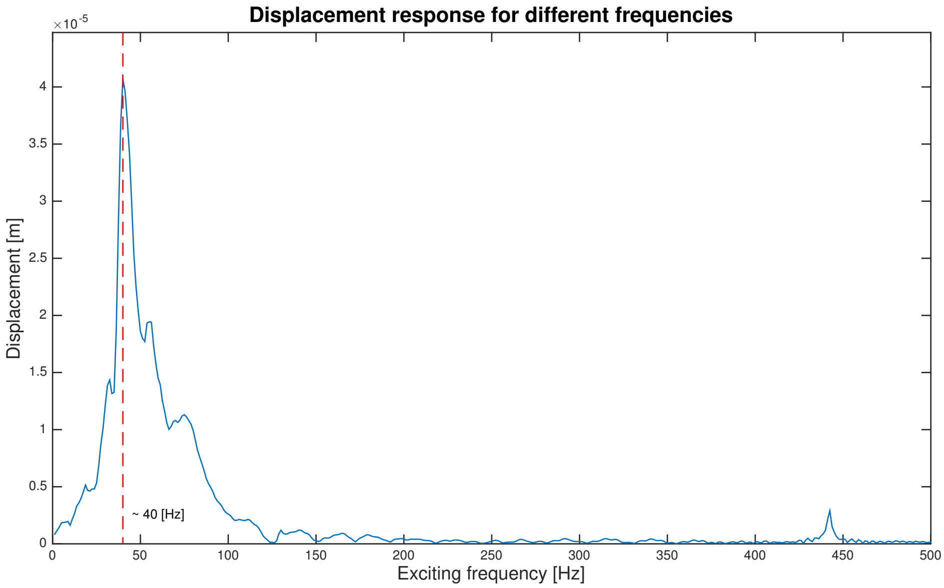

Figure 4.2: Displacement versus frequency for the beam

4.2 Objective Rattle Evaluation

An objective measure of the severeness of rattle was used according to Zwicker's "Psychoacoustic Annoyance" metric, for details see Section 2.1. The results from this objective evaluation can be seen in Figure 4.3.

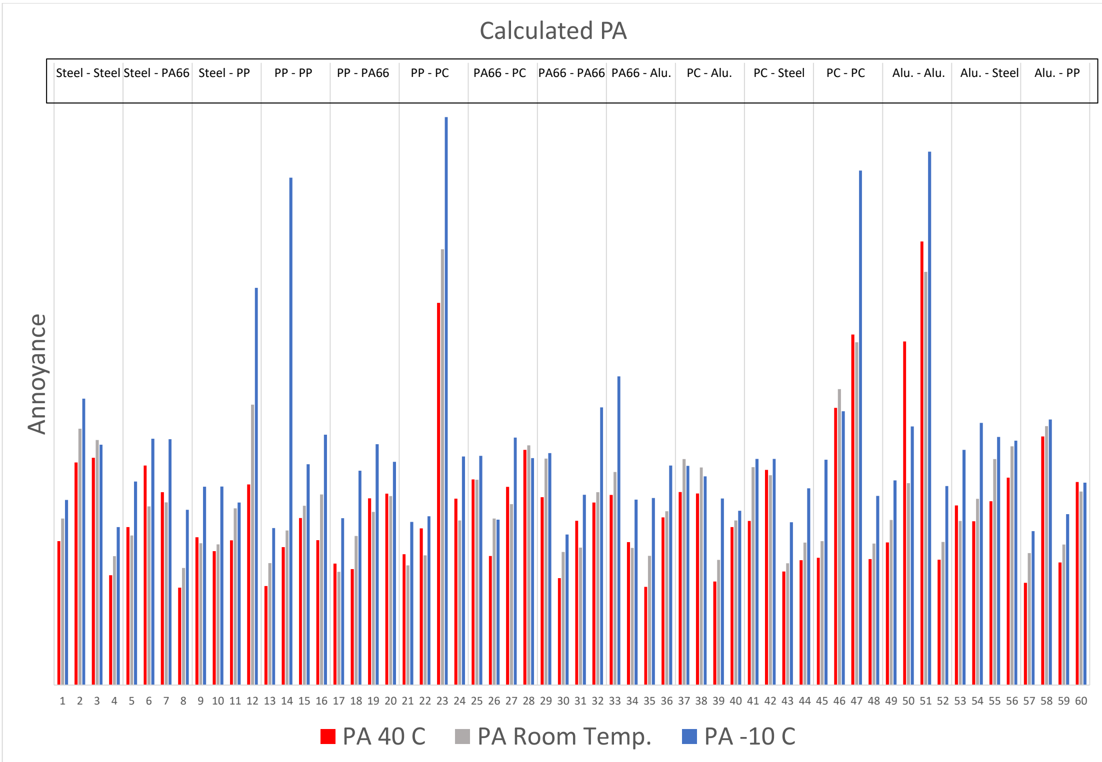

Figure 4.3: Full domain PA values from rattle measurements

The figure is divided by vertical grid lines for the different material pairs with each gap corresponding to one of the four clusters of bars within each grid section. The three bars with orange, blue and grey color correspond to different temperature situations.

4.2.1 Gap Dependence

Figure 4.4 displays the calculated PA values for the room temperature case. From this, gap variance can be seen inside the vertical grid lines and material dependence can be analyzed when comparing clusters, inside each grid line, which correspond to a certain material pair.

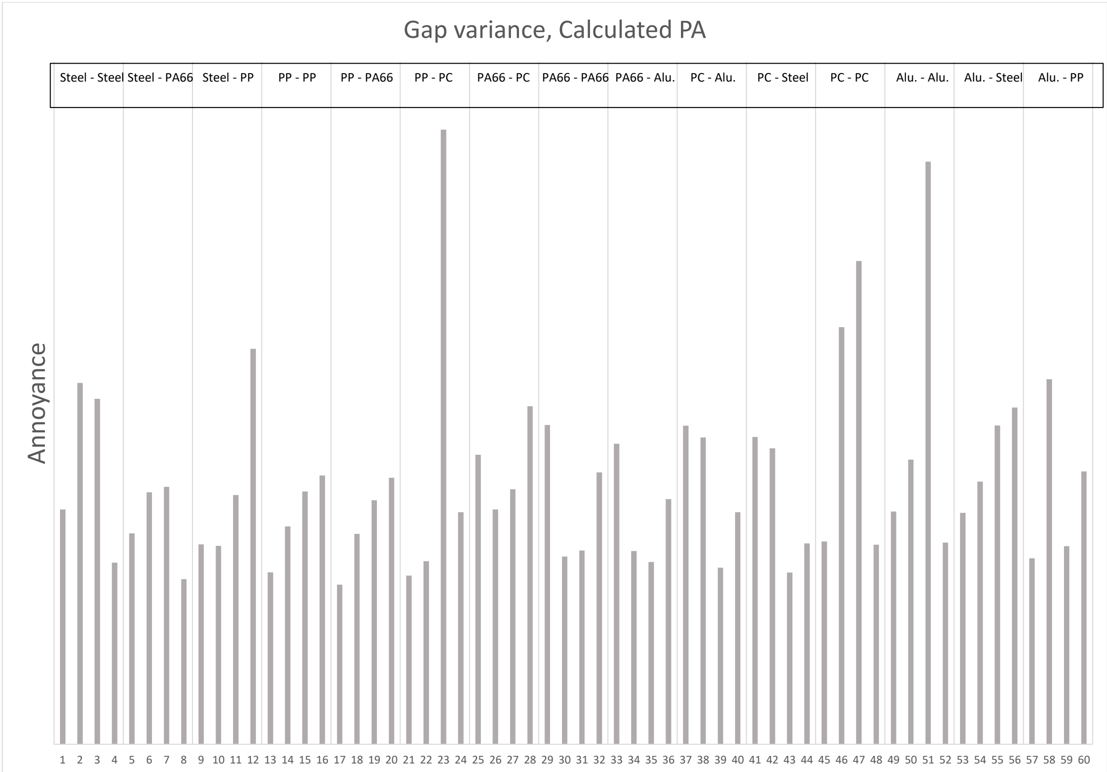

Figure 4.4: Gap/Material dependence from calculated PA values, room temperature

Figure 4.5 displays the gap dependence for the objective evaluation where every room temperature recording is averaged for every gap case.

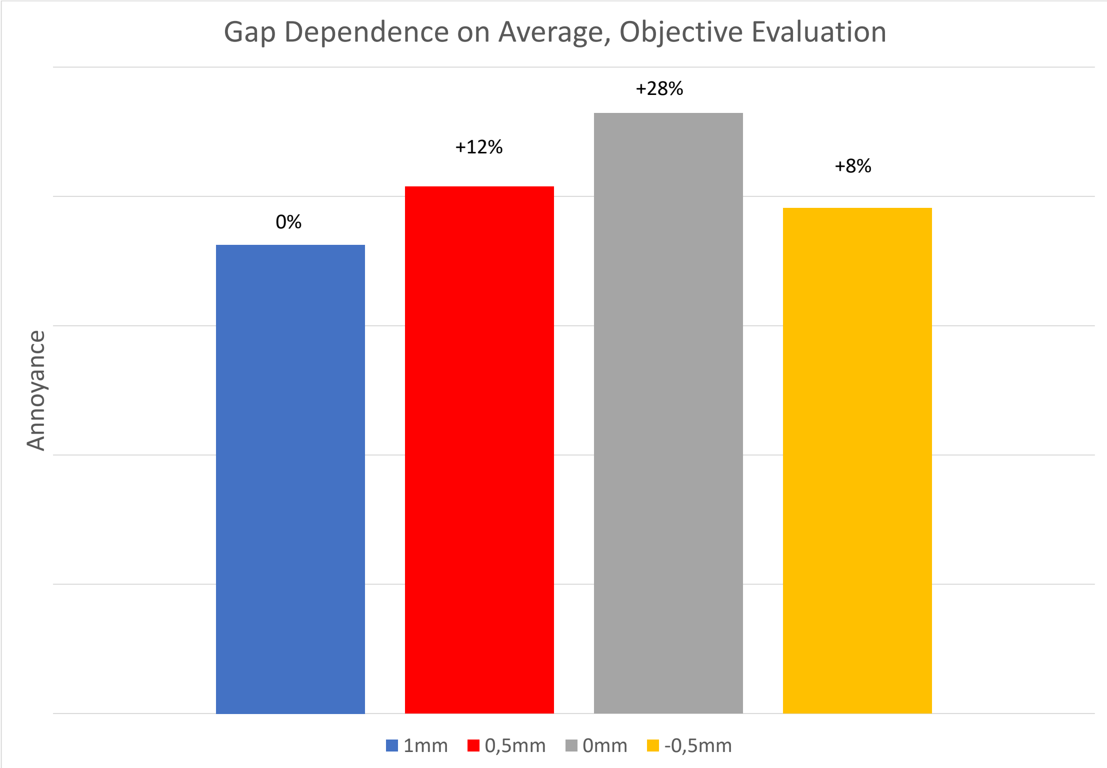

Figure 4.5: Gap dependence from calculated PA values, room temperature

4.2.2 Material Dependence

As for the material dependence, the average objective annoyance values of the three categories discussed in Section 1.7, *Metal - Metal*, *Metal - Plastic* and *Plastic - Plastic* is compared in Figure 4.6. Note that the calculations of average only is performed on the data for the room temperature case since this is the only temperature completely included in the listening clinical trials.

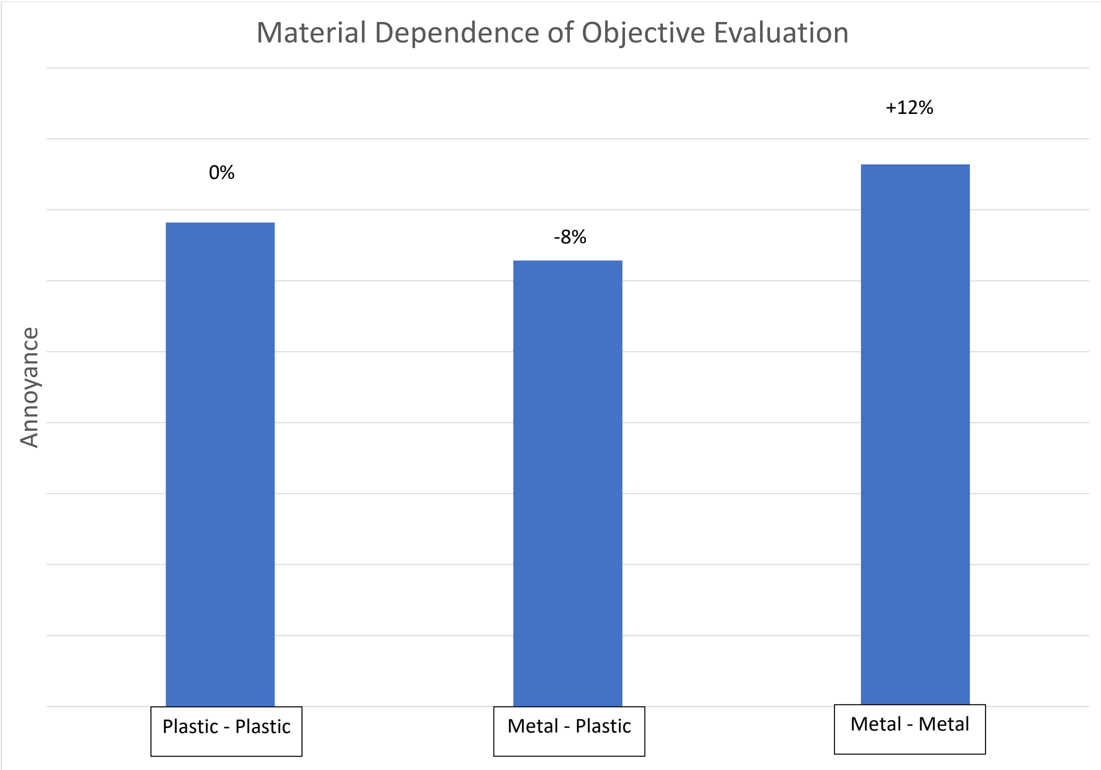

Figure 4.6: Material dependence of objective evaluation

4.2.3 Temperature Dependence

Figure 4.7 displays the temperature dependence for the calculated PA values. In this figure, the gap was chosen to 0 mm gap. The reason to this was to avoid having a figure that is difficult to interpret due to too many bars and too much information.

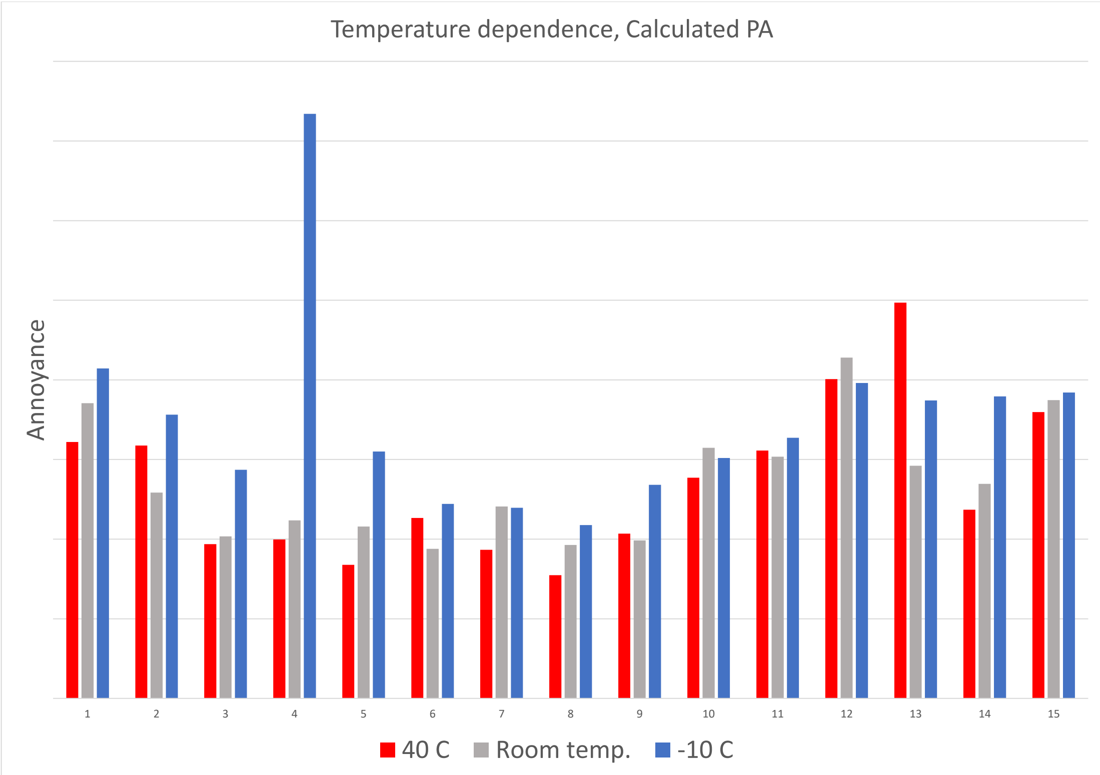

Figure 4.7: Temperature dependence from calculated PA values

Figure 4.8 displays the temperature dependence from the objective evaluation. Recordings corresponding to those included in the listening clinical trials, for all three temperatures, are included and averaged for comparison.

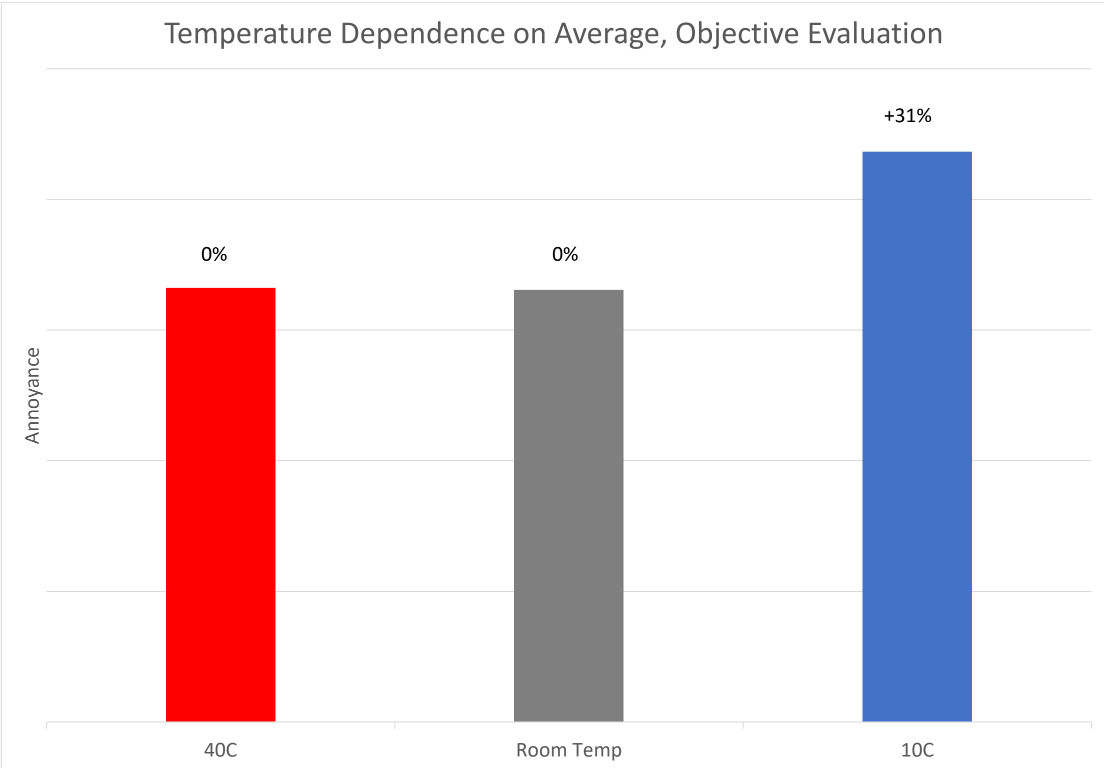

Figure 4.8: Gap dependence from calculated PA values, room temperature

4.3 Subjective Rattle Evaluation

The subjective rattle evaluations presented here originate solely from the listening clinics performed towards the end of the project. Some results from the clinical trials, such as the results from the randomized pairs and the pairs where the playback order was inverted, were left for future studies at VCC. Below, the results for gap, material and temperature dependency are discussed.

4.3.1 Gap Dependence

Figure 4.9 displays the clinical trial results from all 60 recordings in room temperature. Every vertical grid line corresponds to a certain material pair, with the four different gaps in descending order. For example, recording one corresponds to 1 mm gap, recording two corresponds to 0.5 mm gap, recording three corresponds to 0 mm gap and recording four corresponds to 0.5 mm negative offset for the first material pair.

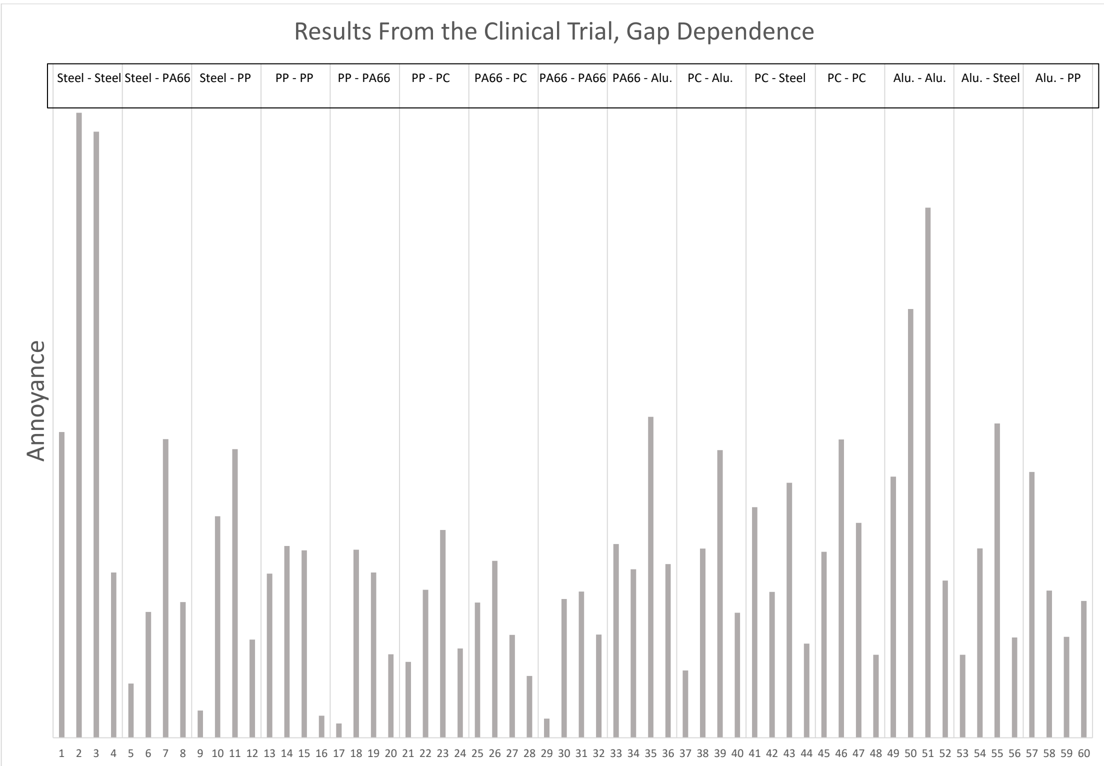

Figure 4.9: Clinical trial results for room temperature

Figure 4.10 displays the gap dependence for the subjective evaluation, on average. Each bar corresponds to one gap case.

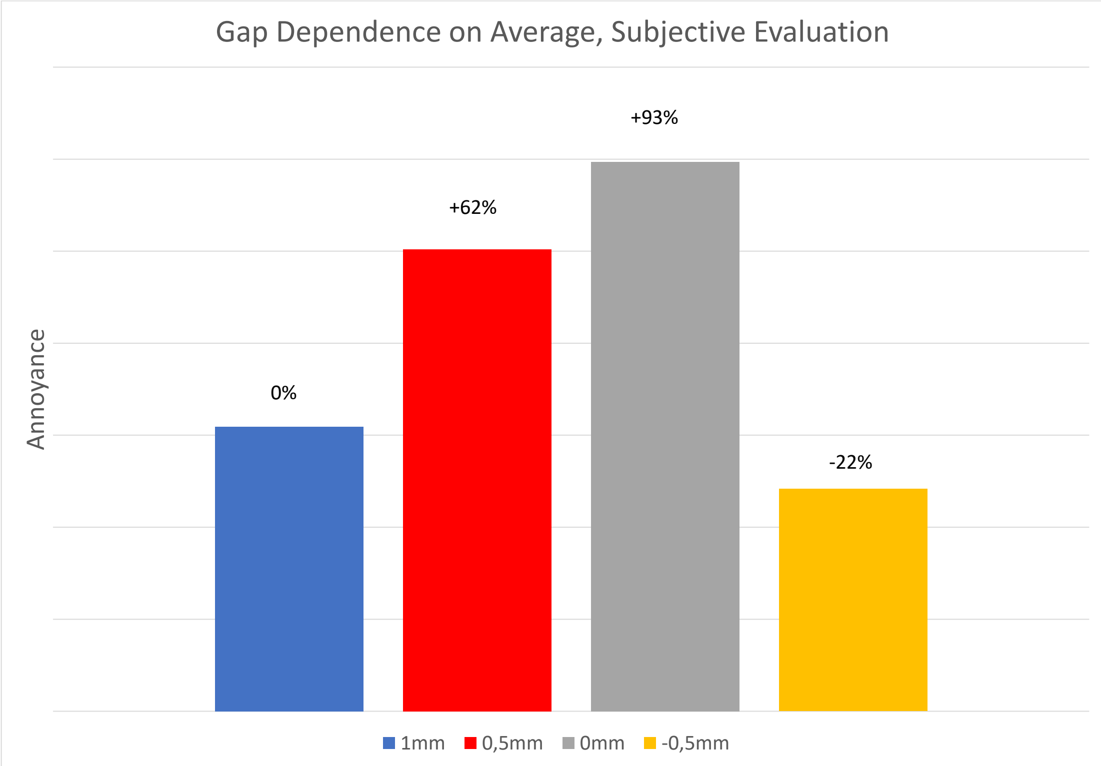

Figure 4.10: Gap dependence from calculated PA values, room temperature

4.3.2 Material Dependence

As for the material dependence, the average subjective annoyance values of the three categories discussed in Section 1.7, *Metal - Metal*, *Metal - Plastic* and *Plastic - Plastic* are compared in Figure 4.11. These calculations are performed on the room temperature case since all recordings of this temperature are included in the listening clinical trials.

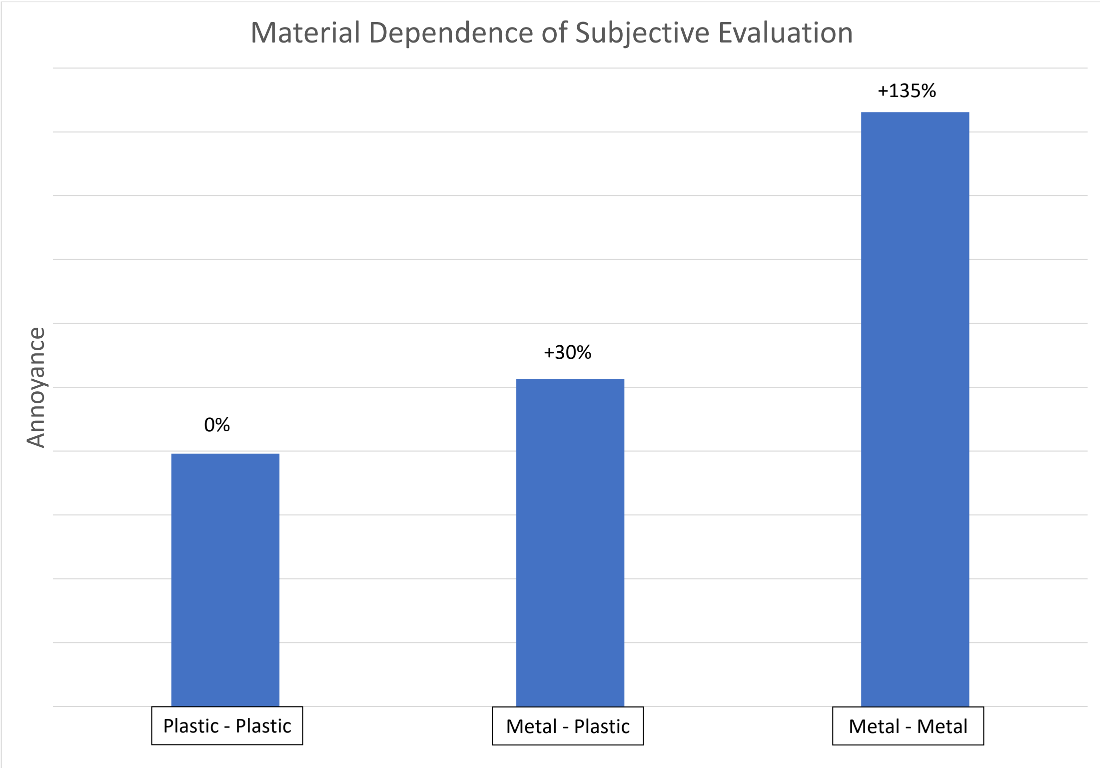

Figure 4.11: Material dependence of subjective evaluation

4.3.3 Temperature Dependence

Figure 4.12 displays the three material pair combinations and the corresponding four gap cases for each of these.

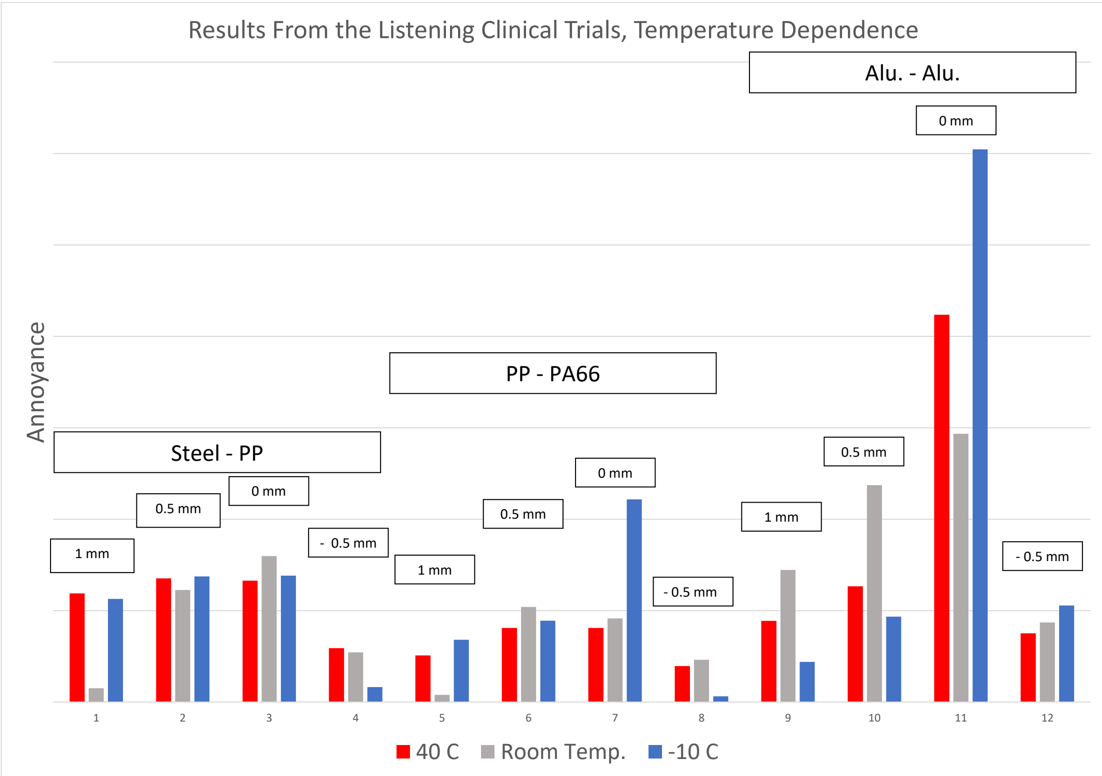

Figure 4.12: Temperature dependence. Values from listening clinical trials are displayed

Figure 4.13 displays the temperature dependence for the subjective evaluation, on average. Every bar corresponds to one of the temperature cases, as mentioned previously.

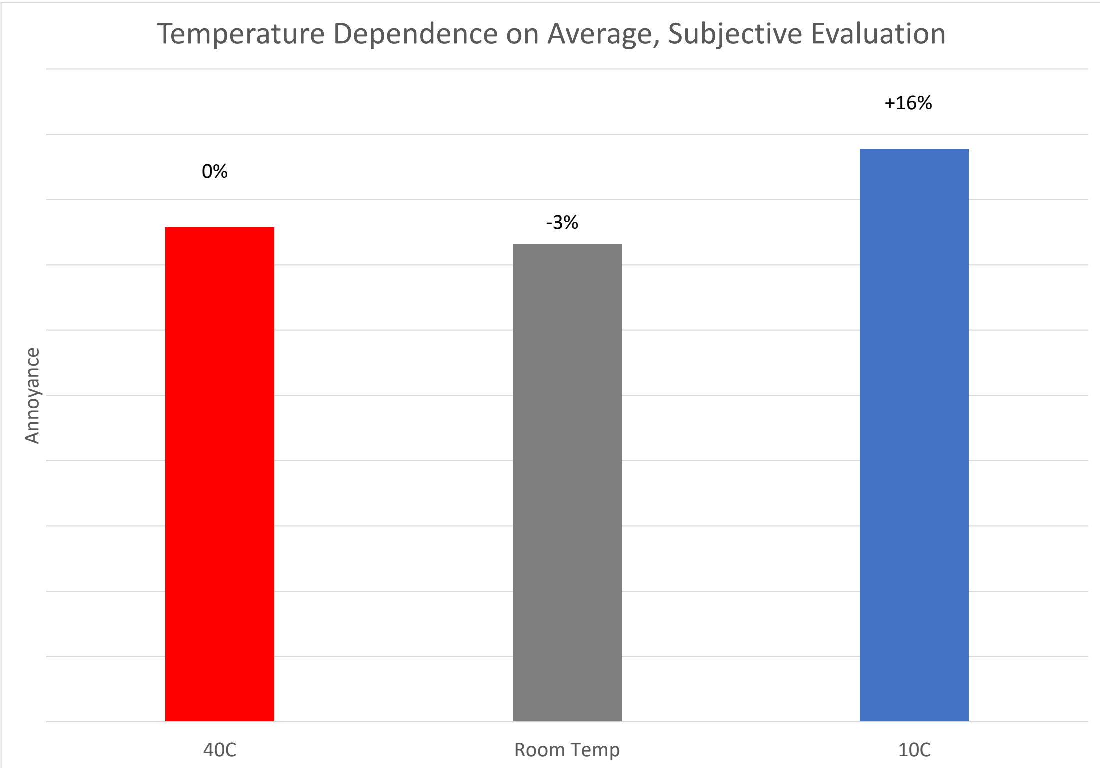

Figure 4.13: Temperature dependence of subjective ratings from the listening clinical trials, averaged

5
Discussion

5.1 Test Rig

The test rig, including design, manufacturing, testing and evaluation, was always the main focus of this thesis and the element from which VCC could continue their research on S&R issues. A great deal of time and resources were therefore put in to both the manufacturing and the evaluation of the test rig.

Besides from verifying the eigenfrequency behaviour of the test rig it is difficult to quantify the test rig in terms of how well it met the goals set up. However the group has performed many rattle measurements with the test rig and thereby verified the functionality and practicality of it.

From subjective evaluations during the rattle measurements it could also be concluded that the hypothesis of the parameters influential on rattle was valid. The temperature, gap size and material inserts were found to clearly influence the experienced annoyance of the produced sound.

Comparing the calculated eigenfrequencies of the beam from Section 3.3.1 and the results from the laser camera it can be seen that the coherence is very high. The laser camera measured a first eigenfrequency of 40 Hz and the calculations gave 40.32 Hz. The coherence beetween the ANSYS simulated eigenfrequencies and the laser camera verification is not as high, although still good. ANSYS simulations, seen in Section 3.3.2, gave a first eigenfrequency of 47.94 Hz.

5.2 Objective Rattle Evaluation

An initial hypothesis put forward by the group was that lower temperatures would produce worse noise. As can be seen from the calculated PA measures in Figure 4.7 this feature seems to be captured more or less consistently by Zwicker's formula. In 7 out of 15 cases, 46,67 % the hypothesis of the project (worse sound for colder temperatures) holds. If only the cold and the warm cases were compared, the hypothesis holds for 13 out of 15 cases, 86.67 %. The two pairs for which this did not hold are *Aluminium - Aluminium* and *PC/ABS - PC/ABS*. In order to get more reliable results, these measurements should be performed multiple times. Another trend that can be identified in the results is that the PA measure varies with the gap size, where the PA measure increases from the greatest gap size (1 mm) to the smallest gap size (0 mm). This holds for 9 out of 15 pairs, 60%, of the cases.

See Figure 4.4 for an illustration of how the PA varies with the gap size. No clear connection between how the pre-loaded cases affect the PA values can be established from this figure. Referring to Figure 4.5 instead, the annoyance is increasing with decreasing gap size to reach a maximum for 0 mm gap. This is in well congruence with the hypothesis stated in the introduction. The yellow bar represents the cases of pretension, which, in general, resulted in lower annoyance than the cases with gap.

Regarding the material dependence shown in Figure 4.6, the groups hypothesis was that there were three overall categories of material pairings; *metal-metal*, *metal-plastic* and *plastic-plastic*. The idea was that these three material pairing groups each should correspond to different levels of annoyance, where *metal-metal* would be the worst and *plastic-plastic* the least annoying. This was also confirmed, subjectively, by the group while performing the rattle measurements. From the figure it can be seen that *Metal - Metal* indeed was calculated to be, on average, the worst case, material pair wise. However, *Metal - Plastic* was calculated as the least annoying, in contrast to the hypothesis. The difference between *Plastic - Plastic* and *Metal - Plastic* was low, at only 8%. Even though the general hypothesis was not held, the results are not far off.

Figure 4.8 displays the temperature dependence for the objective evaluation. In this figure the objectively calculated values are are averaged in order to get a more general understanding of the outcomes. Even though there are some inconsistent results if the warm case is compared to the room temperature case, the figure displays clear evidence of higher annoyance for the cold environment. This confirms the hypothesis stated in the introduction, at least to some extent.

Reasons as to why some of these results are inconclusive may be that the peak PA values were analyzed. The moving mean might have been a better method to use since it might capture a better overall representation of the sounds. The major concerns with the peak PA value are that the loudest part of the signal might come from the surroundings or that the seconds in the vicinity of the peak value are not a good representation of the overall PA value.

5.3 Subjective Rattle Evaluation

As discussed earlier the data from the clinical trials required processing before any meaningful interpretation could be done. Apart from the processing described above the data was also gone through manually by the group to identify faulty insertions or strange outliers.

Referring back to Figure 4.9, some of the material pairs indicate a gap dependency similar to what was discussed for the objective rattle evaluation in Section 5.2. However, the dependency does only hold for 7 out of 15, or 46.67% of the material pairs. However, Figure 4.10 shows that the subjective evaluation for the gap dependence is well in congruence with the groups initial hypothesis with increasing annoyance for decreasing gap. As for the yellow bar, representing the pretension cases, it is obvious that theses cases produce lower annoyance than the gap cases, in general. When studying the averaged values, the hypothesis does hold.

Studying Figure 4.12, there is no clear coherence between the results from the clinical trials and the hypothesis of the project regarding the temperature dependence. Out of the 12 material pairs tested, the correlation of increasing annoyance with decreasing temperature was only strictly held for 2 out of 12 pairs, which resulted in a coherence of 16.67 %. However, considering only the two extremes, warm and cold, the coherence is 7 out of 12 cases, or 58.33%. However, the averaged temperature dependence for the subjective evaluation, displayed in Figure 4.13, shows very similar results to the averaged temperature dependence from the objective evaluation, displayed in Figure 4.8. Comparing the warm and cold cases, solely, the hypothesis of higher annoyance in colder environment is valid, but there are some inconsistent results when comparing the warm case with the recordings in room temperature. A reason for the hypothesis not holding when comparing the room temperature case with the warm temperature case might be that the temperature difference between these two are too small, only 15 Kelvin.

From Figure 4.11 *Metal - Plastic* is rated, on average, 30% worse in annoyance compared to *Plastic - Plastic*, *Metal - Metal* is rated, on average, 135% worse in annoyance compared to *Plastic- Plastic.* This is considered to confirm the groups initial hypothesis regarding the material dependence.

5.4 Comparing Objective and Subjective Results

Once processed, the data from the clinical trials was compared to results from the calculated PA values. The scales were different when comparing the data from the clinical trials and the calculated PA value. Since reference 1 was used as the main reference, the values from the clinical trials were scaled by a factor to make reference 1 equal to its corresponding clinical trial value. See Figure 5.2.

Note that the data in Figure 5.1 is sorted in descending order of the calculated PA and the clinical trial results are sorted in the corresponding order. Linear regression lines were also added to both of the data sets to confirm any trend similarities. As can be seen in Figure 5.1 the results from the clinical trials and the calculated PA values do not show any convincing congruence. The regression lines do show slopes with some congruence but the overall data does not seem to share any trends.

When sorting the data back to the original recording order it seemed like the results from the clinical trials and the calculated PA results had some similar features. By studying the data material pair wise it seems like the gap variation show some similar trends between the two data sets, however, the results from the clinical trials when scaled with reference 1 show generally lower values, see Figure 5.2.

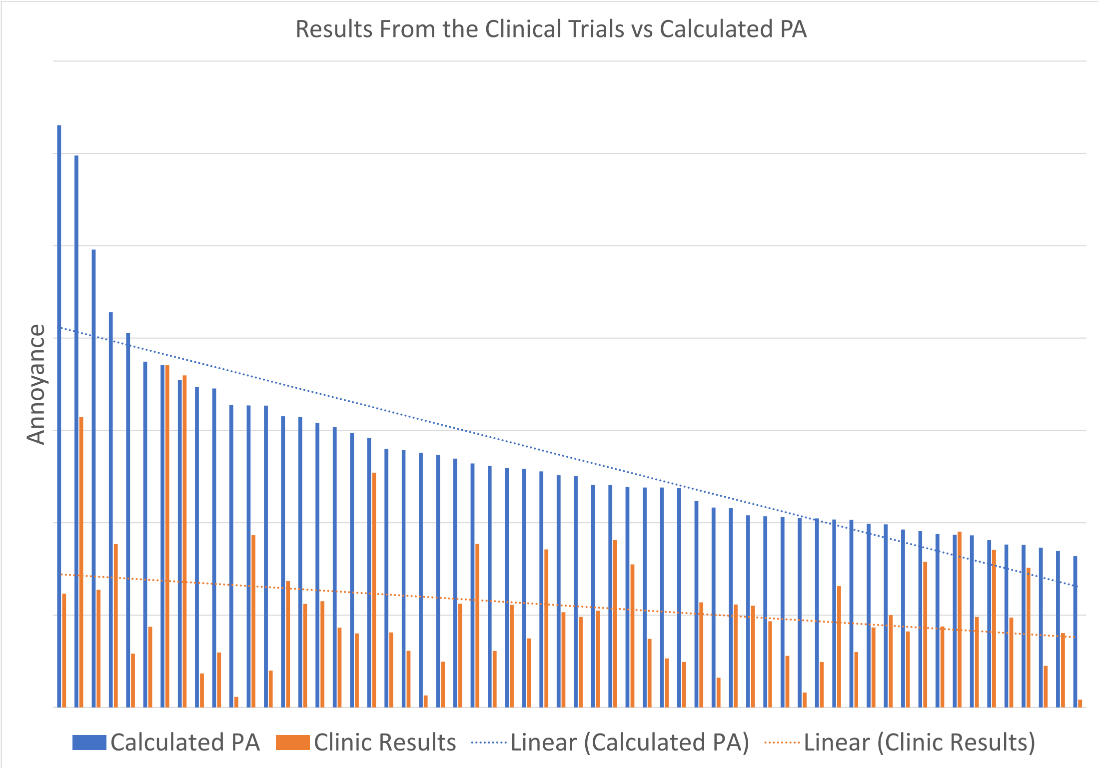

Figure 5.1: Listening clinic trial results and calculated PA values

5.5 Sources of Error

There can be several errors which must be straightened out before any results can be regarded as significant. Below, possible sources of error will be gone through to help future studies within the subject of rattle at VCC.

5.5.1 Test Rig and Rattle Measurements

The rattle measurements are directly correlated with how well the test rig performs and sources of error in the measurements can not be discussed without mentioning the performance of the test rig. However, the group are unable to find any errors from the test rig that significantly distorts the quality of the measurements.

What might have affected the results in a negative manner was the background noise present during the recordings. The room in which the recordings took place was only “semi-acoustic”, which could have failed in shutting out noise from outside the room. Another source that may have added to the background noise was the shaker which had a humming sound during operation.

This would mainly affect the calculated PA values and it could be one reason as to why the group was unable to find any pattern between material pairs. This background sound may have blurred out most of the differences between setups. However, the clinical trails should have been more unaffected by this since humans

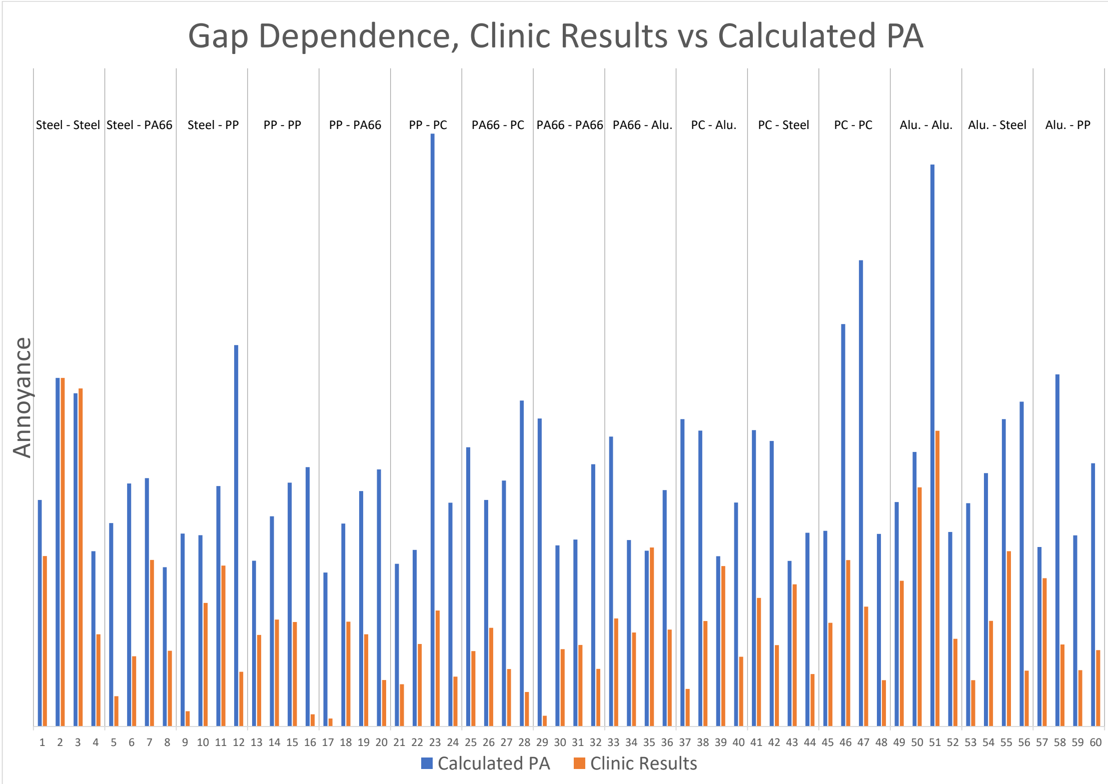

Figure 5.2: Correlation of gap dependence

may be capable of filtering out constant noise. Even though the group has no proof of how good the participants were at doing this, this is the general feeling when conducting informal interviews with the participants after the clinical trials.

5.5.2 Listening Clinical Trials

It was sometimes difficult for the participants to use the scaling method proposed in Section 3.6.2. For example, starting from 100, twice as annoying would have been given a rating 200, whilst half as annoying would have been given a rating of 50. This relative scaling problem was something that was frequently noted a problem by the participants. However, since the clinical trials are subjective, a rating of 50 or 20 does not make any major difference. Even if this could have been done in a more sophisticated way, it should not affect the results significantly.

The main issue with the proposed scaling method was that there were no limits as to how high (or low) the participants could rate the sounds. This is merely a question of subjectiveness, but some limit as too how high/low the rating could be would be preferred. The most widespread participant had a span between 5-99 000, and the least widespread had a span between 20-240. Since 100 was equally annoying to both these individuals, it made it hard to scale in a proper manner. Decreasing/increasing the span of individuals may have distorted the ratings around 100. Ratings around 100 are perceived as equally annoying as the first sound in a pair, and participants are likely to rate these sounds similarly. Figure 5.3 displays these two individuals rating span and how participants are likely to have similar scales around ratings of 100. The further out in the periphery, the more the different scaling affected the rating.

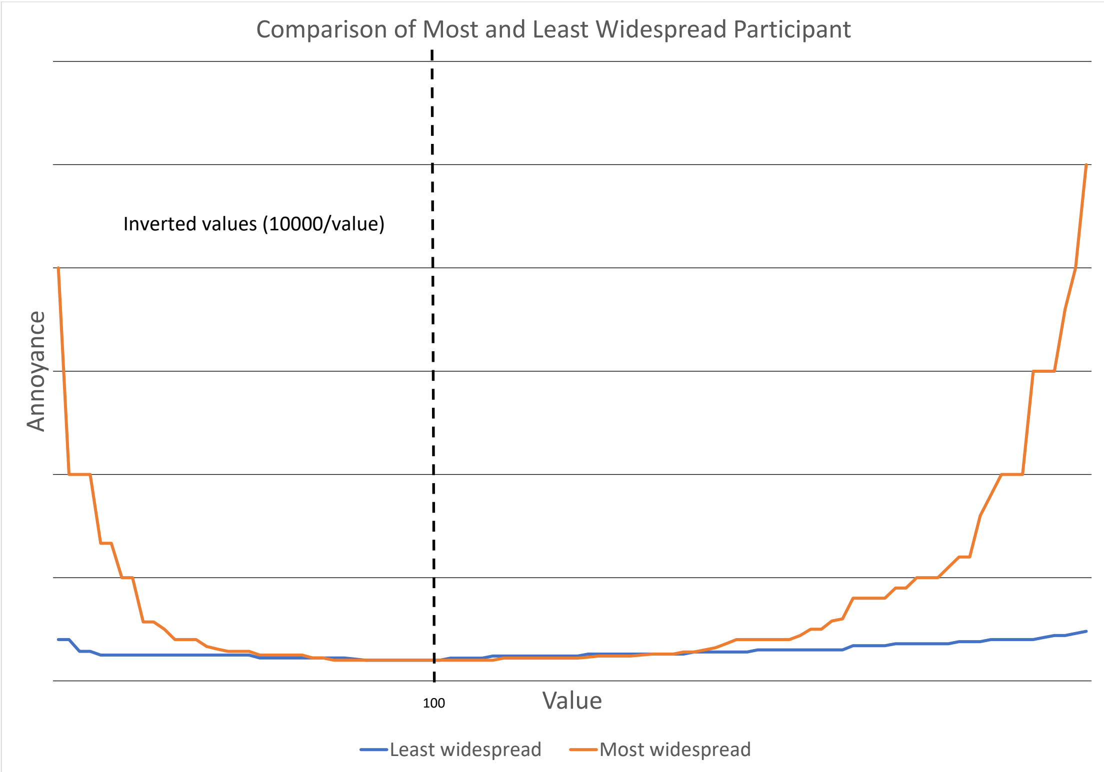

Figure 5.3: Comparison between the most widespread individuals from the clinical trials

This further emphasizes the need for setting a fixed span in which participants are allowed to rate the sounds. Note that Figure 5.3 is made by taking the inverse of the ratings below 100 to make them comparable to the ones above 100. A rating of 50, id est half as annoying as the global reference 1, will be regarded as $10000/50 = 200$. This is only made to compare the different scaling span of individuals. Beside this, the four highest/lowest values are removed from the two participants in Figure 5.3. Without removing the extremities, the differences would have been even greater, but impossible to display and interpret in a plot.

6
Conclusion

There is a number of conclusions drawn from this master's thesis, to keep this chapter as clear as possible it has been divided into sections similar to those in the results chapter.

6.1 Test Rig

There were many concerns along the way that the test rig might not perform as anticipated from calculations and simulations or that the assembled test rig would not fit to the table in the semi-climatic chamber. All of these concerns were, however, put out when the test rig at first try fitted perfectly in the climatic chamber and the cantilever beam and modal hammer produced rattle noises in the anticipated manner.

In all it can be concluded that the test rig has performed very well and that VCC should be able to perform many future tests and recordings by use of the test rig.

The decision of designing and building the test rig ourselves is something that we believe to be a key factor to the success of the build. Many suggestions of improvement were put forward by the research engineers in the Mechanical engineering work shop and the team could also get a better feel for the final product and incorporate design improvements ad hoc. Features such as the gap control screw and the swivel pins for the beam were invented while manufacturing the test rig.

6.2 Objective Rattle Evaluation

The hypothesis formulated in the beginning of the project about gap dependence was held for 60% of the measurements. This, along with the results from the averaged results discussed above, is good proof of a confirmed hypothesis for the gap dependence. As for the pretension cases, which the group were indecisive about from the start, they generally produce less annoying sounds than the cases with gap.

For the temperated cases, if considering only the extreme cases, the measurements correlated for almost 90%, which can be seen as a good value for confirming the hypothesis that a colder temperature is a worse case than a warmer temperature, from a psychoacoustic point of view. Besides this, to further confirm the hypothesis regarding the temperature case, the averaged values discussed in previous sections provide good evidence of congruence with the hypothesis.

In line with the material dependence hypothesis, the *Metal - Metal* material pairs were shown to be the worst case. However the hypothesis failed in predicting the least annoying case. However, the difference between the *Plastic - Plastic* and *Metal - Plastic* is small and might be contributed to the background noises previously discussed.

6.3 Subjective Rattle Evaluation

The gap dependence hypothesis was only held for about 50% of the subjective measurements. However, this figure in combination with the averaged results discussed previously is evidence enough to confirm the hypothesis of increasing annoyance with decreasing gap.

By studying the results from the temperature study, the hypothesis of increasing annoyance with decreasing temperature was held for about 60% of the results from the clinical trials. When averaged numbers are compared, the hypothesis is clearly held, and these results confirm increasing annoyance with decreasing temperature.

The material dependence from the subjective measurements is in perfect congruence with the hypothesis of the group about how different material pairs would affect the perceived annoyance.

6.4 Comparing Objective and Subjective Results

No clear connection can be established between the objective and the subjective evaluations performed in this thesis. Both of these areas need further exploration before reliable enough results can be obtained. The group has, however, confidence in that a connection should be able to be established and with a better setup of the listening clinical trials and an improved objective metric calculation there might be some success within this area.

6.5 Areas of Improvement

The sources of error listed in Section 5.5 are obviously included in areas of improvement. This study was the first stepping stone in a long term project at VCC and many interesting conclusions as to how proceed from here can be drawn.

6.5.1 Test Rig and Rattle Measurements

The overall performance of the test rig was considered very good, and not much could be done as to improve the test rig without re-designing it from scratch. Even with a re-design the group does not see any obvious area of improvement.

For future rattle measurements, another chamber is recommended to be used in order to reduce/remove unwanted background noise that may affect the recordings.

An acoustic chamber with solid isolation from outside disturbances is recommended. As for the shaker, a more modern one may have less background humming which would contribute to more reliable measurements.

6.5.2 Listening Clinical Trials

Another rating method should be used in order to reduce any uncertainties for the participants in rating the sounds. The most severe problem of the proposed rating method is that of the limits, discussed at the end of Section 5.5.2. One option is to have a fixed range of ratings, for example 1-10. This, however, introduce a problem when participants do not know the span of the sounds in beforehand. If one sound is rated a 10, it is likely that it was seen as "worst so far". When another sound is played which would be rated as 15 in comparison to the "worst-so-far" sound, then the participant would be limited by the scale and forced to rate this sound 10 as well.

It should be noted that the listening clinical trials were not a part of the Gantt chart, nor the thesis from the beginning. Inclusion of, and planning of, the clinics at an earlier stage could have improved the final outcomes of the clinical trials. This is an area that needs to be evaluated more deeply and given more time, preferably through an extensive literature survey.

6.5.3 Objective Rattle Evaluation

Something that the group believes could improve the results from the objective evaluation is to incorporate the impacting force and acceleration of the beam in the calculations. This could also help in development of a final FEA based evaluation of rattle, since force and acceleration are integral parts of FE analysis. It should be a fairly simple task to implement in the continuation of this project since the data for both force and acceleration were collected during the measurements. It is merely a question of how to incorporate these in a good manner. Including the frequency of rattle impacts in the calculation of the objective metric is something that might improve the congruence between the objective and the subjective evaluations as well.

6.6 Final Thoughts

To recall back to the hypotheses stated in the introduction, all three are, more or less, confirmed for the objective and subjective evaluations. Gap dependence and material dependence is confirmed to 100% whilst the hypothesis of the temperature has some uncertainties when comparing warm case to the room temperature case. The pretension cases generally produces less annoying sounds than the gap cases.

With the background of both students involved in this thesis being Mechanical Engineering (bachelor's degree) followed by Applied Mechanics (master's degree) it was quite a contrast for the group to be faced with subjective studies and acoustics.

However, these contrasts were an appreciated break from otherwise very specialized studies on mechanics.

The group had, however, many chances of applying knowledge obtained from their studies throughout the project. Especially when designing the actual test rig, as the group could evaluate structural properties and apply product development methodology to the process.

Something else that was highly appreciated by the group was the practical aspect of the project, where the team was given the opportunity to build the final product themselves. This “from design to finished product” has rarely been present during the master’s program before and was seen as a nice end to the academic careers of the group.

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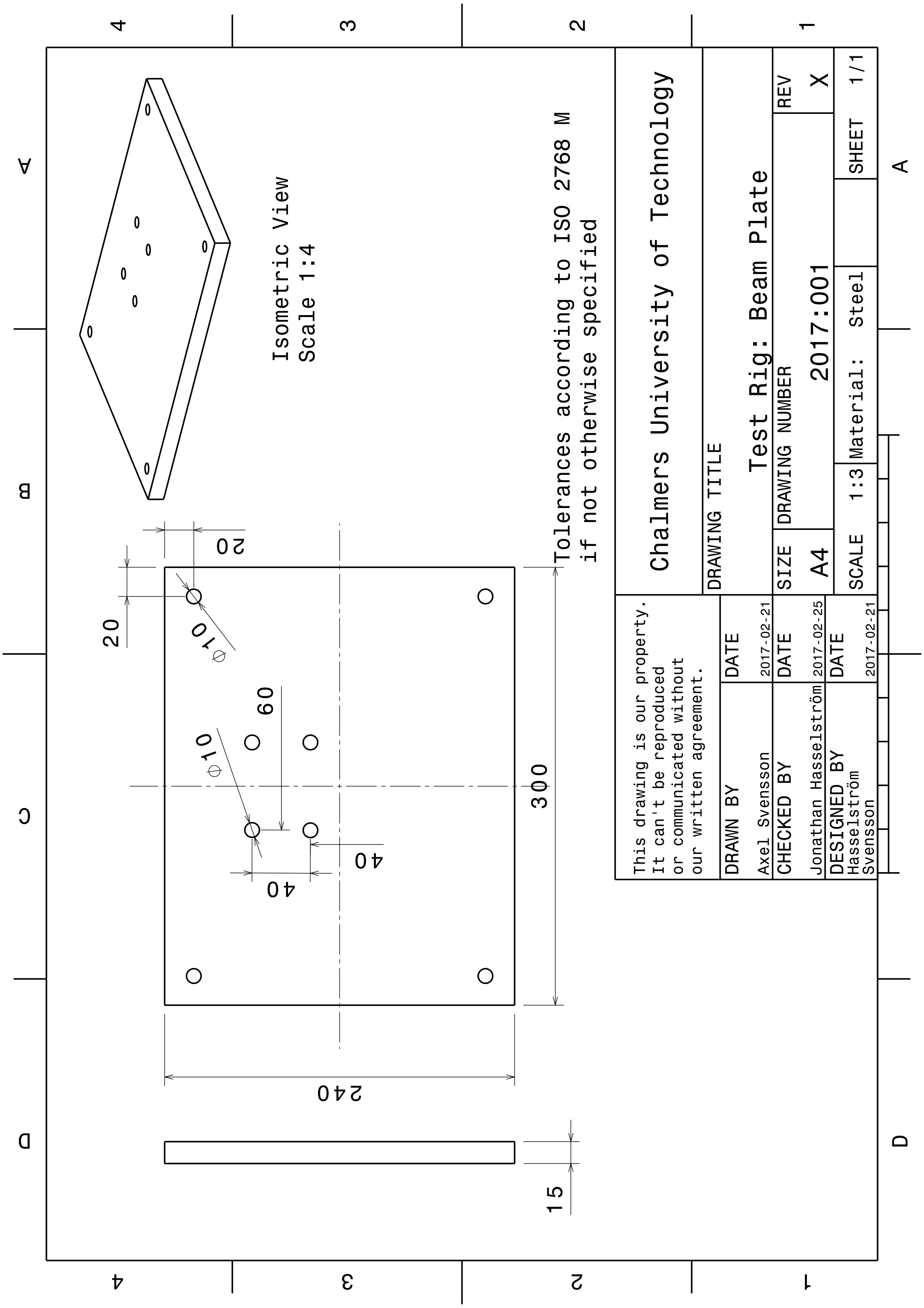
A
Appendix A - CAD Drawings

The CAD drawings created for the components unique to this project are displayed in this appendix. Other CAD components were created too, but merely to aid in the process of visualizing the final assembly and to aid in the development of the test rig. These models are such components that the group used but did not build, or design, themselves.

Note that the size of the drawings are distorted when imported to this appendix, the scales will therefore differ from what is noted in the drawings.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Chalmers University of Technology
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Test Rig: Beam Plate
This drawing is our property.
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or communicated without
our written agreement.
DRAWN BY
Axel Svensson
DATE
2017-02-21
CHECKED BY
Jonathan Hasselström
DATE
2017-02-25
DESIGNED BY
Hasselström
Svensson
DATE
2017-02-21
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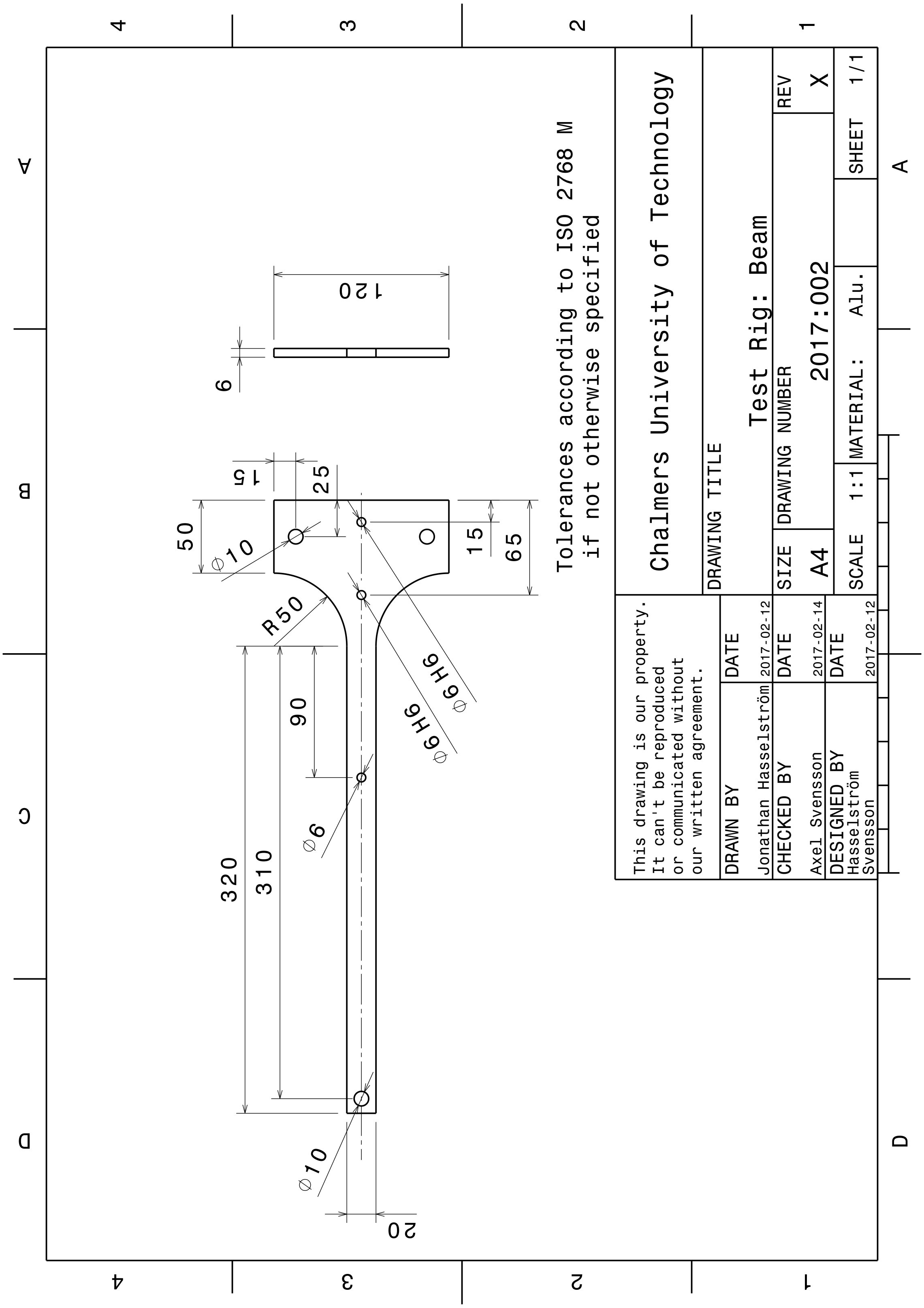
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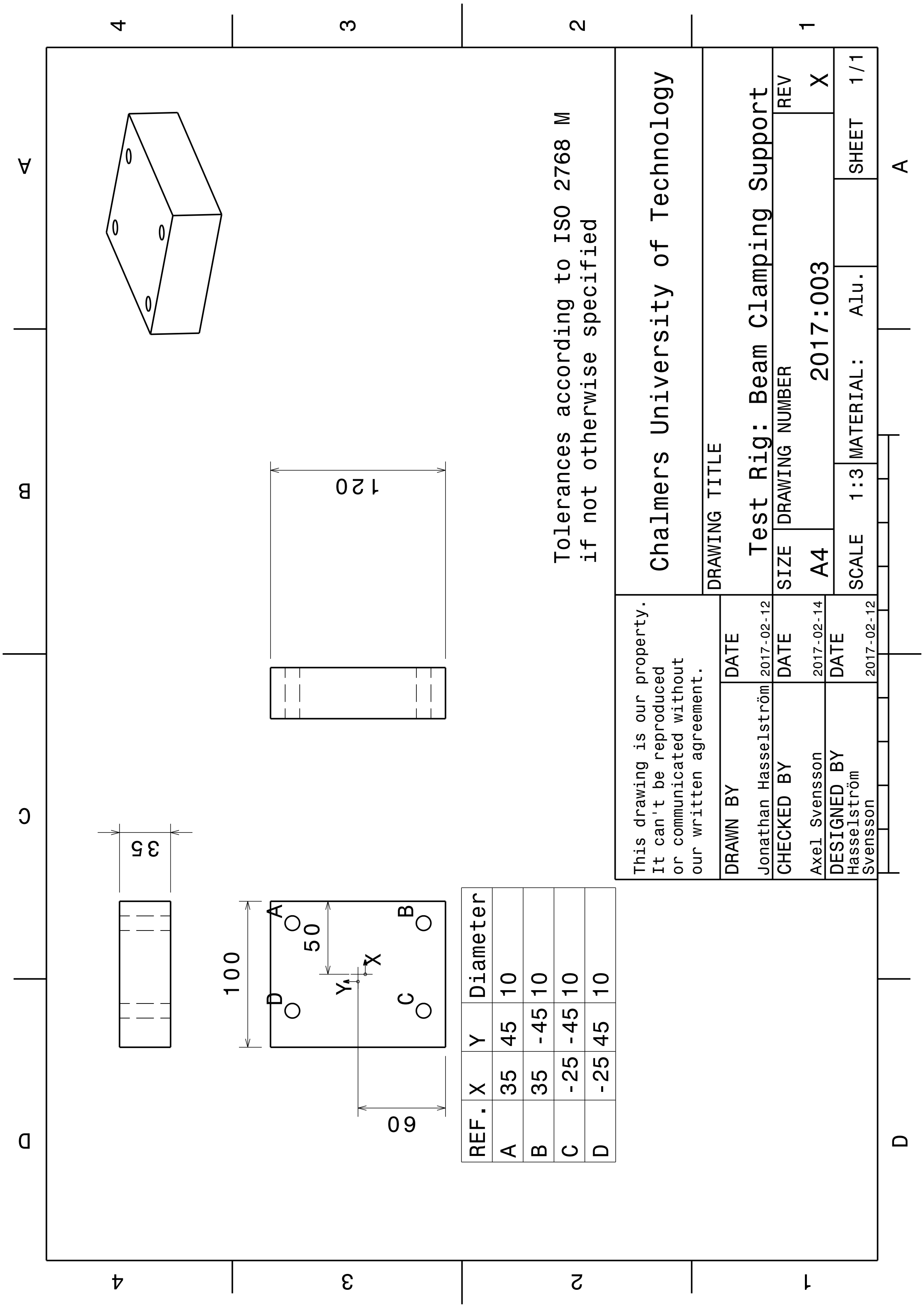
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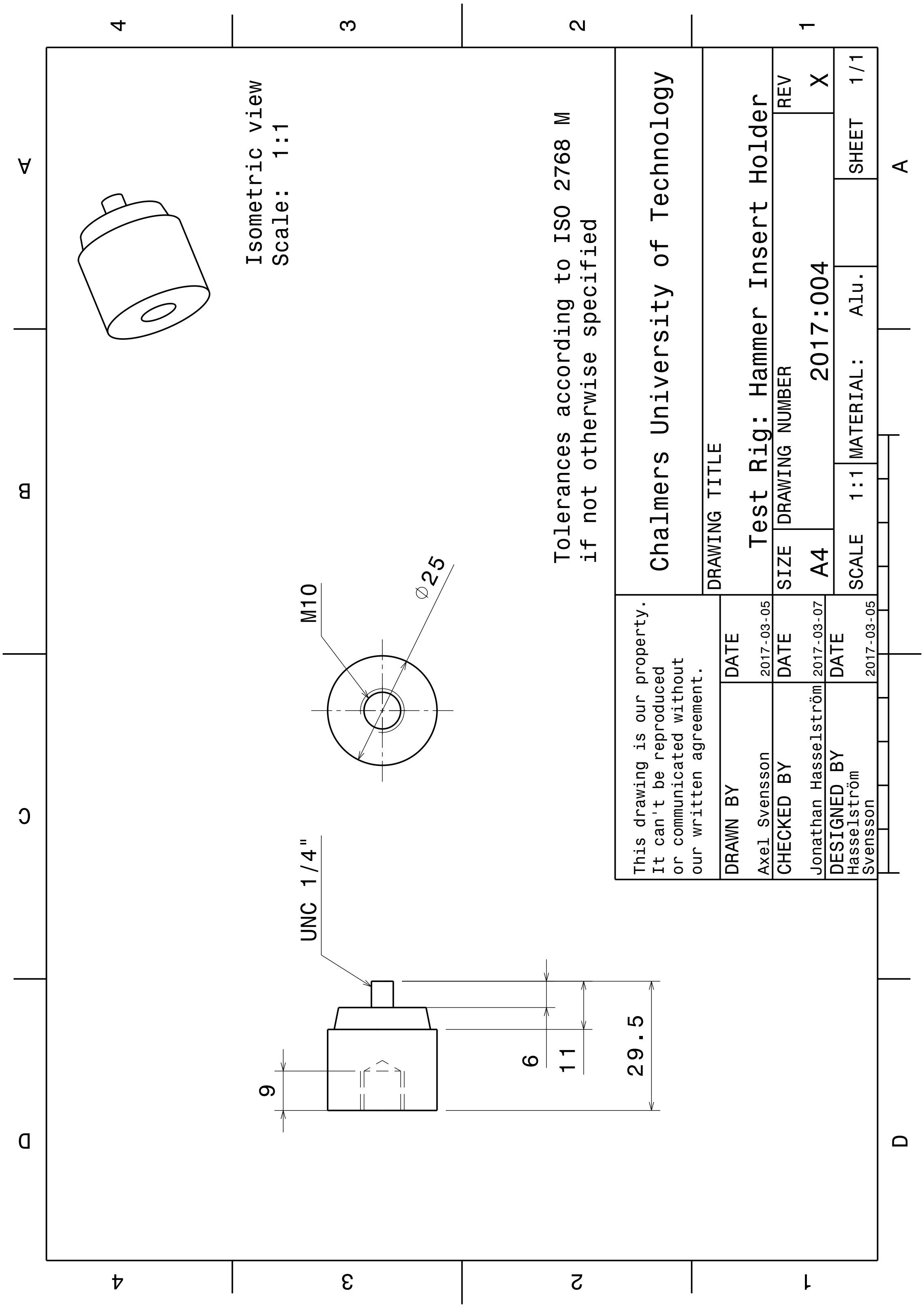
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Chalmers University of Technology
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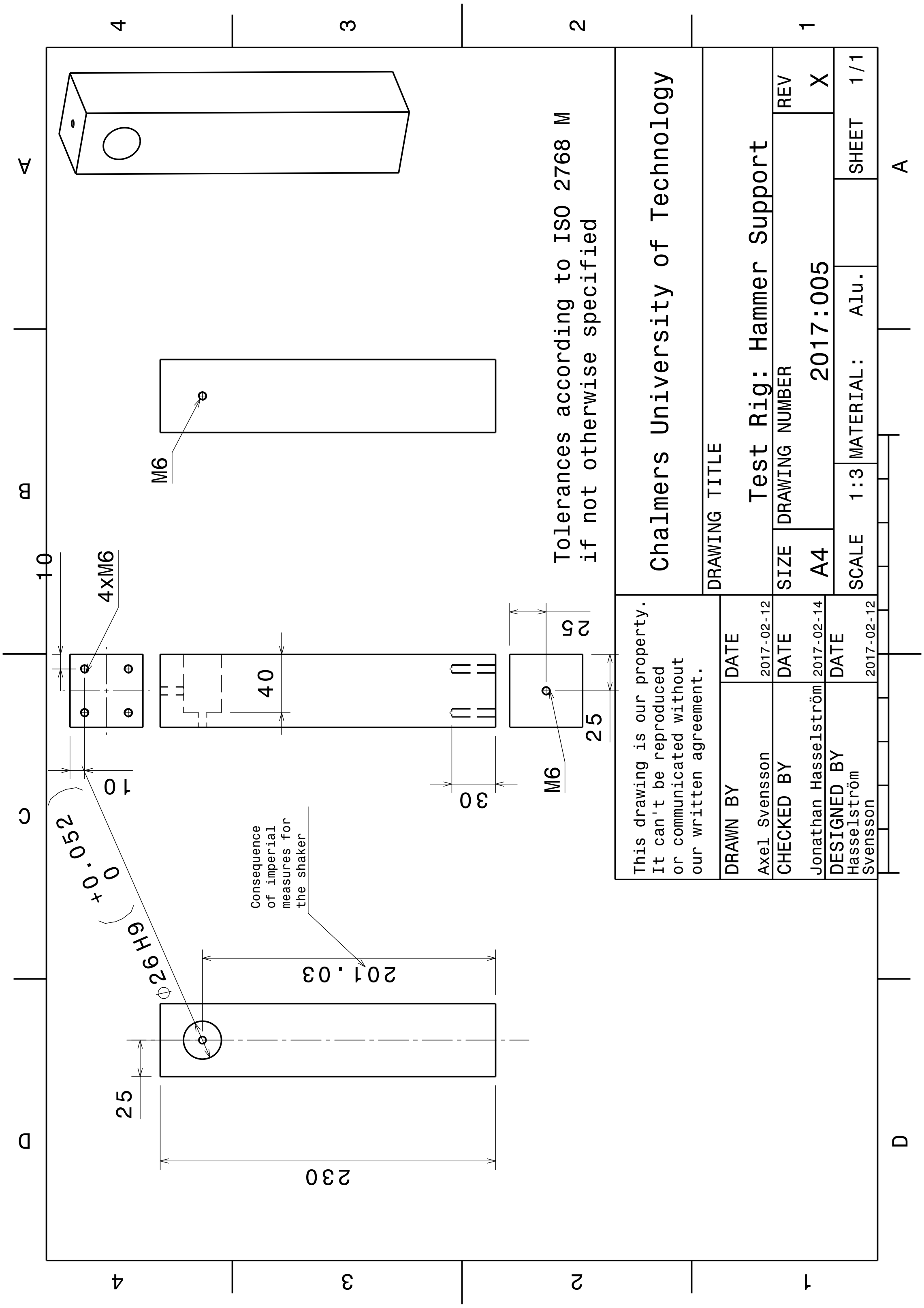
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SCALE
1:3
MATERIAL:
Alu.
SHEET
1/1
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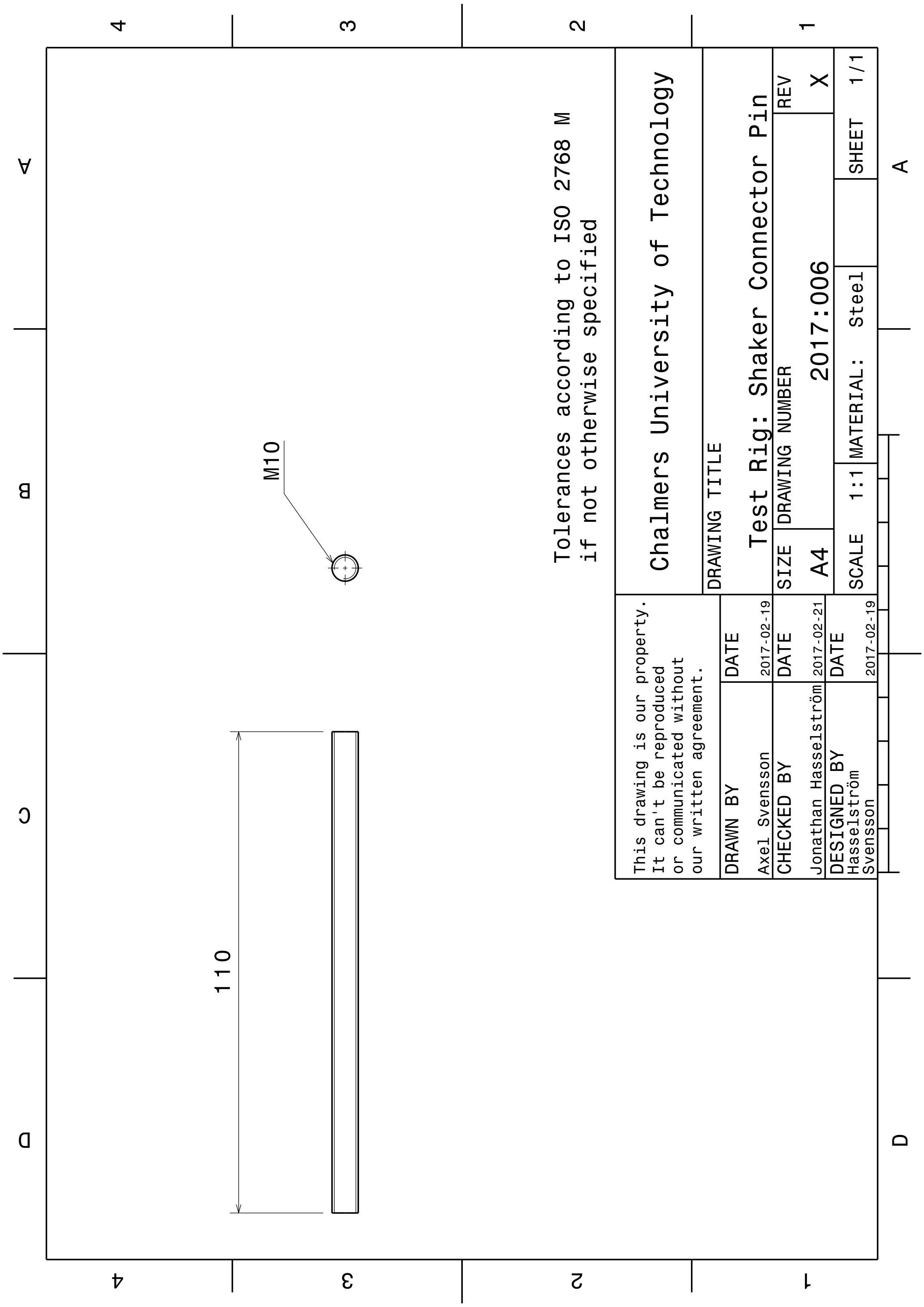
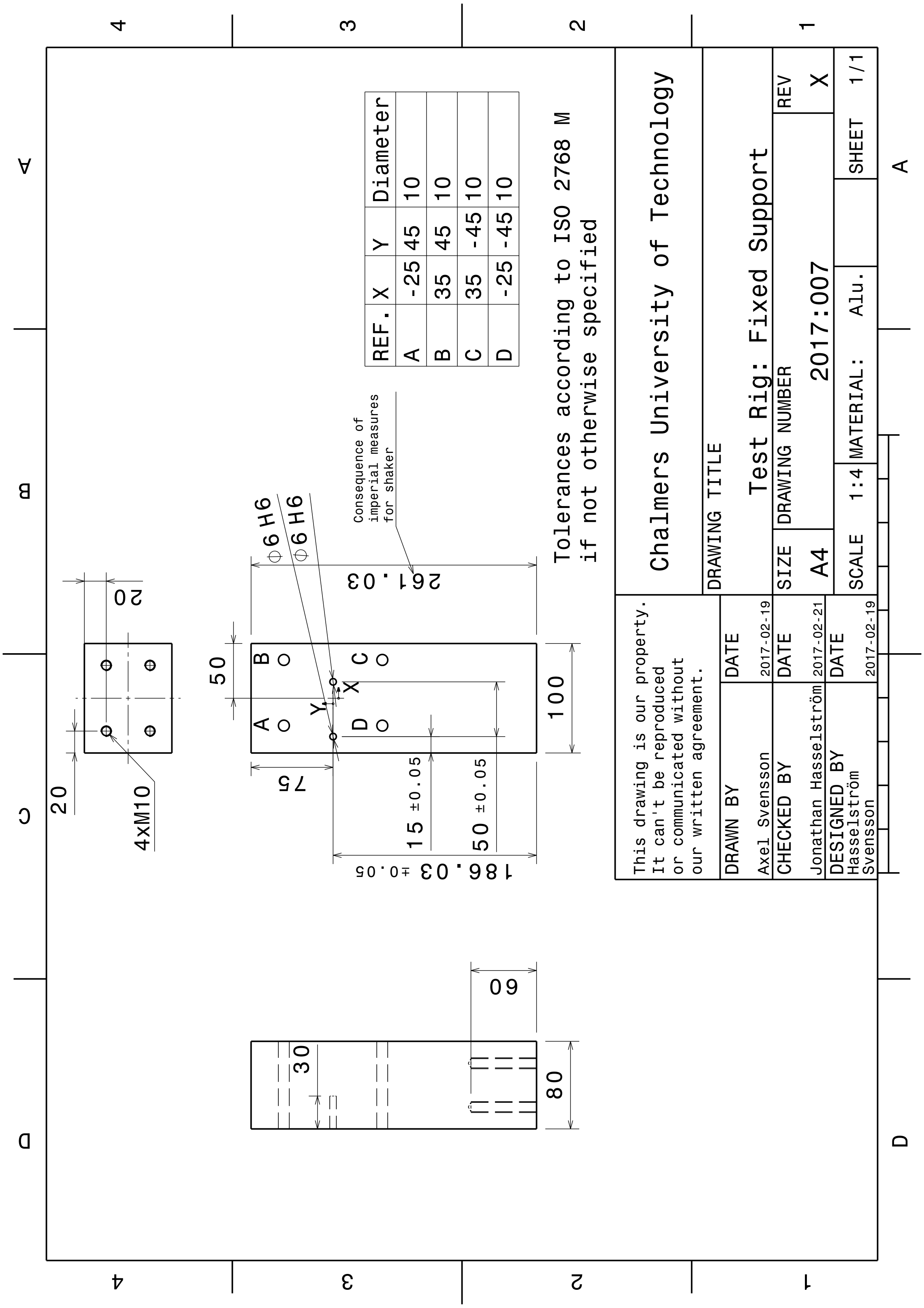
DRAWN BY
Axel Svensson
DATE
2017-02-12
CHECKED BY
Jonathan Hasselström
DATE
2017-02-14
DESIGNED BY
Hasselström
Svensson
DATE
2017-02-12
M6
4xM6
10
40
25
25
M6
30
10
Φ26H9 (+0.052 0)
Consequence
of imperial
measures for
the shaker
201.03
25
230
A
B
C
D
1
2
3
4



Connector Pin.pdf


REF.
X
Y
Diameter
A -25 45 10
B 35 45 10
C 35 -45 10
D -25 -45 10
Tolerances according to ISO 2768 M
if not otherwise specified
Consequence of imperial measures for shaker
φ6 H6
φ6 H6
261.03
186.03 ±0.05
15 ±0.05
50 ±0.05
75
50
100
20
20
4xM10
60
30
80
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Chalmers University of Technology
DRAWING TITLE
Test Rig: Fixed Support
DRAWN BY
Axel Svensson
DATE
2017-02-19
CHECKED BY
Jonathan Hasselström
DATE
2017-02-21
DESIGNED BY
Hasselström
Svensson
DATE
2017-02-19
SIZE
A4
DRAWING NUMBER
2017:007
REV
X
SCALE
1:4
MATERIAL:
Alu.
SHEET
1/1

B

Appendix B - Listening Clinical Trial Questionnaire

Below follows the questionnaire the participants filled in during the listening clinical trials.

Rattle annoyance, experiment 1
Annoyance level estimation with paired comparison

Test Date: ____________________

Participant code (please use your code from interview)

Instructions

1. You will hear two different sound samples separated by 1 second of silence, followed by 5 seconds of silence where you are supposed to rate the sounds.

2. Assume the first sound has the annoyance value **100**, your task is to rate the second sound with respect to the first. If, for example, you rate it 50, you experience it half as annoying as the first sound, and if you rate it 200, then you experience it twice as annoying.

Example 1	A	100
	B	?

Interview

Participant code :____________

How old are you? ____

☐ male ☐ female ☐ other

What is your knowledge and experience in psychoacoustics?

☐ expert ☐ very good ☐ good ☐ limited ☐ none

What is your experience in doing Squeak & Rattle subjective testing?

☐ expert ☐ very good ☐ good ☐ limited ☐ none

How many listening clinics have you attended?

☐ many (>5) ☐ several (3-5) ☐ few (1-2) ☐ none (0)

Do you have normal hearing?

☐ yes ☐ no (Please mention what kind of hearing difficulties you have)

____
____
____
____

Participant code: ___________

Pair 1	A	100
	B	

Pair 2	A	100
	B	

Pair 3	A	100
	B	

Pair 4	A	100
	B	

Pair 5	A	100
	B	

Pair 6	A	100
	B	

Pair 7	A	100
	B	

Pair 8	A	100
	B	

Pair 9	A	100
	B	

Pair 10	A	100
	B	

Pair 11	A	100
	B	

Pair 12	A	100
	B	

Pair 13	A	100
	B	

Pair 14	A	100
	B	

Pair 15	A	100
	B	

Pair 16	A	100
	B	

Pair 17	A	100
	B	

Pair 18	A	100
	B	

Pair 19	A	100
	B	

Pair 20	A	100
	B	

Pair 21	A	100
	B	

Pair 22	A	100
	B	

Pair 23	A	100
	B	

Pair 24	A	100
	B	

Pair 25	A	100
	B	

Pair 26	A	100
	B	

Pair 27	A	100
	B	

Pair 28	A	100
	B	

Pair 29	A	100
	B	

Pair 30	A	100
	B	

Pair 31	A	100
	B	

Pair 32	A	100
	B	

Pair 33	A	100
	B	

Pair 34	A	100
	B	

Pair 35	A	100
	B	

Pair 32	A	100
	B	

Pair 36	A	100
	B	

Pair 37	A	100
	B	

Pair 38	A	100
	B	

Pair 39	A	100
	B	

Pair 40	A	100
	B	

Pair 41	A	100
	B	

Pair 42	A	100
	B	

Pair 43	A	100
	B	

Pair 44	A	100
	B	

Pair 45	A	100
	B	

Pair 46	A	100
	B	

Pair 47	A	100
	B	

Pair 48	A	100
	B	

Pair 49	A	100
	B	

Pair 50	A	100
	B	

Pair 51	A	100
	B	

Pair 52	A	100
	B	

Pair 53	A	100
	B	

Pair 54	A	100
	B	

Pair 55	A	100
	B	

Pair 56	A	100
	B	

Pair 57	A	100
	B	

Pair 58	A	100
	B	

Pair 59	A	100
	B	

Pair 60	A	100
	B	

Pair 61	A	100
	B	

Pair 62	A	100
	B	

Pair 63	A	100
	B	

Pair 64	A	100
	B	

Pair 65	A	100
	B	

Pair 66	A	100
	B	

Pair 67	A	100
	B	

Pair 68	A	100
	B	

Pair 69	A	100
	B	

Pair 70	A	100
	B	

Pair 71	A	100
	B	

Pair 72	A	100
	B	

Pair 73	A	100
	B	

Pair 74	A	100
	B	

Pair 75	A	100
	B	

Pair 76	A	100
	B	

Pair 77	A	100
	B	

Pair 78	A	100
	B	

Pair 79	A	100
	B	

Pair 80	A	100
	B	

Pair 81	A	100
	B	

Pair 82	A	100
	B	

Pair 83	A	100
	B	

Pair 84	A	100
	B	

Pair 85	A	100
	B	

Pair 86	A	100
	B	

Pair 87	A	100
	B	

Pair 88	A	100
	B	

Pair 89	A	100
	B	

Pair 90	A	100
	B	

Pair 91	A	100
	B	

Pair 92	A	100
	B	

Pair 93	A	100
	B	

Pair 94	A	100
	B	

Pair 95	A	100
	B	

Pair 96	A	100
	B	

Pair 97	A	100
	B	

Pair 98	A	100
	B	

Pair 99	A	100
	B	

Page **6** of **7**

Pair 100	A	100
	B	

Pair 101	A	100
	B	

Pair 102	A	100
	B	

Pair 103	A	100
	B	

Pair 104	A	100
	B	

Pair 105	A	100
	B	

C

Appendix C - Gantt Chart

Below is the project Gantt chart, planned in the first week of the project.

January
February
March
April
May
June
W 1
W 2
W 3
W 4
W 5
W 6
W 7
W 8
W 9
W 10
W 11
W 12
W 13
W 14
W 15
W 16
W 17
W 18
W 19
W 20
Literature Survey
Planning Report
Design and Construction of Test Rig
Eigenmode Analysis
Design of Experiments
Rattle Measurements
Analyse Experimental Data
Mid Term Report
Spring Break
Suggest and Evaluate Potential for Improvements
Write Master Thesis Report
Presentation of Master Thesis