THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Squeak and Rattle Prediction for Robust Product Development

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To my family

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ABSTRACT

Squeak and rattle are nonstationary, irregular and impulsive sounds that happen inside the car cabin. For decades, customer complaints about squeak and rattle have been, and still are, among the top quality issues in the automotive industry. These annoying sounds are perceived as quality defect indications and burden warranty costs to the car manufacturers. Today, the quality improvements regarding the persistent type of sounds in the car, as well as the increasing popularity of electric engines, as green and quiet propulsion solutions, stress the necessity for suppressing annoying sounds like squeak and rattle more than in the past. The technical solution to this problem is to approach it in the pre-design-freeze phases of the product development and by employing design-concept-related practises. To nail this goal, prediction and evaluation tools and methods are needed to deal with the squeak and rattle quality issues upfront in the product development process.

The available tools and methods for prediction of squeak and rattle sounds in the pre-design-freeze phase in a new car development process are not yet sufficiently mature. The existing knowledge gap about the mechanisms behind the squeak and rattle sounds, the lack of accurate simulation and post-processing methods, as well as the computational cost of complex simulations are some of the significant hurdles in this immaturity. This research addresses this problem by identifying a framework for prediction of squeak and rattle sounds in the form of a cause and effect diagram. The main domains and the elements and the sub-contributors to the problem in each domain within this framework are determined through literature studies, field explorations and the conducted descriptive studies on the subject. Further, improvement suggestions for the squeak and rattle evaluation and prediction methods are proposed through prescriptive studies. The applications of some of the proposed methods in the automotive industry are shown and examined in industrial problems.

Keywords: squeak and rattle, sound quality, simulation, product development

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APPENDED PUBLICATIONS

Paper A

M. Bayani, C. Wickman, and R. Söderberg, "Effect of temperature variation on the perceived annoyance of rattle sounds in the automotive industry." Published in the *23rd International Congress on Acoustics*, pp. 4397–4404, 2019, Aachen.

Distribution of work: Bayani initiated the idea, analysed the results, wrote the paper and actively supervised students to collect the data. Wickman and Söderberg contributed as reviewers

Paper B

M. Bayani, C. Wickman, and R. Söderberg, "Analysis of sound characteristics to design an annoyance metric for rattle sounds in the automotive industry." Submitted to the *International Journal of Vehicle Noise and Vibration*, 2019.

Distribution of work: Bayani initiated the idea, designed and conducted the experiment, analysed the results and wrote the paper. Wickman and Söderberg contributed as reviewers.

Paper C

M. Bayani, A. P. Székely, N. Al Hanna, H. Viktorsson, C. Wickman, and R. Söderberg, "Nonlinear modelling and simulation of impact events and validation with physical data." Published in *ISMA 2018, International Conference on Noise and Vibration Engineering*, pp. 4299–4313, 2018, Leuven.

Distribution of work: Bayani initiated and developed the idea and collected the experimental data. Bayani, Székel and Al Hanna collected the simulation data, analysed the data and wrote the paper. Viktorsson contributed with technical support for virtual simulations. Wickman and Söderberg contributed as reviewers.

Paper D

M. Bayani, A. Basheer, F. Godborg, R. Söderberg, and C. Wickman, "Finite Element Model Reduction Applied to Nonlinear Impact Simulation for Squeak and Rattle Prediction." Published in the *11th International Styrian Noise, Vibration & Harshness Congress: The European Automotive Noise Conference*, SAE-2020-01-1558, 2020, Gratz.

Distribution of work: Bayani initiated and developed the idea, collected the experimental data and wrote the paper. Bayani, Basheer and Godborg collected the simulation data and analysed the data. Wickman and Söderberg contributed as reviewers.

Paper E

M. Bayani, C. Wickman, L. Lindkvist, and R. Söderberg, "Squeak and rattle prevention by geometric variation management using a two-stage evolutionary optimisation approach." Published in *Proceedings of the ASME International Mechanical Engineering Congress and Exposition*, IMECE2020-23552, 2020, Portland.

Distribution of work: Bayani initiated and developed the idea, ran the simulations, analysed the data, wrote the paper and actively supervised students for model creation and optimisation setup. Lindkvist gave technical support for virtual simulation and reviewed the paper. Wickman contributed as a reviewer. Söderberg contributed as a reviewer and wrote a section in the paper.

ADDITIONAL WORKS

Master's Thesis A

V. Kulkarni and S. M. Nairy, "Squeak and Rattle Sound Database and Acoustic Characterisation." Master's thesis report, Industrial Supervisor: M. Bayani, Examiner: R. Söderberg, Chalmers University of Technology, 2019.

Distribution of work: Bayani initiated and developed the idea, devised the data collection procedure, developed the post-processing methods and actively supervised the students throughout the Master's thesis work. Bayani, Kulkarni and Nairy collected, post-processed and analysed the data. Kulkarni and Nairy wrote the report. Bayani and Söderberg acted as reviewers.

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LIST OF ACRONYMS

CAD – Computer-Aided Design
CAE – Computer-Aided Engineering
CFD – Computational Fluid Dynamics
CMS – Component Mode Synthesis
CMQ – Current Model Quality
CPA – Contact Point Analysis
DOF(s) – Degree(s) of Freedom
DPA – Digital Pre-assembly Analysis
DRM – Design Research Methodology
FEM – Finite Element Method
GA – Genetic Algorithm
ISF – Incremental Space filler
MAC – Modal Assurance Criteria
MAE – Mean Absolute Error
MIC – Method of Influence Coefficients
MOA – Multi-objective Optimisation Approach
MOGA – Multi-Objective Genetic Algorithm
MOR – Model Order Reduction
NMD – Normalised Max Difference
NRMSE – Normalised Root-Mean-Squared-Error
NSTD – Normalised Standard Deviation
NVH – Noise, Vibration and Harshness
PA – Psychoacoustic Annoyance metric
pph – Parts per hundred
RT – Room Temperature
RQ – Research Question
S&R – Squeak and Rattle

LIST OF FIGURES

I

INTRODUCTION

This chapter provides a brief introduction to the research documented in this thesis by reviewing the background of the work, project goals and research questions.

1.1. SQUEAK AND RATTLE

1.1.1. What are squeak and rattle sounds

Squeak and rattle (S&R), refers to irregular and annoying sounds generated in a product as a result of contact between two adjacent parts. Compared to stationary sounds in a passenger car, like the noise from engine, wind and tyres, S&R sounds are unexpected in a product. Demonstration of S&R in a product is understood as a failure indicator by the users. The sound can develop when two parts slide against each other (squeak) or due to a normal impact of two surfaces (rattle). Common examples of rattle noises in the car cabin are rattling of the glove compartment lid or centre display or air vents in the instrument panel and rattling of inner panel trim or armrest in the side door. Common examples of squeak are the squeaking noise from weather-strip or chrome panel in the side door, centre display and air vents in the instrument panel and the sliding or opening mechanisms in the tunnel console. The cause of S&R is mainly the structural vibration induced by road surface or powertrain at low frequencies up to 200 Hz. However, the sounds generated have mid to high range up to 2 kHz and 5 kHz for rattle and squeak sounds, respectively.

1.1.2. Significance of the subject

Perceived quality [1] not only shapes the personality of an automotive brand but also plays an important role in making the profit from a product. Among different quality aspects, interior sounds in passenger cars play an important role in the user perception of the functionality of the car and its systems [2]. A considerable contributor to expenses in aftermarket services among automakers is the cost related to the complaints about the interior sound quality, both for premium brands and volume auto-makers [2]. A survey, carried out by J.D. Power [3], indicates the high share of internal noises among total noise quality complaints in Germany, as indicated in Figure 1. The report also expresses that a similar trend can be witnessed in almost all major auto-markets around the globe [3].

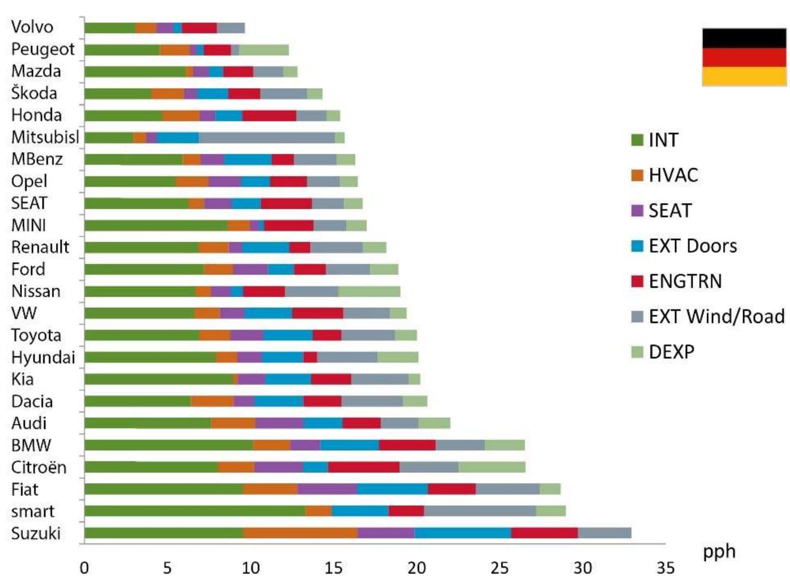

Figure 1: Composition of specific noise complaints, as parts per hundred (pph), shown for different OEMs in Germany's car market in 2017 [3].

As can be seen, the in-cabin sounds (including interior trim, seats and closures) account for more than half of the complaints. On average, more than 10% of the cars sold had a warranty complaint related to in-cabin noises, where S&R were among the prominent sounds. Indeed, the existence of S&R in a product is perceived as a quality defect by the user and often leads to a workshop referral. Therefore, eliminating the quality issues related to S&R not only promotes a brand, but is also a cost-saving measure. To stay competitive, there is a strong growing tendency towards detection and elimination of S&R sounds in auto-makers. In passenger cars, advancements in electrification, the introduction of autonomous driving and the consequent new use cases, such as sleeping, living and working in a car, [4] and the quieter in-cabin environment, due to improvements in emitted operational sounds, further stress the continuous need for elimination and refinement of nonstationary noises in the car cabin, including S&R.

1.1.3. Current status

Car manufacturers endeavour to deal with quality issues earlier in the product development process, to avoid late-phase changes. Enormous effort is devoted to shifting engineering activities to pre-design-freeze phases in the development process. As far as S&R is concerned, traditional problem detection and solving is relying on the subjective judgement of hands-on engineers with a find-and-fix approach [5]. To facilitate the early phase treatment of S&R issues without the need for physical complete vehicle prototypes, tools and methods are needed. However, the complexity of the prediction process of S&R sounds has been an obstruction for the practical development of virtual methods for S&R detection. This complexity originates from the sporadic and nonstationary nature of S&R sounds that complicates the virtual simulation of the events. While analysis methods for noise, vibration and harshness (NVH) in automotive engineering are considerably well-developed for the stationary phenomena [6]–[8], S&R simulation is mainly limited to linear finite element analysis (FEA) [2] using simplified evaluation metrics. NVH analysis methods have been mainly developed for stationary phenomena like powertrain and tyre noise and vibration, the operational sound quality of the subsystems in the car or the wind noise.

Computer-aided engineering (CAE) should be considered as the ultimate solution for the prediction and prevention of S&R problems in the design phase of product development. In addition, the use of subsystem test rigs can be considered to be a complementary or intermediate solution. To facilitate this, assessment and verification tools and methods need to be adjusted and further developed accordingly, and substituting quantitative objective requirements for qualitative subjective methods is inevitable. In other words, besides efficient robust tools, tried and trusted metrics are required to be able to reliably and robustly predict the status of S&R problems in a car in good time. Further work is needed to develop new metrics based on calculated kinematics and kinetics of mechanical impact and sliding events and to identify transfer function between the psychoacoustic metrics and contact mechanics parameters. The modelling details might need to be adjusted according to the new objective parameters. Further, to enable the involvement of S&R requirements in the design optimisation loops, objective metrics and robust virtual analysis methods are needed. All these are required to be encompassed in a framework that holds the different pieces of the prediction puzzle together. Such a framework, which covers a wide range of activities in different engaged domains in the prediction process of S&R sounds, is currently missing in the industry.

1.2. SCIENTIFIC MISSION

1.2.1. Research goal

As stated in section 1.1.3, the industrial need for a complete pre-design-freeze verification loop of S&R status in the automotive industry should be addressed using robust tools and methods for this purpose. In addition, the complexity of the S&R problems has resulted in unsatisfactory implementation of the available NVH tools and methods directly to treat the S&R problems. Thus, the main goal of this research can be stated as follows:

- To identify, further improve and support the applicability of an analysis framework for the pre-design-freeze prediction and verification of squeak and rattle noises in the automotive industry.

By developing such a framework, it is expected that this research has achieved the three main objectives of understanding the needed pieces of the puzzle for developing such a framework to avoid the occurrence of S&R, improving the prediction capabilities in the pre-design-freeze phase by investigating the contributing elements to this framework and proposing solutions and methods to address them and further demonstrating the applicability of the proposed solutions in the automotive industry.

1.2.2. Research Questions

Based on the research goals and the identified gaps through literature and field studies, the following research questions were formulated and addressed in this work.

RQ1: *To objectively evaluate squeak and rattle sounds, what elements are needed to establish a robust simulation framework?*

This research question is framed to identify different activities needed in different disciplines to predict the squeak and rattle sounds in the pre-design-freeze phase of the product development process in the automotive industry. By referring to the literature, accessible and available industrial resources and field studies, the main elements of a prediction process, the domains they belong to and the main contributing parameters must be identified. This can be presented in the form of a cause and effect diagram.

RQ2: *How to improve the current status of the available tools and methods for inclusion of elements involved in the squeak and rattle prediction framework?*

By referring to the findings from the answers to the first question and conducting descriptive studies, the current level of maturity of the prediction methods can be determined. Further, the potentials for improvement of these methods and the knowledge gaps hindering the development of the methods can be identified. Through descriptive and prescriptive studies these knowledge gaps are explored and solutions are proposed for further developing the S&R prediction framework.

RQ3: *How can the proposed framework be used in the new product development process prior to the pre-design-freeze phase?*

In order to maximise the applicability and industrial relevance of the identified framework and the proposed enhanced prediction methods, the proposed solutions can be implemented in industrial cases. Through descriptive studies, the application of the proposed methods in the industrial problems can be illustrated and the usefulness and applicability of the outcomes of this research can be judged.

1.2.3. Scientific and Industrial Relevance

This research work deals with academic research challenges and industrial considerations. The problem of interest was initiated from an industrial need: the necessity of dealing with S&R problems before the design-freeze phase in the automotive industry. However, the research presented here also addresses the fundamental theoretical formulations of the problem with the goal of improving knowledge about the characteristics of the phenomenon under study.

As far as the scientific relevance is concerned, the research aims to expand the theories for quantifying S&R events, that are expandable to other nonstationary types of sound. Also, the research covers the exploration of virtual analysis methods of S&R, identifying the potential points for improvement to accord the evaluation methods and to study some of the contributing parameters behind the S&R generation.

Considering the industrial relevance, this work addresses the need for having an S&R analysis framework by developing such a framework and further studying and improving the tools and methods needed within the devised framework. This includes improving the assessment criteria by replacing qualitative methods with quantitative methods, or improving existing objective metrics both for sound analysis and structural dynamics behaviour. In addition, the modelling approach to support the S&R prediction is improved. Accordingly, simulation methods, including the pre- and post-processing, are enhanced. Although the study cases are taken from passenger cars, the principle theories developed will be applicable in other industrial disciplines where structural vibration induced sounds have importance, such as aeronautical and ground vehicle industries, home appliance and construction industries.

1.2.4. Delimitations

There are different contributing factors to study the S&R sounds, their cause, impact and treatment. Squeak and rattle sounds in a product are perceived by humans and this perception can be studied under psychoacoustics. The sounds, their signature and significance can be studied under acoustics. Ambient condition, ageing and degradation, manufacturing quality, user experience and expectations, brand signature, driving condition and background noise, as well as the utility purpose are among the known factors influencing the evaluation of S&R sounds. The study of system behaviour as the structural vibration can be addressed by structural dynamics. The virtual simulation of the dynamic response of the system is covered by numerical methods in mechanics for noise and vibration. Signal analysis, from pre-processing and system excitation to post-processing and response quantification is done under the signal processing domain. Therefore, to completely address the problem, extensive research work is needed to study the cause and effect of all of the contributing factors in all involved disciplines and domains. However, the work presented here focuses more on developing a framework for S&R analysis to be employed in the pre-design-freeze stages and by virtual simulations. Although some studies included in this work address some of the contributing factors, the main objective of the studies were to better understand the pieces of the puzzle needed to form the prediction framework.

The study cases are taken from the automotive industry and mainly focus on the interior subsystems that are more prone to S&R problems. The reason for this was to deal with the cases with higher significance due to proximity to the car users. Nevertheless, the principles behind the problem and the theories governing these phenomena are the same in other similar industrial cases. Therefore, it is assumed that the findings from this research hold true for other equivalent settings or in other similar applications.

Where controlled sound and vibration signals were needed, laboratory apparatuses were used to allow control over the test conditions. Since repeating tests to generate S&R sounds in the car cabin, especially due to road surface excitation, does not lead to identical results, using a laboratory environment helps to achieve repeatability in the research. Also, generating S&R sounds in the car cabin under desired controlled conditions is a hard task to achieve, if not impossible. For the subjective tests, the expert panels ware mainly chosen from the analysis engineers working with the S&R sounds as their profession in the automotive industry. Practicality and ease of access to these expert panels drove this choice. In the virtual analysis, finite element models of the structures were used, and the coupling to the computational fluid dynamic models of the volume for acoustic simulation was skipped. The main reason for this was to try to quantify S&R in affordable ways, considering available computational resources in the industry. Nevertheless, this coupling can be the topic for future studies that can be built upon the outcomes of this work.

1.3. THESIS STRUCTURE

This thesis report is divided into six chapters. In the first chapter, a brief description of the phenomenon under study and its industrial and scientific significance is given. The scientific mission of this research is stated as the main goal, and the research questions, the scientific and industrial relevance and the boundaries of the conducted research are described. In the second chapter, a definition of the phenomenon as perceived by the author, a brief review of the available prediction and evaluation tools and methods and an introduction to the central concepts involved in this research are given. Chapter three deals with the methodology employed in this research and the data collection methods used are mentioned. In chapter four, the results of the research, the main outcomes and their industrial and scientific relevance are reviewed. The answers to the research questions are given in chapter five. A brief review of the main industrial and scientific contributions of the outcomes of this work is presented and the validity and acceptability of the studies performed are discussed. In the sixth chapter, the entire work is summarised and an outlook for the future works is given.

2

FRAME OF REFERENCE

In this chapter central concepts and theoretical backgrounds governing the main disciplines engaged in the research presented in this thesis are addressed.

2.1. SQUEAK AND RATTLE SOUNDS

2.1.1. Definition and Sound Signature

In a car, the emitted sounds can be categorised into two groups of stationary and nonstationary sounds. The stationary sounds, as the name suggests, encompass sounds with constant or slowly changing or continuously changing characteristics. The common stationary sounds in a passenger car are the powertrain noise, the tyre noise, the wind noise and the operational sound of the mechanisms inside the car cabin. In contrast, nonstationary sounds have sporadic and irregular characteristics. They are impulsive and usually last for a short duration but can occur frequently. Squeak and rattle are the most common nonstationary sounds in a passenger car that are unexpected by the users, unlike the stationary sounds, such as the powertrain sound that is usually sound designed in passenger cars. As mentioned in 1.1.2, the presence of S&R in a car is perceived by the users as a quality defect and failure indicator and often leads to a workshop referral. Thus, automotive premium manufacturers and mass producers invest heavily in avoiding the generation of S&R sounds in their products.

Squeak is a friction-induced noise. It is the sound that is generated when two parts with relative planar movement slide against each other at specific relative speeds and normal force. The generation mechanism behind the squeak sound is the stick-slip phenomenon. The schematic description of a stick-slip event as the friction force acting in the contact surface of two sliding parts is illustrated in Figure 2. At the start of the relative motion, the two parts stick together as the reaction force increases. During this period, the motion energy is stored in the parts in the form of the elastic strain energy due to local deformations at the interface. When the reaction force reaches the static friction force limit, a drop in the friction force happens to the so-called dynamic friction force. As a result, the stored elastic strain energy bursts into kinetic energy and the two surfaces start to slip. This kinetic energy is quickly exhausted due to the confronting friction force and the two parts stick together again. When squeak producing stick-slip events happen, this cycle continues in a loop, resulting in an unstable impulsive vibration in the surface of the part. This unstable impulsive vibration is the cause of squeak sounds and depends on the relative speed between the two parts, the acting normal force, surface profiles, material characteristics and the ambient condition. A slight change in any of the above-mentioned parameters can change the frequency and properties of the stick-slip event, thus making it a very unstable phenomenon.

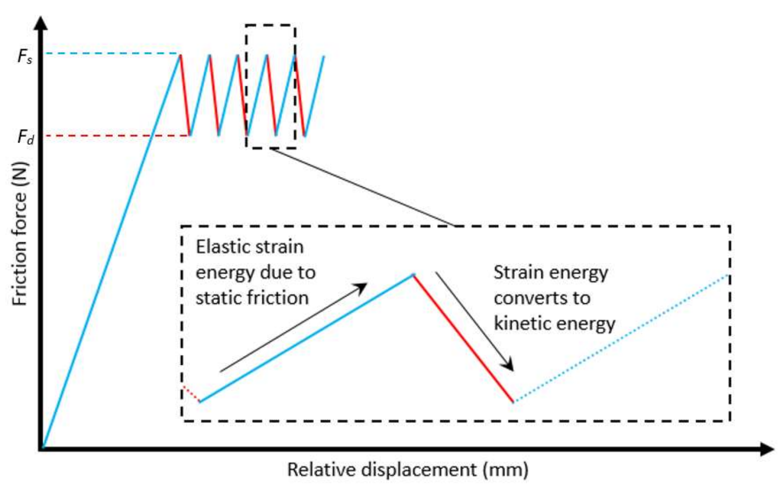

Figure 2: Schematic illustration of the stick-slip event.

Contrary to squeak sounds, rattle is an impact-induced sound that is generated as a result of the impact between two solid surfaces. Akay [9] reviewed the generation mechanisms of impact sounds. In elastic impact events, four different mechanisms were mentioned to be behind the sound generation [9]. Air ejection is the pressure pulsation that happens in the cavity entrapped between the surfaces in contact. The rigid body radiation is the pressure disturbance created in a medium as a result of the periodic rigid movements of a part. The other mechanism behind the generation of impact noise is the so-called pseudo-steady-state radiation and is the sound that results from the transient damped harmonic vibrations of the impacting parts. In the impact events involving flexible bodies and plates, radiation due to rapid surface deformation is also a source of impact noise generation. The generated sound, in this case, is in the form of a peak pressure pulse at the start of the impact event, before the pseudo-steady-state sound is generated.

Squeak and rattle sounds are broadband sounds. Squeak sounds are classified as mid- to high-frequency-range sounds, usually between 500 to 8000 Hz, while rattle sounds usually have lower frequency content in the range of 200 to 5000 Hz [7]. However, the excitation sources causing these phenomena have lower frequency ranges between 20 to 200 Hz, mainly originating from road surface profile, power train and operational vibration induced by the mechanisms in the instrument panel, body closures and seats. The sound pressure level spectrum of two rattle sounds from inside the car cabin that are generated from a polymeric pair contact and polymer-steel contact is given in Figure 3(a) and Figure 3(b), respectively. The respective nonstationary loudness (DIN 45631/A1) and sharpness (DIN 45692) graphs for these sounds are shown in Figure 3(c) and Figure 3(d). The frequency spectrums of two squeak sounds from the instrument panel and the side door are illustrated in Figure 4(a) and Figure 4(b), respectively. The nonstationary loudness and sharpness curves related to these sounds are given in Figure 4(a) and Figure 4(b).

2.1.2. Common squeak and rattle problems and solutions

Common areas for demonstration of the rattle noise inside the car cabin include:

- the instrument panel, such as glove compartment lid, steering column attachment, AC louvres and cover panels
- the body closure, such as inner panel trim, armrest, side door pocket, window, speaker attachments, sunroof and wiper mechanism and inner panels in the liftgate
- the seats, including the position adjusting mechanisms in the front seats

The common problematic areas for squeak are:

- the sealings, such as the door sealings
- the body closures, including the window regulator
- the upholstery, such as the seat leather cover
- the instrument panel, including air vents, fasteners and centre display

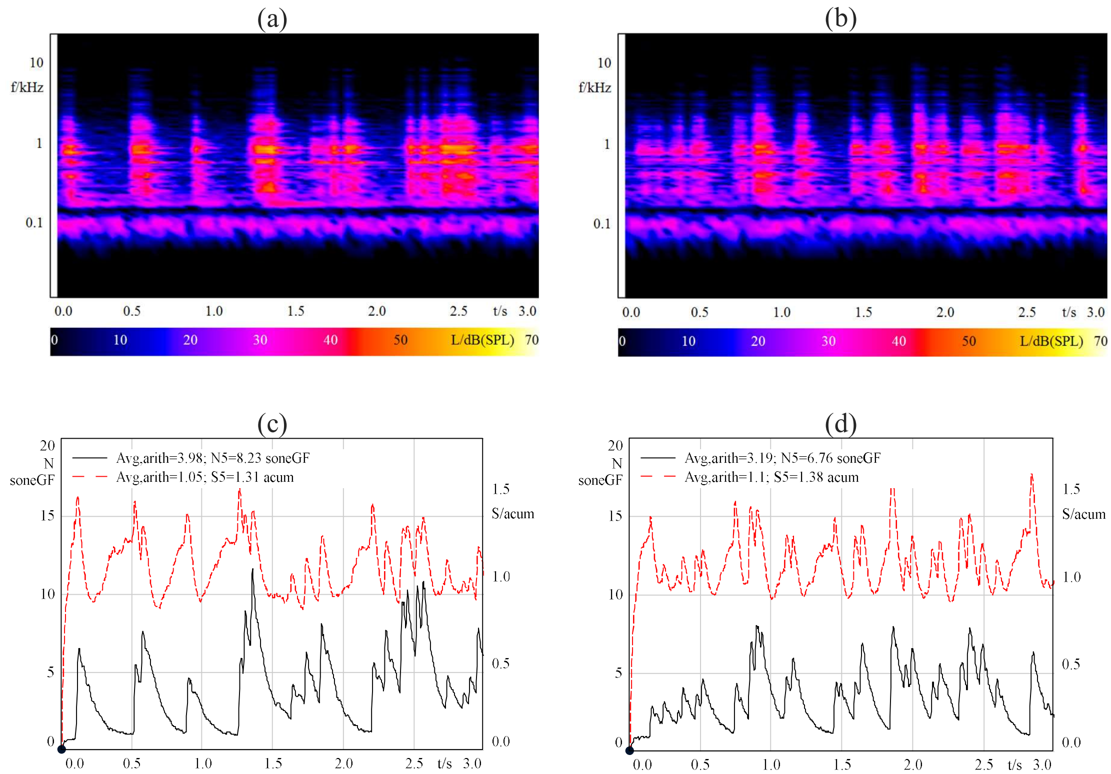

Figure 3: Sound pressure level spectrum for a polymeric pair rattle (a) and a polymer-steel pair rattle (b). The nonstationary loudness (DIN 45631/A1) and sharpness (DIN 45692) curves for the same rattle sounds are given in (c) and (d).

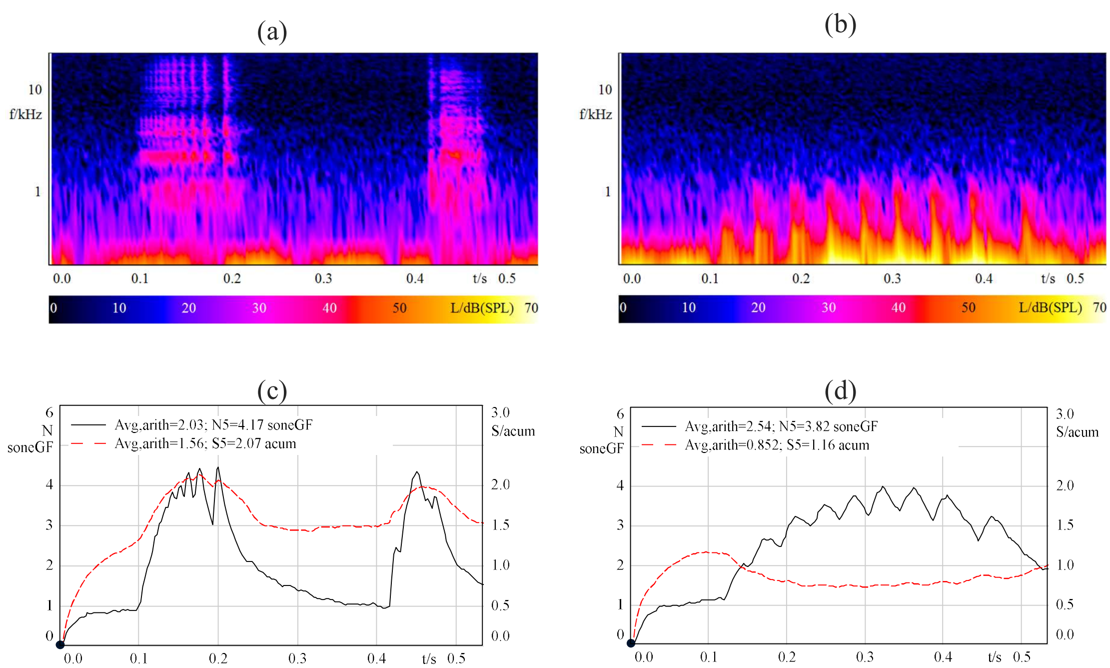

Figure 4: Sound pressure level spectrum for a polymeric pair squeak in the side door (a) and a polymeric pair squeak in the instrument panel (b). The nonstationary loudness (DIN 45631/A1) and sharpness (DIN 45692) for the same squeak sounds are given in (c) and (d).

To prevent or eliminate S&R sounds in passenger cars, there exist measures that relate to the design concept, including modifying the connection configuration in a subsystem assembly, the choice of connection types and the allowable play, adjusting the clearance targets, the modal separation between connected or adjacent parts, blocking the load transfer passes, stiffening the parts and considerate material selection. In addition to the concept related solutions, other provisions are also taken into account that are mainly rooted in the traditional and find-and-fix approaches of treating S&R problems, like adding absorbent materials or lubricants in the contact interfaces and surface treating of parts. Compared to the concept-related measures, the later counteractions impose high production costs on the car manufacturers and therefore more and more are being outweighed by the concept-related approaches, wherever possible.

2.2. SQUEAK AND RATTLE PREDICTION AND VERIFICATION

2.2.1. The Product Development Process

As Ulrich et al. define, the product development process encompasses all the activities required by an enterprise to conceive, design and commercialise a product [10]. It is the process of bringing a product from an idea to the market. All the relevant activities within the three domains of the marketing, design and manufacturing are covered by a product development process. The generic product development process proposed by Ulrich et al. consists of the six main stages of planning; concept development, system-level design, detail design, testing and refinement, and production ramp-up [10]. The commonly employed stage-gate product development system in the industry has the same stages [11]. In the traditional stage-gate approach, requirements are cascaded and set at the different system, subsystem and component levels. The concept of the stage-gate system is to add a quality control checkpoint or gate between each stage. At each stage, the deliverables are quality controlled against the pre-set requirements at the concept integration and product definition phases. An alternative approach, that has evolved through the software developing businesses, is the agile product development system [12]. The fundamental difference between an agile system and the traditional stage-gate system is the approach to quality control. In the stage-gate paradigm, a separate testing gate always appears after the workstations. In contrast, in the agile approach, development and testing happen at the same stage. The other main difference is that in the stage-gate approach, each stage or step is required to be completed in its entirety before the next stage can start. However, in the agile approach, the cross-functional team in charge of developing a subsystem decides on the release of the sub-product based on its maturity level and upgraded value. In fact, the mindset in the agile system is to support a product, rather than a project in the traditional stage-gate system. Independent from the employed product development system, to evaluate the attributes of a product, such as S&R in the passenger car, measurable requirements are needed to verify a product. Therefore, an attribute evaluation framework is always needed independently of whether the requirements are set at the very early stages of the project or through the iterative loops of an agile system. This research aims at identifying such a framework to evaluate the status of S&R sounds in a car before the design is finally judged and frozen and the manufacturing activities enter the tooling stages. This framework enhances the analysis and prediction capabilities of a product or sub-product from the concept integration phase to the final design judgement.

2.2.2. Experimental Squeak and Rattle Analysis

Due to the complexity of S&R sounds, their characteristics and the mechanisms behind their generation, yet experimental analysis and verification methods prevail over the other analysis methods. Here, the common experimental methods and tools used in the product development process for evaluating S&R are briefly mentioned.

2.2.2.1. Excitation Test Rigs

The test subject can be the complete vehicle, either on public roads, or the proving grounds or maybe laboratory test rigs. The common excitation road surfaces used for S&R evaluation include the patterns that excite the car in a wider range in the frequency domain, either having a more stochastic nature, such as Belgian pave (Figure 5), or a cobblestone road, or with regular patterns exciting the car in a certain frequency range, like the frequency modulated speed bumps or rumble strips [13]. The laboratory test rigs simulate the excitations from the road surface by imposing equivalent vibrations either to the whole car, as in a four-poster (Figure 6), or to the car body, called direct body excitation [14]. The advantages of using test rigs, compared to the proving grounds or public roads, are the ease of repeatability, control over the climatic condition, controlled background noise, the possibility of eliminating the powertrain, tyre and wind noise, removing the uncertainties introduced by the human drivers and facilitating physical measurements as well as the objective assessments. On the other hand, the introduction of the additional sources to the background noise, limitation in the excitation frequency imposed by the rig, accessibility to the relevant excitation signals and missing the real driving context in subjective evaluations can be regarded as the main disadvantages of using test rigs rather than the proving grounds or public roads.

Figure 5: Belgian pave road surface [15].

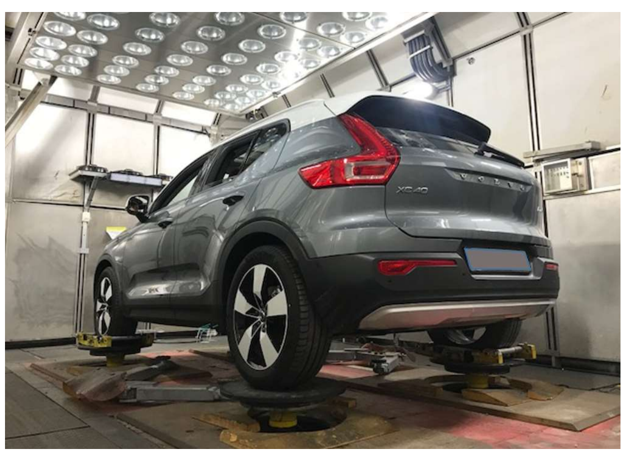

Figure 6: The climatically controlled four-poster rig at Volvo Car Corporation.

The experimental tests can also be carried out at the subsystem level as shown in Figure 7(a). Since the subsystem test rigs have considerably smaller sizes compared to the complete vehicle test rigs, it is more economically feasible to have them in climatic controlled or anechoic chambers. The subsystem test rigs better suit the agile product development system, as the subsystems can be tested without the need for the physical complete vehicle prototypes. This also helps to investigate a subsystem isolated from the noises emitted from the rest of the car. However, in defining the boundary conditions and using the fixtures, special consideration should be taken to avoid unrealistic system modelling. The other important parameter that risks the credibility of using a subsystem test rig is the definition and selection of the excitation signals in the interfaces of the subsystem with the rest of the car. The other limitations imposed by the subsystem test rigs are the limitation in the excitation degrees of freedom, limitation in the displacement range vs excitation frequency, the missed in-cabin context and the vicinity of the test subjects to the emitted sounds from the rig shakers. It is also possible to evaluate components of a subsystem with smaller component shaker rigs like the one shown in Figure 7(b).

(a) (b)

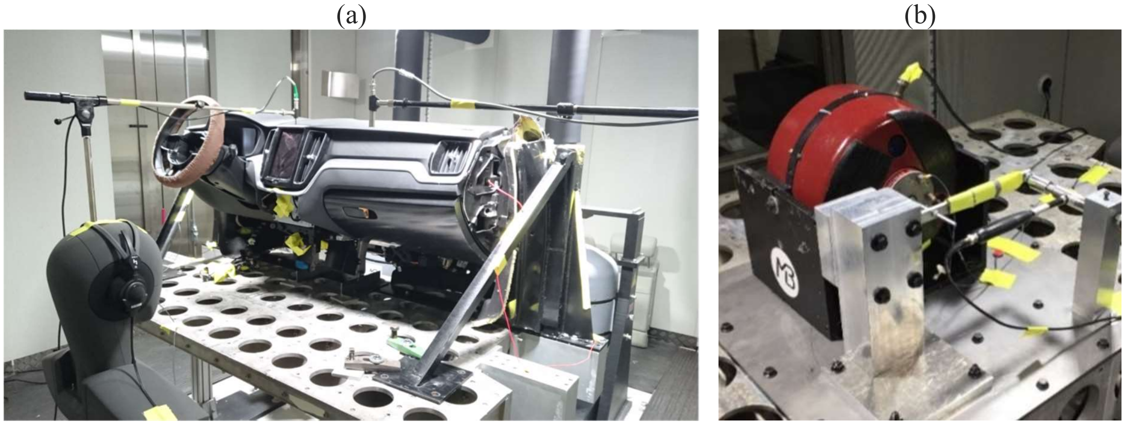

Figure 7: (a) An instrument panel mounted on a subsystem test rig in a climatically controlled semi-anechoic chamber at Volvo Car Corporation, and (b) a quiet component shaker.

Special test equipment is used in the industry for testing material samples for S&R applications. The most widely used type of such test equipment is the stick-slip test machine, such as the one shown in Figure 8. Using this machine, different material pairs, under prescribed preloads and relative speeds, can be tested for the risk of generation of squeak. The machine outputs a risk rating number, denoting the risk level of generation of squeak if such material pairs come in contact in the interfaces in a product. The car manufacturers build compatibility matrices by using the results from this machine and consider this during the material selection phase.

2.2.2.1. Subjective Evaluation

Subjective evaluation means to conduct a qualitative evaluation of the quality of an attribute of a product based on the judgement of the users or experts and analysis engineers. Mostly, subjective tests are done in connection to the testing of a complete vehicle. The main reason is to put the test subjects in the real product context. However, subjective testing is sometimes done at subsystem or component level. In the industry, there are internally standardised norms for subjectively grading the quality of a product. Different rating scales from verbal to numeric are used but the latter with a scale from one to ten linearly reflecting the quality level is the commonly used subjective scale in the automotive industry.

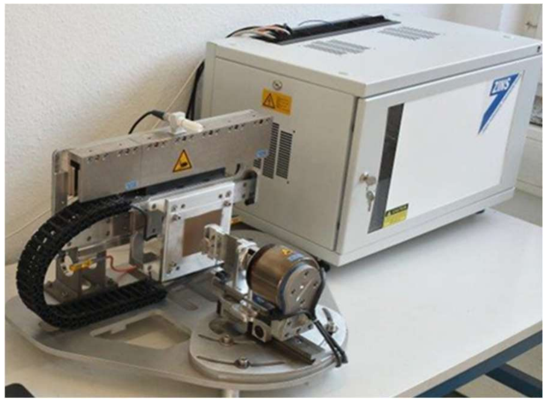

Figure 8: Stick-slip test machine, SSP-04 from Ziegler-Instruments [16].

2.2.2.2. Objective Evaluation

By objective evaluation, the response and behaviour of a product or subsystem of a product is measured in the form of quantified metrics. In the verification phase, these measurements are compared to the pre-set requirements for the product. The objective evaluation is often done using the measured response of a system in the experimental tests. However, by evolving the virtual simulation processes, some of these objective metrics are possible to be calculated from the virtual simulation results. Two types of parameters are often collected in the experimental tests in S&R analysis; the sound signal and the vibration response. Vibration response is collected either by accelerometer sensors or laser vibrometers for the direct measurement of the point displacement, although the application of the latter is very limited in the industry. To capture the relative movement of two parts at an interface, using accelerometer sensors, the type and sensitivity of the sensors (often AC-response accelerometers), the placement of the sensor on the part, noise handling and filtration and the selection of the measurement location influence the measured signal. For the S&R application, it is common to calculate the displacement signals from the measured acceleration signals. This often results in unrealistic drifts in the displacement signal due to the accumulated measurement noise during the double integration process that needs to be treated in proper ways, such as using the method proposed by Mercer [17]. The evaluation criteria are either based on the statistical calculations of the measured acceleration levels or the calculated relative displacement between the two measured points at the problem interface, as shown in Figure 9.

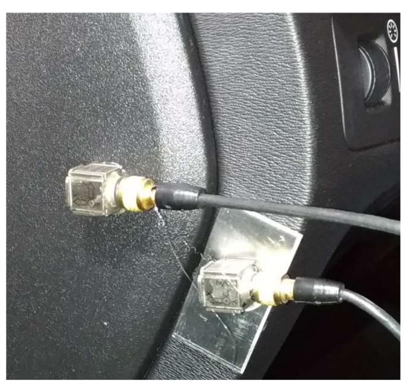

Figure 9: Two triaxial piezoelectric accelerometers placed on the cockpit left cover to measure the relative motion between the two parts.

Sound measurement can be done by diffuse-field microphones inside the car cabin or test chamber, or free-field microphones, in the outside environment or anechoic chambers. If the intention of sound measurement is to reproduce the sound in future, binaural sound recording technology is needed. As shown in Figure 7(a), the emitted sound from the instrument panel was measured both by two microphones and the BHS II binaural headset mounted on the HMS IV artificial acoustic head, both from Head-Acoustics GmbH. When collecting sounds, the background noise needs to be measured, isolated from the sound source wherever possible. The use of test rigs, compared to public roads or proving grounds, facilitates the background noise measurement process. To assess the quality of S&R sounds the measured sound is used to calculate objective metrics. The most commonly used sound quality metrics for S&R involve the calculation of sound pressure level and the psychoacoustic Zwicker loudness [18], see [19]–[21]. The use of other psychoacoustic metrics or statistical calculations remains very limited in the automotive industry [22]–[24], as well as for the evaluation of impulsive sounds in the other disciplines [25], [26].

2.2.2.3. Subjective Sound Listening Tests

To develop objective sound quality metrics, subjective sound listening tests or listening clinics are widely used in the industry. For this purpose, the subjects are exposed to some broadcast sound stimuli and are asked to judge the quality of the played sounds. A review of the different subjective sound listening tests that are commonly used in the automotive industry is described in [27]. The most commonly used methods are the paired comparison method, response (rating) scale, semantic differential and magnitude estimation. For the description of these methods, the reader is referred to [27]–[29]. Specific considerations should be taken for sound recording, selection and preparation of sound stimuli, employment of the test method, training of subjects, the communication and media type, the test environment and ambient condition, test duration and difficulty level, sound reproduction and selection of the test subjects [27]. The test can be conducted in a listening room, such as the one shown in Figure 10, or inside the car cabin. The former is widely used in the automotive industry. The subjects can make their judgements using printed questionnaires, as was used in [30], or through a digital interface, as was employed in [28]. It is highly important to check the quality and confidence level of the conducted test by statistical calculations [27]. One way of doing so is to calculate the subjects' self-consistency and concordance as described in [28]. The results from a subjective listening test can be used to design sound quality metrics for objective evaluation of S&R sounds.

Figure 10: Listening room for conducting subjective listening surveys.

2.2.3. Virtual Methods for Problem Analysis

2.2.3.1. Contact Point Analysis

Contact point analysis (CPA), as the process is described by Daams [31], is a procedure to identify S&R risks early in the car development programs via analysis of digital models. For this purpose, mature 3D CAD models are needed. The analysis is performed during the industrialisation phase of the car programs. The first analysis occurs at the detail design phase and the final analysis is conducted before the design freeze, and during the final design judgement, and therefore sometimes referred to as digital pre-assembly analysis (DPA) in the automotive industry [32]. The analysis is done by analysis engineers who are experts within the field of S&R and the analysis results are reported to the stakeholders including the design teams. Depending on the maturity level of the CAD, the focus of CPA analysis changes. At the earlier stages, when the CAD has a lower maturity level, the focus is given to the design concepts, including the connection configuration and material choice. At the later stages, details of the design can be checked using mature CAD models. During the analysis, the requirements at the complete vehicle level and system level, material compatibility matrices, documented knowledge from the previous programmes and products and available geometric variation analysis results need to be referred to. Each component in an assembly is analysed against its neighbouring parts, considering the connection configuration, boundary condition, gaps in the interfaces and material combinations. The identified risks will be analysed and discussed in a group involving S&R experts, the design teams and CAE engineers. Based on the identified risk level, a decision for further analysis by CAE or physical testing or applying changes to eliminate the risk is made [32].

2.2.3.2. Structural Dynamics Analysis

Virtual simulation of S&R in the industry mainly involves linear finite element analyses, using linear models. Finite Element Method (FEM) is the most commonly used virtual analysis method in structural dynamics problems. The main idea behind FEM is to divide a geometrically complex system into smaller parts or to discretise the solution domain. This activity is called the meshing process. In the automotive industry, different commercial mesh generating tools are used, among which Hypermesh© and Ansa© have gained the most popularity. The partial differential equations for the structural dynamic response of the discretised geometrical model are solved by numerical methods and by forming a system of algebraic equations or ordinary differential equations [33]. The Newton law as a system of equations in a structural dynamics problem can be written in the following form:

$$\mathrm{M}\ddot{q} + \mathrm{K}q = F \tag{1}$$

where M and K are the mass and stiffness matrices and F and q are the external load vector and the nodal DOFs vector, respectively. If the mass and stiffness matrices in the FEM problem can be considered constant during the simulation process, the system is treated as linear and the numerical solution converges faster. In the presence of nonlinearities, such as contact, nonlinear material properties or geometrical nonlinearities, the mass and stiffness matrices in equation (1) need to be updated in each iteration of the numerical simulation process. This makes the nonlinear FEM simulations computationally expensive.

For simulating S&R events by solving the FEM problems, different commercial tools are used in the automotive industries. MSC.NASTRAN© and ABAQUS© are among the most commonly used tools for FEM solutions for simulating S&R problems. The results of the FEM analysis can be retrieved in the form of data tables for selected degrees of freedom or sets of elements, or used to make two-dimensional graphs or three-dimensional contour plots for the system response. The post-processing graphs can be done in the frequency domain as well. The common post-processing tools used in the industry for S&R simulations are Meta© and Hyperview©, in which some statistical methods for evaluating the results are given in the S&R toolboxes.

The common FEM analysis used for S&R simulation in the industry includes modal analysis, time transient analysis and frequency response analysis. The purpose of modal analysis in structural dynamics is to understand the mode shapes and the eigenfrequencies of a component or assembly. Often the results of the modal analysis (the eigenfrequencies) are compared against the modal map of the subsystems in a product like a car. Verification is done with reference to the requirements set on the complete vehicle level or system and component level.

Transient response analysis is a computational method to calculate the forced dynamic response of a system in the time domain exposed to a time-varying excitation. The excitation can be applied as time history data of forces or prescribed motions of certain degrees of freedom in the finite element model. In FEM solvers, such as MSC.NASTRAN© and ABAQUS©, the solution is done either by direct transient response or modal transient response methods. In the direct transient response, the equations of motion are solved as a set of coupled equations by direct numerical integration. For numerically heavy problems, the alternative approach is to use modal transient response analysis. In this method, the system response is approximated as a superposition of the eigenvectors of the system. This results in a set of decoupled equations of motion in the absence of damping in the model, which is computationally more efficient to be solved. However, the selection of mode shapes to be involved in the response approximation, the inability to be used for initially conditioned systems and losing the efficiency for systems with damping are the considerations that should be taken when employing this approach. For large FEM models, and when a fine resolution in time is needed for the response, the modal transient response method is more applicable. This method is the most commonly used method for analysing S&R in the automotive industry. The method introduced in [34] is based on the results from the transient response analysis. System response in critical interfaces for S&R are output as a relative displacement between the predefined node pairs in a FEM model excited in the time domain. The mean value of a fixed percentage of the biggest relative displacements during the excitation time is used as an indication for the risk for S&R. For rattle, this metric is compared against the nominal gap in each interface node pair and a judgement of the risk of generation of rattle is made. The results from the geometric variation analysis can also be considered when the judgement is made to account for the tolerance propagation effects. For squeak, the same metric is calculated in the contact plane at the node pairs. The metric can be compared to the minimum allowed relative displacement for the respected material pair to avoid squeak sounds, if available. Such data can be extracted from the results of a stick-slip test machine (2.2.2.1), although the available commercial stick-slip machines do not directly output such information today. A similar statistical evaluation can be done based on the force acting in a node pair. The results can be compared to the defined preload in a connection for rattle, or the squeak triggering friction force based on the stick-slip test results. In Meta© and Hyperview©, a post-processing toolbox for this purpose is available.

Frequency response analysis aims at calculating the steady-state structural dynamic response of a system to a cyclic excitation in the frequency domain. Similar to the transient response analysis, system excitation can be defined as force or prescribed as motion in certain DOFs, although the system excitation is defined in the frequency domain. Like the transient response analysis, frequency response analysis can either be solved directly or by an approximation of system response in terms of its eigenvectors. The latter is called modal frequency analysis, with the same considerations as the ones mentioned for the modal transient response method. FEM frequency response analysis is not used as widely as FEM transient response analysis for S&R applications. Frequency response analysis was used in [35] to calculate the rattle risk. The steady-state relative displacement values in the node pairs were scaled by the kinetic energy to better predict the risk for the generation of rattle events. A similar concept is discussed in [36] but the author did not give details of the method or how the risk metric was calculated.

For S&R evaluation using finite element simulation, apart from post-processing the relative displacement data, Her and colleagues used a metric as a function of relative impact velocity to predict the impact sound pressure level for a single DOF mass-damper model [37]. The results showed good accordance with the experiment outside the resonance regions. In another study [38], the surface velocity in the Rayleigh integral equation was used to estimate the sound pressure level of the impact sound. These two methods have not been implemented in practice in the automotive industry by the car manufacturers or by the CAE software developers.

2.2.3.3. Geometric Variation Analysis

Geometrical variation is one of the main contributors to the generation of S&R sounds inside a car cabin [31]. The deviation of the geometrical dimensions of a physical part from the nominal design may happen as a result of the tolerance stack-up originating from the introduced tolerances in the connection points in an assembly or the part variation due to manufacturing. The introduced geometric variation can cause an interface gap to change from its nominal value. This can result in tighter gaps and increase the risk for the contact between the parts, or can change the prescribed preload at the connection points. Geometric variation analysis refers to virtual simulation of the geometric changes in a part or an assembly as the result of disturbances that can be imposed by part manufacturing or the assembly process. Different methods for geometric variation simulations are reviewed in [39]. A method for robustness evaluation and geometrical stability analysis was proposed by Söderberg and Lindkvist [40]. Direct Monte Carlo (DMC) simulation [41] was introduced as a statistical method to simulate geometric variation problems. In this method, a probabilistic statistical population of the contributing parameters is defined. The geometric variation in the intended dimensions is computed as a result of the parameter changes as sampled from the statistical population. For large assemblies, like the panels inside the car cabin, the use of compliant geometric variation analysis are introduced to capture the local deformations of the non-rigid parts more accurately [42]. To make the compliant geometric variation simulations computationally efficient, the method of influence coefficients (MIC) [43] was proposed and today is widely used in variation simulation.

The most commonly used metric, as a calculated value from the geometric variation simulation results, is variations as six times the standard deviation (6σ) and deviation as the difference between the calculated mean value of a dimension and its nominal value. There exist commercial tools for the geometric variation analysis in the automotive industry that use DMC and MIC methods, such as RD&T©. Nevertheless, for S&R prediction, the use of geometric variation simulation is limited to adjusting the nominal static gap values in CPA analysis, as described in section 2.2.3.1, or setting the threshold values for relative displacement results in finite element structural dynamics simulations, as mentioned in section 2.2.3.2.

2.3. OPTIMISATION

Mathematically, an optimisation method aims to find the solutions to a problem resulting in an extremum response from the system. The system response needs to be quantified by using objective functions that reflect the fitness level of a solution. Traditionally, the most challenging task for an optimiser is to find the absolute optimum value and not to become trapped in the local optima. To address this issue stochastic search approaches are introduced. Contrary to the deterministic optimisation approaches that risk yielding a local optimal solution for high-dimensional, discontinuous and multimodal engineering problems [44], the stochastic search approaches overcome this defect by enhancing the global search. Evolutionary algorithms are branched from stochastic search methods based on the evolution processes in nature. Although the evolutionary algorithms do not necessarily guarantee to find the absolute optimum, they always result in finding good solutions, close enough to the real optimum, if the optimisation problem is framed correctly. Genetic algorithm (GA) is an evolutionary optimisation method that has gained high popularity in the application. GA is based on Darwin's theory of 'survival of the fittest'. At each step of the optimisation, the fittest solutions based on their objective values are selected to build the population for the next generation of solutions. The solutions in each new generation are evaluated and this process continues until reaching the optima. To generate the population in each next generation, genetic algorithm operators are used, among which directional and classical cross-over, selection and mutation are the most commonly employed operators in practice.

2.3.1. Multi-Objective Genetic Algorithm

In an optimisation problem, when the suitability of solutions is defined based on more than one objective function, multi-objective optimisation approaches (MOA) are used. An MOA gives a group of the fittest solutions, the Pareto front solutions, that each result in a set of optimal objective functions. This way, the choice of the best solution can be achieved through a manual trade-off among the conflicting objectives. The MOA methods and algorithms that are widely used in engineering design are reviewed in [45]. The multi-objective genetic optimisation method (MOGA) was first introduced by Fonseca and Fleming [46]. In this method, the fitness of an individual is determined by calculating its domination factor. The domination factor for a solution is the number of individuals performing better than that solution. Thus, the domination factor of the Pareto front solutions is zero. In MOGA, the fitness value is calculated based on the ranking of the individuals with respect to their domination number. To empower the global search, fitness scaling approaches are used, such as the linear fitness scaling [47].

3

RESEARCH APPROACH

In this chapter, the research design and framework used in the research presented in this thesis is discussed. Further, the methods used in different stages of the scientific studies performed in this thesis are outlined.

3.1. RESEARCH FRAMEWORKS

Design research has two distinctive characteristics: it deals with diversified human activities and tasks; and tries to improve human performance within these complex tasks by introducing practical methods and tools [48]. Design research is therefore aimed at understanding a phenomenon and improving the methods or tools to process its design, creation and evaluation [49]. In the research that is concerned with delivering tools and methods for industrial applications, there are four fundamental study fields: How design is done within the phenomenon of study; Introducing theories to understand the mechanisms governing the phenomenon; developing tools and methods to model, simulate and predict the phenomenon; and implementation and validation of the developed tools and methods [48], [50]. Design research involves heterogeneous topics and methods. Diversity is in essence of potential merit to create value. However, diversity in turn increases the risk of discrete unconnected research activities that make it hard to conclude a scientific value for the whole work [51]. This underlines the need for a methodology to bind all the research activities to nail results with generic and practical validity. The research presented in this thesis addresses activities in the product development process, in particular, the pre-design-freeze verification process of a phenomenon, and is categorised under design research.

3.1.1. Design Research Methodology

Within different design disciplines, diversity of methods and topics raises the risk of lacking mainstream when conducting design research. DRM [50] was introduced to overcome this risk by giving a framework to a generic and systematic design research methodology with the aim of increasing the academic credibility and industrial applicability of design-related research studies. DRM framework, as also summarised in Figure 11, consists of four main stages:

Research Clarification (RC), through initial literature and field studies, the main plan for the research is devised. The goals are clarified and set. This stage includes defining the research questions and setting the success criteria in the form of measurable terms.

Descriptive Study I (DS I), in this phase detailed literature reviews, empirical data gathering and field interviews are employed to give an in-depth description of the phenomenon and the available governing theories. The potential factors for improvement are identified.

Prescriptive Study (PS), The main purpose of this phase is to find solutions and develop tools to improve the current status to address the identified gaps from the previous phase.

Descriptive Study (DS II), in order to describe the degree of usefulness and applicability of the proposed solutions within the context, the prescribed success criteria are evaluated.

The proposed methodology does not necessarily demand that the proposed stages are carried out sequentially and different stages can be done in parallel. Even, in some research studies, some stages of the methodology can be suppressed or focused on more [50].

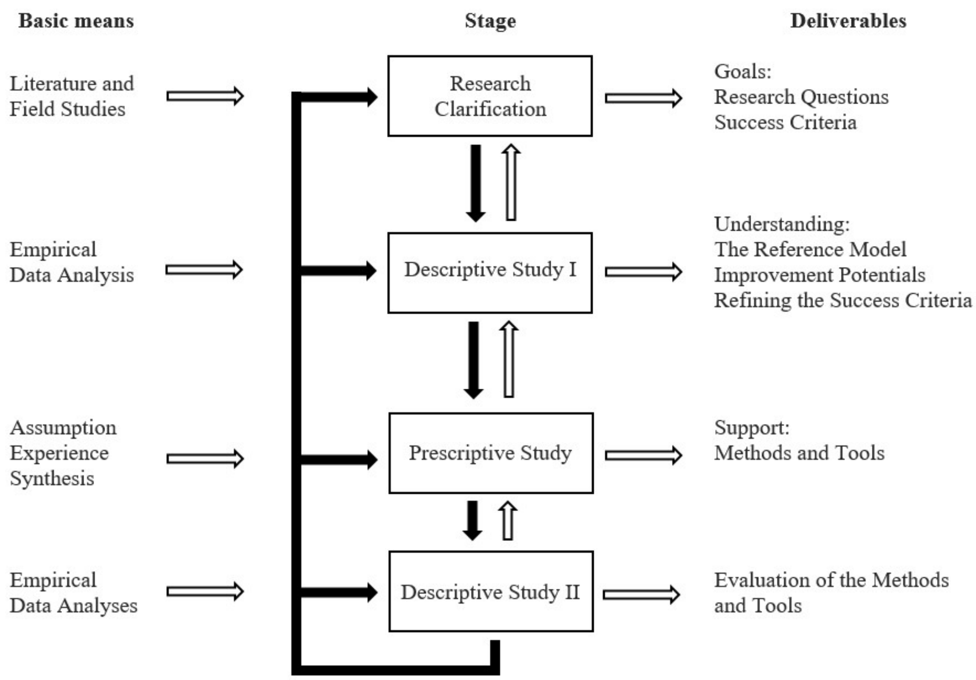

Figure 11: The Design Research Methodology framework, redrawn from [50].

3.2. RESEARCH DESIGN

3.2.1. Applied Research Methodology

This research work deals with the simulation of an attribute (S&R) of a product (car) in different design and development activities during the product development phases (before the design freeze). Therefore, the research activities fit well in the DRM framework. In modern engineering mechanics, the pragmatic theory prevails over other understandings of truth. In other words, in mechanics, true statements produce useful results if they are put into practice and often the truth of a statement is verified by experiments or observations. The dominant view of knowledge through all performed and planned studies in this research is based on the pragmatic approach with the aim to discover the laws and norms governing the phenomenon under study. To take the pragmatic view in this research work, customisation of the DRM stages, wherever activities required it, was assumed to be allowable.

3.2.2. The Big Picture of the Research Framework

The research is divided into different sub-studies. Based on the information gained by referring to the literature, accessible industrial resources and unstructured field interviews and studies, the current status of treating the problem in the industry and the available knowledge about the governing theory behind the phenomenon under study was reviewed. The data was gathered through different conducted studies, through discussions with experts and by being involved in the development process of the running programmes in the industry. By integrating the information gathered, the current status of the S&R prediction process was represented in the form of a cause and effect diagram. The potential areas for improvement were identified. Through descriptive studies, the industrial and scientific knowledge gaps, hindering the evolvement of the tools and methods, were recognised. By performing prescriptive studies, solutions to address the pinpointed gaps were proposed, either by proposing a new method or applying an existing method in the context of the study. In some of the studies, the proposed methods and solutions were applied to industrial problems to judge their credibility, validity and generalisability.

Overall, as the research questions are framed, the studies in which the intention was to answer the first research question, belong to the first two stages of the DRM, namely the research clarification and descriptive study I. The aim was to review and understand the current status governing the phenomenon, to form the prediction framework and use it as a basis to further explore the problem. To answer the second research question, prescriptive studies were needed, that shape the third stage in the DRM. In this stage solutions to the identified problems are given in the form of tools and methods. For the last research question, where the application of the findings in the industry was the aim, this was addressed by descriptive studies targeting the applicability and validity of the outcomes. These studies by essence belong to the fourth stage of the DRM.

In Figure 12, the structure of the whole research, in the form of the performed studies, the respective research questions addressed by each study and the level of connection of each study to the DRM stages are summarised.

	Research Question	RC	DS I	PS	DS II
Study I (Paper A)	RQ1	❋	❋		
Study II (Master Thesis A)	RQ1	❋	❋		
Study III (Paper B)	RQ1, RQ2	❋	❋	❋	
Study IV (Paper C)	RQ1, RQ2	❋	❋	❋	
Study V (Paper D)	RQ2, RQ3	❋	❋	❋	❋
Study VI (Paper E)	RQ1, RQ2, RQ3	❋	❋	❋	❋

Figure 12: Research results in the DRM framework [50]. The size (small or big) of star and RQ denotes the contribution level (low or high) of a study to the respective DRM stage or RQ.

3.2.3. Research Success Criteria

As DRM [50] suggests, each research study starts with the research clarification activity. The main output from this activity is to define the criteria to judge the outcomes of the research, the success criteria. For different types of studies, different measurable success criteria can be set. In this work, based on the nature of different studies conducted and the method used to carry out the work, different success criteria were defined that hereinafter will be briefly mentioned. In the discussion chapter, 5.3, these criteria are referred to in order to discuss the success level of the research conducted in this PhD work.

- *Acceptance by experts* is a common criterion to judge the acceptance level of the conducted research. The publications that are peer-reviewed by the experts within the field in academia and industry can be used for the evaluation.
- *Accuracy of the proposed methods* can be evaluated by comparing the research

outcomes with the other methods or against the experimental data using statistical measurements.

- *Generalisability and robustness* are important attributes of high-quality research work. The evaluation can be done in numerous ways, in which the validity of the research outcomes, when used in cases other than the ones studied, can be judged.
- *The efficiency of the proposed methods* is another criterion to check the success of research work. Among other things, efficiency can be measured as the required time to conduct a simulation or design process.
- *Applicability in the industry* is also one of the main success criteria, specifically in research studies like the one presented in this thesis, as the need for initiating this work arose from the automotive industry.

3.2.4. Data Collection Methods Employed

To develop the S&R framework, a holistic view of the nature of the problem, its generation, causes, characteristics and impacts is demanded. Since the study involves different disciplines, various data collection methods have been employed to date, including:

Literature studies: to get an overall understanding of the current status of available applicable evaluation methods in industry, accessible industrial resources have been studied. Also, to understand the state-of-the-art theories and methods governing the phenomenon of interest and to further develop these methods, relevant scientific resources and published previous research works were reviewed.

Unstructured field studies: since not all of the available knowledge is documented, specifically in the industry, unstructured field interviews and field observations have been carried out to better understand the current status of the evaluation methods.

Questionnaires: during the subjective listening tests, to elicit the users' perceptions, questions of type paired comparison with magnitude estimation were used. In an initial study, printed questionnaires were used. For the latter study, a digital interface was designed to facilitate data collection and compilation as well as to reduce the possible human error risks during data transfer and compilation.

Experimental data: empirical data collection, both from generic material samples in S&R test benches and real car parts, form a major part of the data collection process in this study. The data collected was in the form of sound, acceleration and force signals, in addition to the parameters defining the test conditions. Real car parts were either used as in a subsystem assembly in the subsystem test bench or in the complete trimmed vehicle both in test rigs or in proving grounds. For mechanical signal collection, calibrated devices were always used. Whenever possible, the physical measurements were repeated multiple times to reduce the effect of measurement errors due to uncertainties in the test conditions.

Virtual simulations: result data from virtual simulations are used in studies focussing on methods for virtual simulation as the main data source. Wherever needed and feasible, for model validation and verification of the findings, simulation results were compared against experimental data.

4

RESULTS

The research activities have to date resulted in the five papers that are appended. This section provides a summary of the motivation, methods and important results connected to each of the respective appended papers. The reader is referred to the appended papers for the complete descriptions of the theory, methods and results of each work.

4.1. SQUEAK AND RATTLE ANALYSIS FRAMEWORK

As one of the main objectives of this PhD research work, developing a framework and identifying its main elements has been a central concept of the different studies performed so far. The main sources of data for devising such a framework were literature reviews, accessible industrial resources, field observations and interviews with experts active within the field, as well as the experiments and trials performed for exploring and understanding the phenomenon. This includes, but is not limited to, involvement in the product development activities of running programmes within the respected company, from planning and benchmarking activities to production activities and aftermarket support; discussions and knowledge transfer with researchers within the field through technical forums and conferences; technical discussions with suppliers of the test equipment and CAE tools; critical review of the current virtual simulation methods; review of the applicable requirements and the process of requirement setting; reviewing and analysing the accessible lessons-learned reports and the current model quality (CMQ) data. It is of importance to mention that most of these industrial resources are classified as proprietary information with restrictions for publication. These studies yielded the squeak and rattle prediction framework in the form of the cause and effect diagram as depicted in Figure 13. The whole framework is divided into three main domains as described hereinafter.

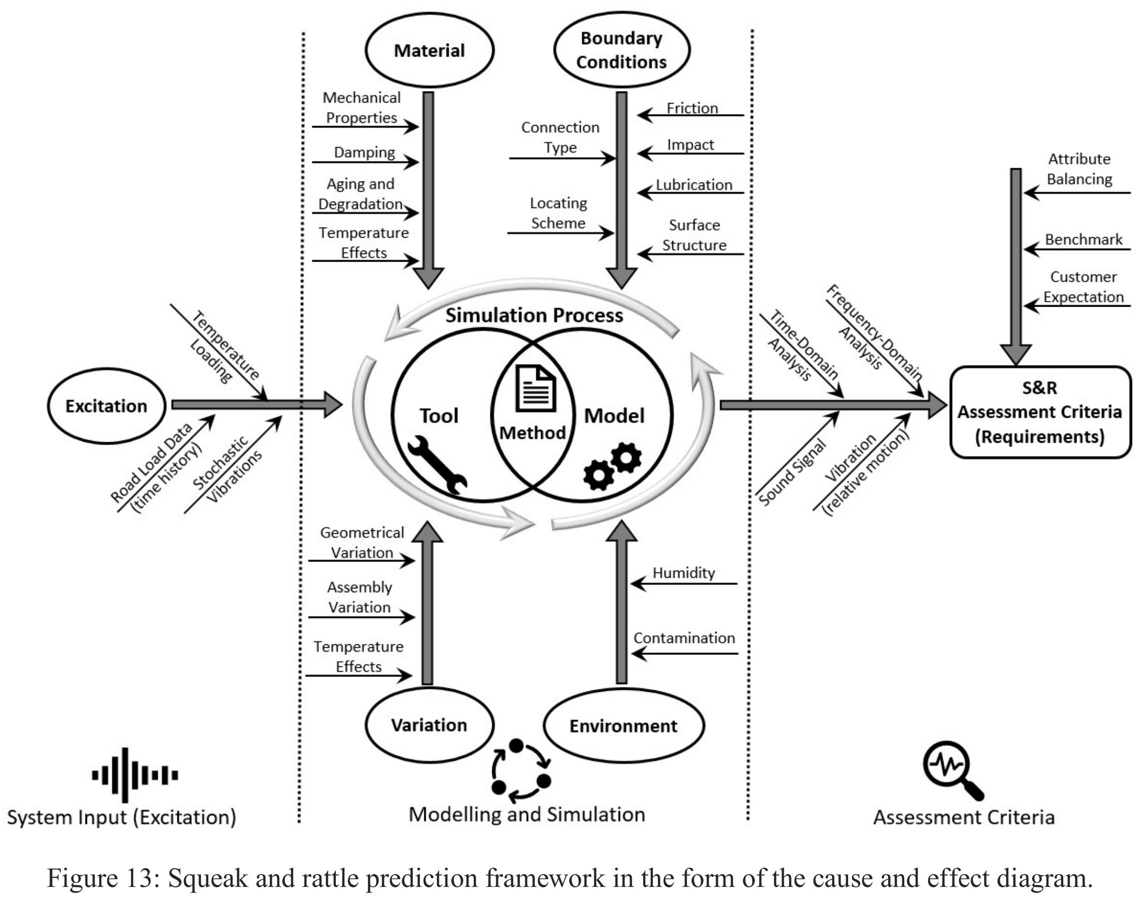

Figure 13: Squeak and rattle prediction framework in the form of the cause and effect diagram.

Modelling and simulation: This area is the core part of this research work. Depending on the simulation process, different contributors can be considered for S&R prediction. Material properties are important contributors to the generation of the S&R. Mechanical properties of a part affect the dynamic response of it and influence the characteristics of the generated sound. The mechanical properties can vary due to ageing and degradation and ambient condition. Damping is an important material parameter that influences the simulation process by changing the dynamic response of a system and the quality of the generated sound. The prescription of the boundary conditions of a physical or virtual model affects its response. The friction and impact parameters in the interfaces between parts change the system response. Surface condition and lubrication can also influence the interaction between parts. The connection configuration in an assembly, and the type of connectors play an important role in the static and dynamic behaviour of an assembly and, resultantly, the risk for the generation of S&R. The environmental condition in which the simulation process happens affects the results. Humidity and contamination can change the surface properties and mechanical characteristics of a part. Another important contributor to the generation of S&R is the product variation introduced in different production and usage stages. While part- and assembly- level manufacturing variations can result in geometrical variation in critical interfaces for S&R, usage conditions, such as the temperature, can also magnify this risk.

The squeak and rattle simulation process involves the three elements of the model, the tool and the method, as illustrated in Figure 13. Some of the important current simulation methods and tools applicable to the prediction of S&R are briefly mentioned in section 2.2. A model can be a physical model, a CAE virtual model or a geometrical virtual representation of the real product in the form of CAD models, as depicted in Figure 14. Throughout the model development and simulation processes, these models are interrelated. CAE models are built based on CAD models and are then often validated against physical models. A CAE model can represent the complete vehicle, a subsystem in the car, a single part, or even a portion of a part or subsystem. Based on the purpose of the modelling and simulation, the available resources and the maturity of the CAD models, the CAE models can vary in type and details. In the initial stages of the concept or design phase of the product development process, CAE models can be developed from scratch and may not be based on CAD models. These CAE models are then used as input for generating more mature CAD models. This process can be done recursively. CAD models are also used for building physical models. A physical model can be an exact replication of the final product or can represent some attributes of a product by using simplified or adjusted parts. A physical model needs certain interfaces to be used in a simulation or test process. To define these interfaces and validate the non-exact representative physical models, CAE models can be used as the reference. CAD models are often developed through a gradual evolvement process within the product development process. Throughout the development, the maturity level grows by exchanging the data with CAE and physical models. In the S&R prediction process, apart from the development of CAE and physical models, CAD models are used in CPA. Based on the CPA results, a decision for the other required types of physical or virtual simulations can be made.

Assessment criteria: When studying an attribute feature of a product, besides the type of system input, model type and simulation and analysis methods, assessment metrics are needed to define the required criteria for the product verification. For S&R prediction, these criteria can be set as objective or subjective metrics. The metrics may need to be adjusted based on the maturity level of the system input, modelling and simulation process and analysis methods. These quantified criteria are used in the requirement setting phase to clarify the product quality. It was an important part of this research work to explore this area to understand the current status and identify workflows for improving the existing and defining new assessment criteria. The assessment metrics can be calculated using the data gathered from the physical tests or virtual simulation and analysis. The collected system response can be in the form of sound or vibration signals. The analysis to calculate the metrics can be done in the time-domain or the frequency-domain.

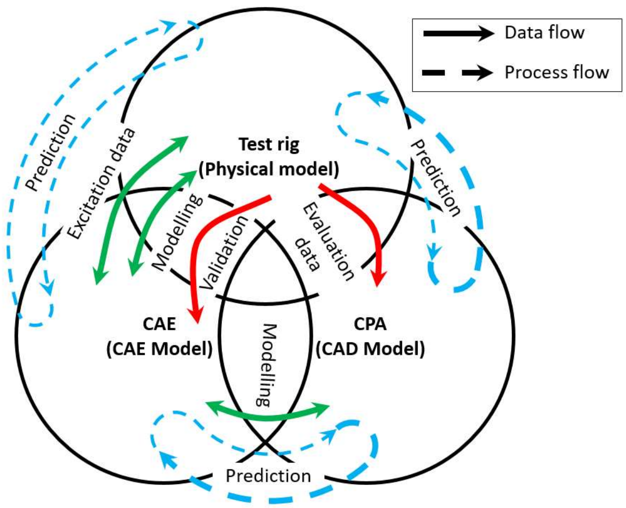

Figure 14: Interactions between squeak and rattle simulation models.

System input: The quality and the confidence level of the judgements made through the S&R prediction process also depends on the quality of the system input. By system input we mean how the system should be excited. Independent from using physical or virtual models and employing different simulation and analysis methods, for a robust judgement the system excitation should cover the whole operational condition known to be problematic for S&R generation. Furthermore, to use the different available modelling and simulation approaches interchangeably, the system input needs to be adjusted for a reliable and repeatable judgement. For instance, in the S&R attribute verification process, for subjective sound analysis using the physical complete vehicle prototypes in the proving ground, or structural dynamic response analysis using the finite element model of a subsystem in the virtual simulation, homogenised and level-adjusted system inputs are required. The excitation data can be gathered from the complete vehicle, subsystems of the car, or even parts under operational conditions. This data can be transferred between different system levels and the physical and virtual models. One of the important operational loadings for S&R simulation is the temperature loading that can change the estimated risk level for the generation and severity of S&R sounds. The system excitation can also be in the form of stochastic signals. However, these stochastic excitations are required to be defined with reference to the collected signals under operational conditions.

In Figure 15, the studies that have been carried out in this research work are positioned in the three main domains of the S&R prediction framework and the level each study addresses the research questions. Hereinafter, a brief review of the goals of each study, the methods, main outcomes and industrial and scientific contributions for each of the conducted studies are described.

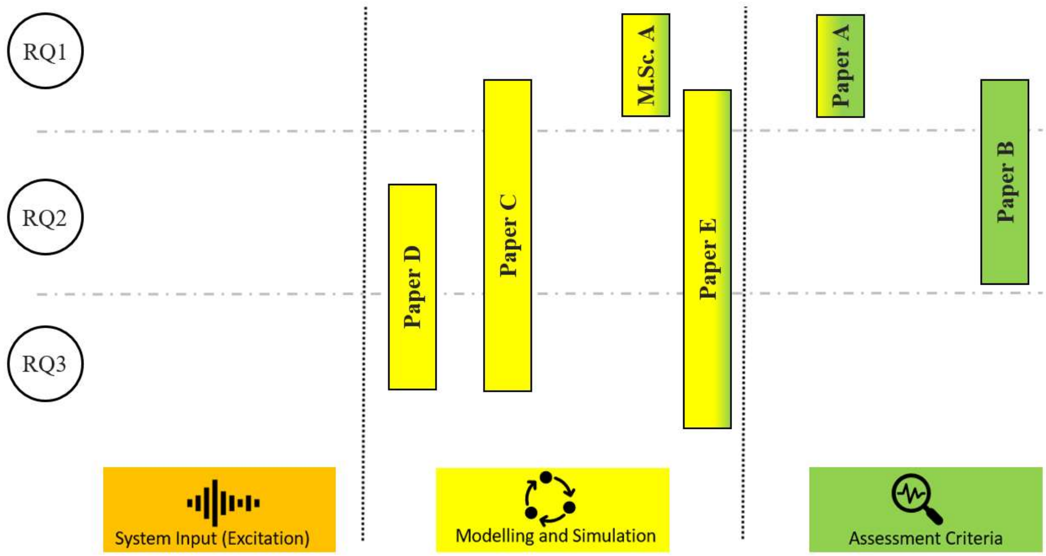

Figure 15: Positioning the conducted studies within this PhD in the S&R prediction framework and against the research questions.

4.2. STUDY I (PAPER A): EFFECT OF TEMPERATURE VARIATION ON THE PERCEIVED ANNOYANCE OF RATTLE SOUNDS IN THE AUTOMOTIVE INDUSTRY

Background: The main purpose of this study was to explore the cause and effect relationship between the phenomenon and one of its causes. Ambient conditions are known to be one of the main sources of S&R. Temperature changes can result in geometrical variation imposed by expansion or shrinkage of parts and can contribute directly to the generation of S&R sounds. Moreover, temperature and humidity affect the mechanical properties and surface condition of impacting parts [52] and resultantly the quality of the generated sound. The quality of generated S&R sounds have been studied under temperature changes [53], but this did not include the cold conditions that are proposed to be one of the worst-case scenarios for S&R evaluation [52]. Previous studies [19], [23], [24] have shown that psychoacoustic metrics are needed to specify the signature of S&R sounds. Thus, to study the contribution of the ambient conditions to the generation of S&R sounds, psychoacoustic metrics need to be incorporated. This has not been sufficiently addressed in the literature. This work studies this effect on the rattle sounds over a wider temperature range compared to previous works, and for selected metallic and polymeric material pairs from the car cabin.

Method: To generate the sounds in a controlled environment a rattle producing apparatus was designed and built [54]. Sound collection and generation were done in an ambient controlled semi-anechoic chamber. The collected sounds were used to run a subjective listening test with the method of paired comparison with magnitude estimation. The data retrieved from the listening test was used to identify the important psychoacoustic and statistical metrics best describing the stimuli. These metrics were employed to study the ambient condition significance in the rattle sound generation.

Outcome: It was shown that ambient variation has a significant effect on the perceived annoyance of generated rattle sounds. Overall, a drop in temperature increases the risk for the generation of more annoying rattle sounds. The perceived annoyance level can rise by 40% for a temperature change from +40 ºC to -10 ºC as shown in Figure 16. However, in a few cases, the opposite effect was observed.

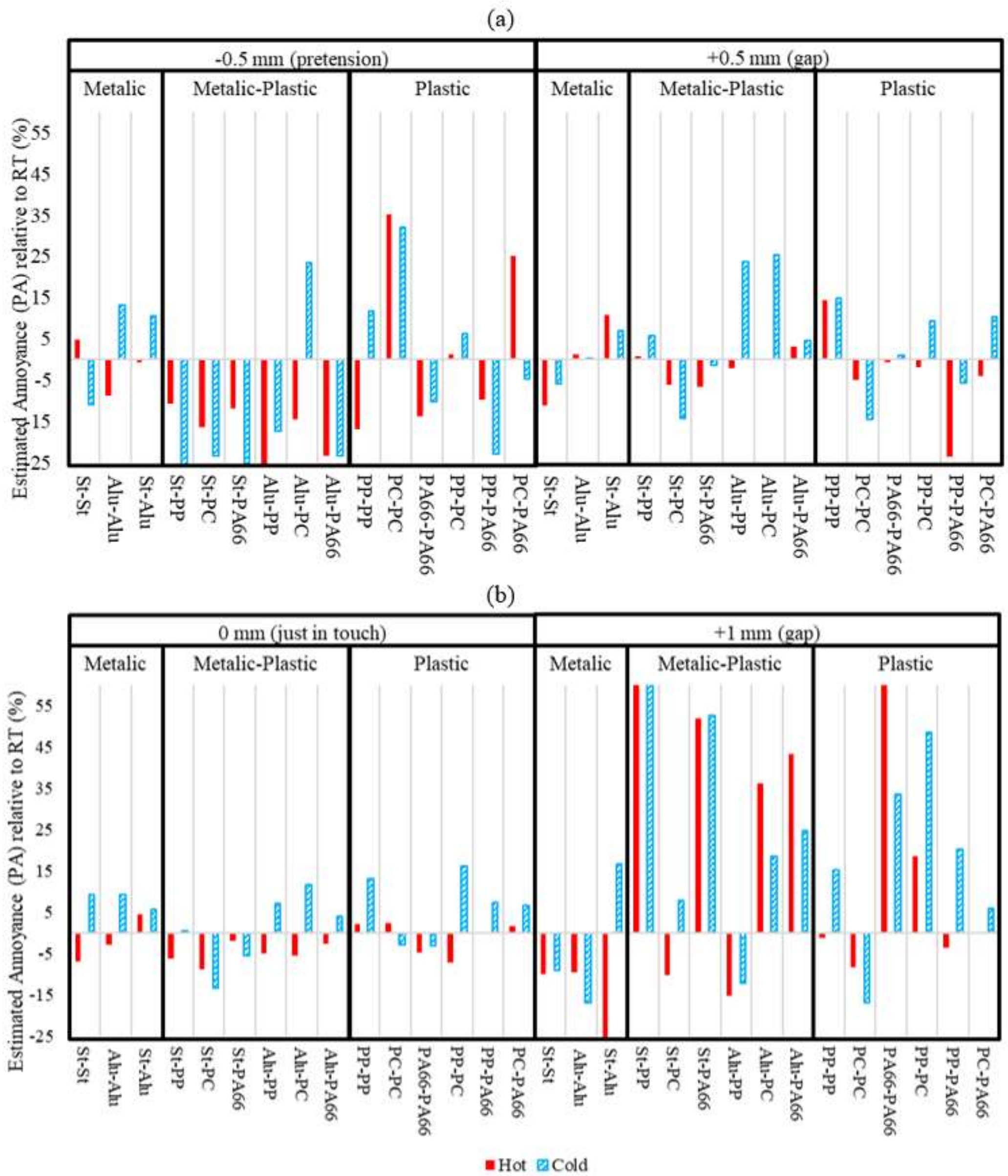

Figure 16: Estimated annoyance by psychoacoustic annoyance metric (PA) relative to room temperature (RT) for clustered material pairs. (a) -0.5 mm and +0.5 mm gaps; (b) 0 mm and +1 mm gaps [30].

The subjective listening method and the incorporated psychoacoustic metrics used resulted in an annoyance metric with a coefficient of determination of 0.60. One conclusion from this could be that in order to have more robust metrics to evaluate S&R sounds, a robust subjective listening test is needed to elicit the perception of the test subjects. Moreover, this might indicate the need for other statistical measures to better quantify the rattle sounds. This was the motivation to do other studies addressing these issues.

Scientific and industrial contribution: As per scientific contribution, this study supports the hypothesis of the influence of ambient conditions on the annoyance level of impulsive types of sound, such as rattle. It is concluded that the degree of influence varies for different test setups. However, the cause of this difference is not investigated. Concerning the industrial contribution, the results show the significance of considering the effects of temperature when treating rattle problems in the automotive industry. Furthermore, the annoyance level of emitted rattle sounds as a result of temperature variation, for different material pairs in different installation setups, as practised in this work, can form a database to be used as a material selection reference for upfront prediction and prevention of rattle events in car design and the development process.

4.3. STUDY II (MASTER'S THESIS A): SQUEAK AND RATTLE SOUND DATABASE AND ACOUSTIC CHARACTERISATION

Background: To evaluate S&R sounds using physical testing, different tests at different system levels are performed in the automotive industry, as is briefly introduced in section 2.2.2. While the test results from different system levels may vary, the main S&R problems are still expected to be pinpointed during the experimental process. However, there exists a lack of research on a comprehensive study to collect and compare S&R sounds from the equivalent test scenarios. This study was primarily aimed at identifying and comparing the test scenarios used for S&R evaluation during different phases of the product development at the system and subsystem levels, and then also collecting and forming a comprehensive database of the in-cabin S&R sounds. Moreover, a side study was made on the effect of replacement of the combustion engine with the electric motor on the generation and severity of S&R.

Method: Test cases were planned at two levels of complete vehicle and subsystem level. For the complete vehicle level, tests were done both at the proving ground and using a four-poster shaker rig intended for S&R evaluation with controlled climatic conditions. At the subsystem level, three different subsystems (the instrument panel, the side door and the front seat) were mounted on a climatically controlled shaker rig dedicated to S&R evaluation. Four different passenger cars from different segments of a single premium car manufacturer were used in this study. The test plans were accorded to the test setups used for S&R analyses and requirement verification in the industry. Sound signals were collected at different locations inside the car cabin, using both the binaural sound recording and single microphones.

Outcome: As one of the main outcomes, a huge database of S&R sounds with defined and controlled test conditions and accurate measurement setups was formed. This consisted of more than 3000 S&R sounds, although the majority of these were rattle sounds. The other output of the study was a comparison made among different test levels (subsystem or system level). The excitation and results were analysed both in terms of their subjective severity, the frequency content of the signals, the psychoacoustic metrics and the time-domain characteristics. This information can also be considered when selecting different physical verification methods to define the confidence level of the results. The cloud of the sounds of this database in terms of the most important metrics considered in the study is illustrated in Figure 17. The range over which these measures change for S&R sounds can be directly retrieved from the data. Also, the effect of temperature was observed in both system- and subsystem-level tests. At both test levels, a drop in temperature resulted in an increase in the number of S&R sounds detected and their severity. The results from the temperature study accorded with the findings from the previous study [30] where generated rattle sounds in the laboratory were used, and this emphasised the significance of considering the ambient conditions for verification test planning. In addition, by switching from the combustion engine to the electric engine, the number of detected S&R sounds increased by 41%, while on average the perceived annoyance remained constant.

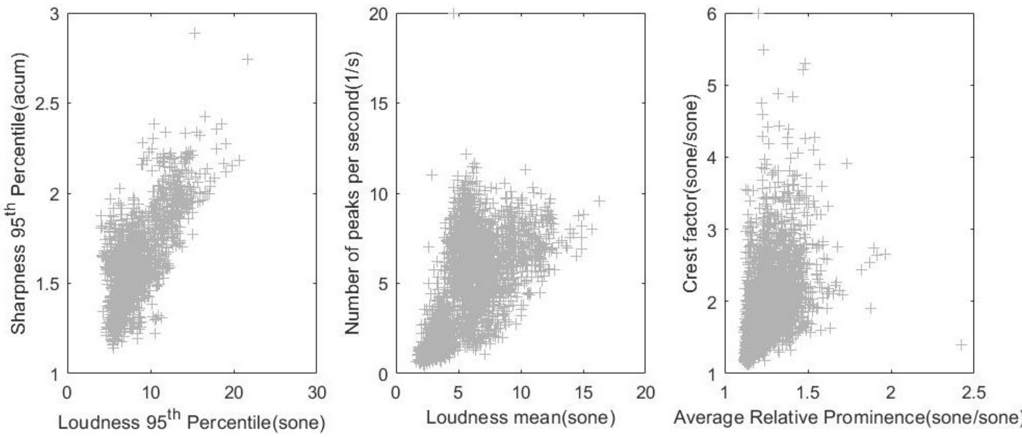

Figure 17: Scatter plot of the selected stimuli for the listening test compared to the cloud of squeak and rattle sound database.

Scientific and industrial contribution: The main scientific contribution of this work was the study on the range of the psychoacoustic and statistical measures for S&R sounds in different system and subsystem level verification tests. As per the industrial relevance, the compiled sound database, including the measured and analysed characteristics of the sounds, is a major consideration when planning physical verification tests at different product development phases.

4.4. STUDY III (PAPER B): ANALYSIS OF SOUND CHARACTERISTICS TO DESIGN AN ANNOYANCE METRIC FOR RATTLE SOUNDS IN THE AUTOMOTIVE INDUSTRY

Background: To advance the treatment of S&R sounds in the product development process, the need for having robust objective metrics was identified by literature studies. Following the study done before [30], [55], it was concluded that to have an objective metric to evaluate S&R sounds, besides the standard psychoacoustic metrics, other sound characteristics need to be incorporated. This research work further explored the characteristics of rattle sounds to be employed in the objective metrics. Also, in the previous study it was shown that the subjective listening test method impacted the accuracy of the designed metric. Therefore, it was decided to further work on the listening test method to increase the accuracy and confidence level of the process for designing S&R objective sound quality metrics.

Method: To elicit the users' perception of annoyance when exposed to rattle sounds, a subjective listening test was conducted. The test condition was designed such that it represented the real in-cabin condition as closely as possible. The tests were done inside the car cabin and the sound stimuli were played back using calibrated open headphones. The digital user interface for conducting the test was designed to accord the specific needs for collecting the relevant details of the subjects' responses. Sound stimuli used in the test were produced in the laboratory, using the apparatus built during the previous study [30]. The selection of sounds was made to assure dependent and independent variation of the involved acoustic measures in the study, within the range identified in another previous study [55]. The subjective test method was an adjusted version of the paired comparison method with magnitude estimation [27], [29]. The drawbacks of the method were attempted to be overcome by insights from unbounded response rating and semantic differential methods [27]. The results of the listening test were used in a stepwise nonlinear regression problem to define a sound quality metric for the rattle sounds.

Outcome: The method for designing an objective sound quality metric for S&R sounds was the main outcome of this work. The efficiency and accuracy of the proposed subjective test method were evaluated based on the data retrieved from the interviews with the subjects and their performance during the test. By calculating the objective measures from the test results, the interquartile values for self-consistency and concordance [28] were between 66% to 77% and 77% and 88%, respectively as shown in Figure 18. For a hard task of judging the annoyance level of impulsive sounds, for both expert and standard users, these high ranges imply the robustness and accuracy of the method used. Also, the task was judged to be slightly difficult and the majority of the subjects claimed that they could keep the judgement consistent throughout the test.

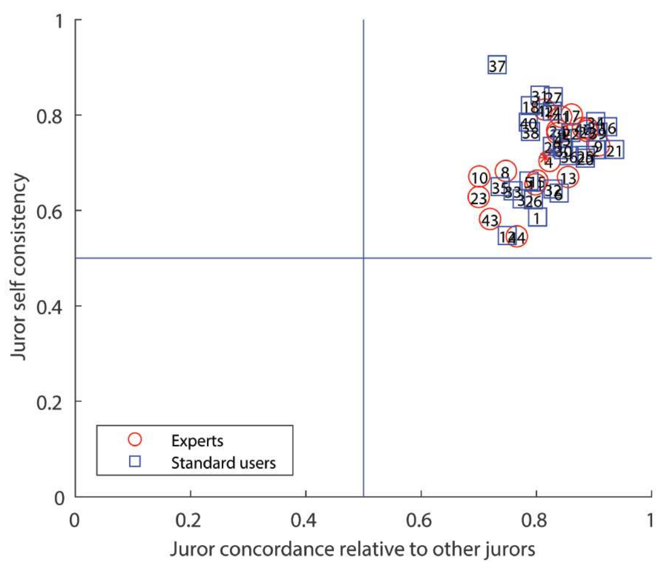

Figure 18: Jurors' self-consistency vs concordance relative to other jurors, with 1.0 denoting 100% consistency/concordance [28].

In addition, introducing different groups of sounds into the design of the listening test, each targeting specific variables in the study, facilitated the use of a stepwise regression method. The inclusion and exclusion of different variables could then be partially independently studied. In addition to the proposed method, the results were used to design a rattle annoyance metric by incorporating psychoacoustic metrics and statistical measures of the sound signal. The predicted and observed annoyance levels for the sound stimuli are shown in the plot in Figure 19. The root-mean-squared-error of the prediction compared to the observed perceived annoyance was 0.0479, with a coefficient of determination (R-squared) value of 0.929. This together with the prediction and observation confidence intervals [56] reflects the quality of the fit and the accuracy of the proposed annoyance metric. However, to examine the validity of the proposed metric, recorded sounds from the car cabin should be used in a subject listening test to evaluate accuracy. This remains a subject for future work in the application of the designed metric in the industry.

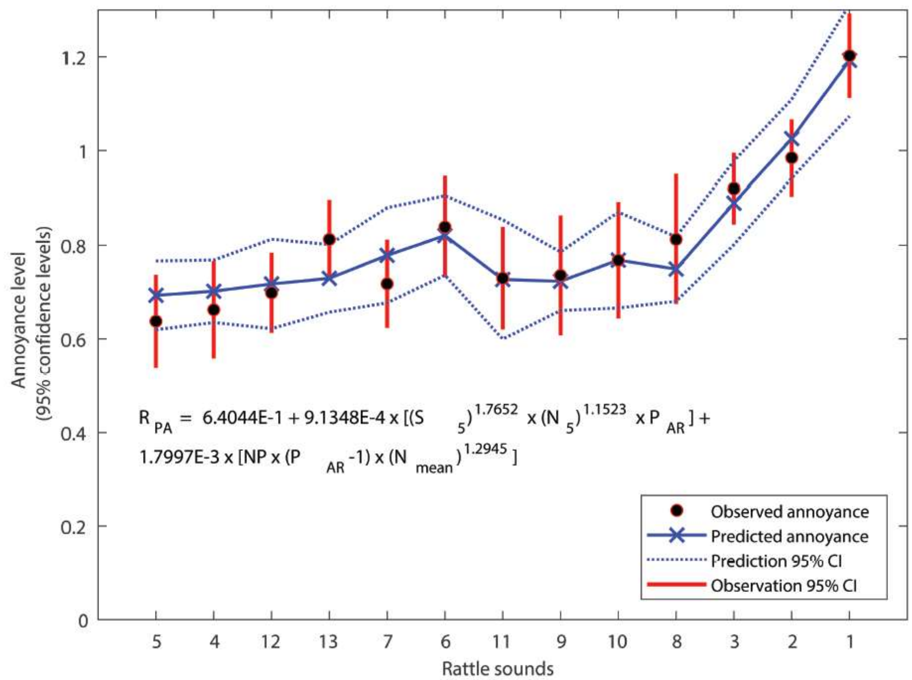

Figure 19: Observed and predicted annoyance levels [28].

Scientific and industrial contribution: This study scientifically contributes to further improving the setup of the subjective listening tests by proposing a new method for subjective testing. It builds upon the existing method of paired comparison with magnitude estimation and suggests provisions to suppress the drawbacks of the method. Further, it introduces the new statistical metric of average relative prominence to be used as a correction factor for psychoacoustic metrics and time-dependent characteristics of impulsive sounds, such as rattle. As per the industrial application, this work gives detailed instructions for planning, conducting and analysing the results of a robust subjective listening test in the automotive industry. In addition, a new annoyance metric for evaluation of rattle sounds is proposed in this work.

4.5. STUDY IV (PAPER C): NONLINEAR MODELLING AND SIMULATION OF IMPACT EVENTS AND VALIDATION WITH PHYSICAL DATA

Background: Previous studies [9], [37] have indicated the significance of relative velocity, impact acceleration and momentum of impacting parts in the generation of impulsive sounds. Choi et al. [38] demonstrated the employment of surface velocity to estimate the severity of rattle sounds in a passenger car. However, the common practice to predict S&R events in the automotive industry is limited to the evaluation of relative displacement between interfaces through linear finite element analysis, [34], [35]. In order to understand the modelling details needed to accurately capture the kinetics and kinematics of the contact in impact events, the study described below was carried out.

Method: The case study in this research was the rattle producing machine that was built earlier [30]. The nonlinear finite element model of the apparatus with the contact definition at the impact region was built and a parameter study on the modelling parameters was done in Abaqus. Response evaluation was done in terms of kinetic and kinematic measures most contributing to the severity of generated rattle sounds, based on the literature [9], [37] as well as a field study [28]. The results were compared to the experimental data gathered under the laboratory conditions.

Outcome: The main result from this work was the modelling guideline for nonlinear simulation of impact events. Various modelling parameters in contact modelling and their significance on the system response was summarised. The summary table of the parameter study for the steel-steel material pair is shown in Table 1. For details of the parameters please refer to [57]. Furthermore, the best correlating parameters from the system response were identified.

Scientific and industrial contribution: As far as scientific significance is concerned, this study was expanded [58] to include other material pairs of plastic-plastic and plastic-metallic combinations in addition to the metallic-metallic case presented. The observation made on how the sensitivity of the model parameters changes for different material combinations adds to the available knowledge about nonlinear modelling of impact events to better simulate the mechanism involved in the event. As per industrial contribution, the summary tables of the parameter study work as a modelling guideline for nonlinear simulation of impact events resulting in impulsive sounds, such as rattle. When the finite element model is needed to be tuned to improve the system response, in terms of known kinematic and kinetic parameters, the simulation parameters with the highest significance can be chosen from these tables. Moreover, when defining an objective metric for evaluation of rattle events using the results of the structural dynamics simulation, the identified best-correlated system outputs can receive higher importance.

4.1. STUDY V (PAPER D): FINITE ELEMENT MODEL REDUCTION APPLIED TO NONLINEAR IMPACT SIMULATION FOR SQUEAK AND RATTLE PREDICTION

Background: As indicated in the literature [9], [37], [38], accurate prediction of S&R events depends on accurate prediction of the kinetics and kinematics of the contact events that generate the sound. However, it was revealed [57] that nonlinear simulation of contact events, even for small finite element models, is computationally expensive. To further study these phenomena using nonlinear finite element models, provisions are needed to be made to make the simulations computationally efficient, while not sacrificing quality. Dynamic substructuring approaches, as first introduced by [59], aim at decomposing the problem into subsystems and solving the smaller models, while data transfer happens at the interfaces of the subsystems. Component Mode Synthesis (CMS) extended substructuring methods by employing Model Order Reduction (MOR) methods [22], [60]–[62] for the substructured models. The Craig-Bampton [61] CMS method has been widely applied to industrial problems for linear complex substructures [63]. Although there have been studies addressing the employment of the Craig-Bampton method in problems with geometric nonlinearities [63]–[67], the application in models with a large number of interface degrees of freedom or when nonlinearities appear in the vicinity of the interfaces was not promising. Thus, the application of the Craig-Bampton method in problems with nonlinearities of contact type remains an interesting subject for research in structural dynamics field. Exploration of this application was the purpose of this study.

Table 1: Parameter design space and system response from the sensitivity analysis of the contact model.

Case number	Contact definition: CP: Contact Pair, Gen: General Contact	Contact mechanics: Kin: Kinematic, Pen: Penalty	Damping Stiff: Rayleigh, stiffness component Mass: Rayleigh, mass component Con [value]: Contact damping [with a critical damping fraction]	Small Sliding	Friction: with the friction coefficient of 0.2	Frequency of biggest bounce [Hz]	The ratio of the height of bounce to impact velocity [mm/mm/s]	Peak impact force [N]	Impact power = Impact force times impact velocity [N.mm/s]
1				×	×	244.50	0.001254	105.90	8969.54
2					×	243.31	0.001255	105.30	8918.29
3			Stiff			242.72	0.001275	88.34	7438.86
4	CP	Kin		×		243.31	0.001324	88.31	7434.48
5						242.13	0.001324	87.88	7387.63
6[1]						242.72	0.001322	87.88	7397.47
7			Mass			245.70	0.001375	85.70	7195.45
8			Stiff; Con [0.2]		×	244.50	0.001289	82.54	-6982.52
9						241.55	0.001164	71.64	-6138.49
10			Stiff			241.55	0.001154	71.67	-6143.95
11	CP	Pen	Con [0.05]			241.55	0.001164	71.64	-6139.00
12			Con [0.1]			241.55	0.001163	71.64	-6140.12
13			Con [0.2]			241.55	0.001161	71.64	-6142.09
14			Mass			242.72	0.001284	69.24	-5929.06
15					×	264.55	0.001280	82.58	-6870.29
16						246.31	0.001390	84.21	-7098.09
17	Gen	Pen	Stiff			245.70	0.001366	84.34	-7168.12
18			Mass			243.31	0.001299	81.02	-6904.45

[1] node-to-surface contact type.

Method: The problem of interest was the nonlinear simulation of the S&R events in a subassembly in Abaqus. The finite element model of a side door assembly was obtained and by referring to a digital pre-assembly report [32] and field interviews with analysis engineers the critical interface for generation of S&R was defined. The original finite element model was substructured into linear and nonlinear regions, as depicted in Figure 20(b). The nonlinear region contained the contact interfaces for capturing the dynamics of the S&R events defined based on the guidelines from [57]. The Craig-Bampton method [61] was employed to reduce the linear part of the model. To study the effect of the vicinity of the substructure interface to the nonlinear region and the retained degrees of freedom, the system was substructured and then reduced in different ways, as can be seen in Figure 20(a). The cost of computation was the main parameter to be minimised while quality constraints over the accuracy of the response were defined and monitored for each reduced model. The quality criteria were defined as measures of Modal Assurance Criterion (MAC) [68], frequency response comparison of the nonlinear event using the Normalised Root-Mean-Squared-Error (NRMSE) [69] and the contact time, location and force in the nonlinear event. For details, please refer to [70].

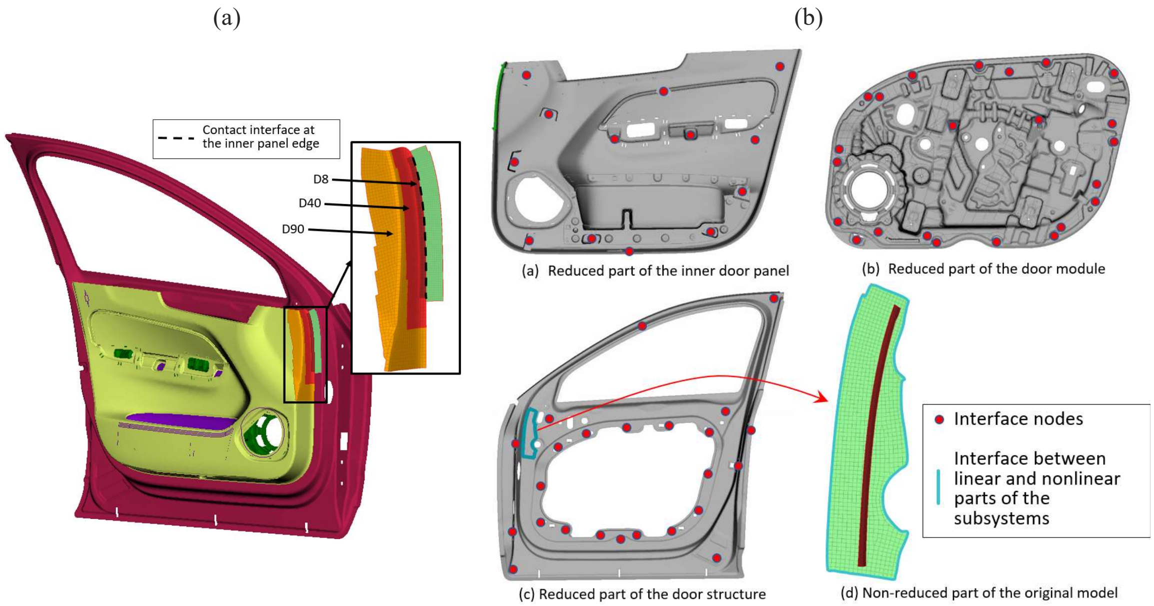

Figure 20: Finite element model of the side door. (a) Different substructure interface definitions (b) reduced linear and non-reduced nonlinear substructures of the side door according to [70].

Outcome: The study presented the successful employment of the standard Craig-Bampton method [61] in simulating nonlinear S&R events. The computational time, compared to the original non-reduced model, could be decreased by 98%, while the quality of the dynamic response of the system was maintained by monitoring the defined criteria. By employment of some of the reduced models, a good approximation of the system response was achieved, namely 0.98 and 0.93 for MAC and NRMSE metrics, respectively. While in a few events contact force was estimated with 2.5% to 22% error on average, the location and time of the contact events were captured accurately by the reduced models. As one of the main conclusions from the study, it was shown that the definition of the substructure interfaces closer to the nonlinear region (up to the distance equal to the size of one element) does not negatively influence the system response, while the gain on the computational cost is considerable.

Scientific and industrial contribution: The main scientific contribution of this study was the exploration made of the employment of the standard Craig-Bampton method [61] in finite element simulation, including contact nonlinearities. The study of how the substructure interface definition influences the response quality, although vital for the application of the method, was not available in the literature. Furthermore, similar to other attempts [63], [71] to implement interface reduction approaches in the Craig-Bampton method, this study was further stretched to introduce an interface reduction method based on the system response in terms of S&R criterion. This work is not yet documented for publication. As per the industrial application, the use of a CMS method for nonlinear simulation of S&R events, where high accuracy of the dynamics of the contact events is needed, was illustrated in this work. It was shown that a great reduction in computation time can be achieved, measured as 98% reduction for the studied model [70].

4.2. STUDY VI (PAPER E): SQUEAK AND RATTLE PREVENTION BY GEOMETRIC VARIATION MANAGEMENT USING A TWO-STAGE EVOLUTIONARY OPTIMISATION APPROACH

Background: One of the main sources of S&R problems in cars, is the geometric variation [2]. The connection configuration or the location of the fasteners in vehicle subsystems contributes to the geometric variation [72] and resultantly in the generation of S&R [73]. The connection configuration refinement in assemblies by geometric variation simulation has been previously researched [43], [72], [74]–[76], but with the main focus on sheet metal assemblies and the aesthetic properties of the product. Today, the use of geometric variation simulation results in S&R prevention is confined to adjusting the clearance requirements in critical gaps [73]. Nevertheless, the non-rigid geometric variation simulation can be used in optimisation loops to find the optimum connection configuration in assemblies to reduce the risk for S&R. The main obstacle in this application is the computational cost of such an optimisation process for the large assemblies in a car. In this research, a two-stage optimisation method is proposed to reduce the risk for S&R by optimising the location of connections in an assembly.

Method: The schematic sketch of an assembly of two parts is shown in Figure 21. To make the optimisation process faster, the finite element design space for the connector location is coarsely discretised. Observation points, called measurement points, are added to the model, where relative variation and deviation between the two parts is monitored. In each measurement point two measurements are defined: one linear measurement in the direction of the possible impact, namely the rattle direction, and a planar measurement in the normal plane to the rattle direction, namely the squeak plane. Geometric variation, V_i, and geometric deviation, D_i, in the i^{th} measurement point is defined as:

$$V_i = 6\sqrt{\frac{1}{N_r - 1}\sum_{j=1}^{N_r}\left(d_{j,i} - \mu_i\right)^2}\ , D_i = \mu_i - \mu_{ni}.$$
$$\mu_i = \frac{1}{N_r}\sum_{j=1}^{N_r} d_{j,i}. \tag{2}$$

The objective functions for variation, f^V, and deviation, f^D, are defined as:

$$f^V = \alpha\sqrt{\frac{1}{n}\sum_{i=1}^{n}(V_i)^2} + \max_{i=1\ to\ n}(V_i)$$
$$f^D = \alpha\sqrt{\frac{1}{n}\sum_{i=1}^{n}(D_i)^2} + \max_{i=1\ to\ n}(D_i). \tag{3}$$

These objective metrics can be defined in the rattle direction, $f^{V,R}$ and $f^{D,R}$, and in the squeak plane, $f^{V,S}$ and $f^{D,S}$. For the explanation of terms used in equation (2) and equation (3) please refer to [77]. In this work, the variation simulation method used was DMC embedded in RD&T software [78].

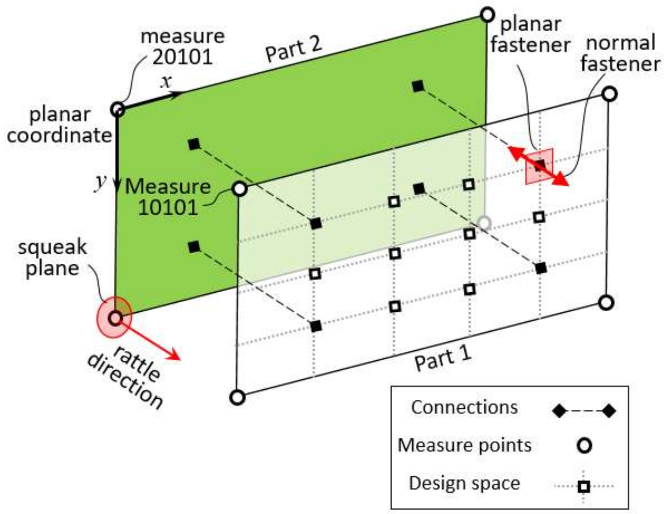

Figure 21: Schematic depiction of the assembly of two parts.

To fully restrain the relative movement of the parts in a large flexible assembly, in addition to the six degrees of freedom, additional constraint points are needed to avoid the relative motion of the parts due to their flexibility. Positioning systems are used to constrain the normal and planar degrees of freedom between two parts. Finding the location of all these constraints simultaneously makes the optimisation computationally expensive. One provision proposed in this study was to decompose the connection DOFs into two groups: the DOFs with the primary influence on the measurements in the rattle direction and the DOFs with the primary influence on the measurements in the squeak plane. To decouple the optimisation in two phases of the rattle direction phase and the squeak plane phase, this assumption is made: the effect of constraints from the rattle direction group on the squeak plane measurements is of a secondary order, compared to the effect of constraints from the squeak plane group. So, in the first phase of the optimisation, only the constraints from the rattle direction group are involved and the objective is only defined in the rattle direction. In this phase, to restrain the two parts in the squeak plane, a set of dummy fasteners are added to the model to make the simulation computationally stable. This assumption was studied for six different generic assemblies with simplified geometries, as shown in Figure 22. These geometries, the boundary conditions and their mechanical properties and modal behaviour resembled the common large assemblies in the car cabin prone to S&R problems. To falsify the stated assumption, the results of the geometric variation analysis are compared for the design cases for each assembly with and without the presence of the dummy fasteners in Table 1. Results indicate that for all cases, apart from case 6, the mean absolute error (MAE) for inclusion and exclusion of the dummy fasteners, for both the variation and deviation metrics in the rattle direction is considerably lower than the normalised maximum difference (NMD) observed among the designs of a case, varying between 3% to 24% and 3% to 48% for $f^{V,R}$ and $f^{D,R}$, respectively. Also, for all cases, apart from case 4 and 6, compared to the normalised standard deviation (NSTD) among the designs of a case, MAE is relatively low, accounting for 9% to

55% and 15% to 61% of the NSTD for $f^{V,R}$ and $f^{D,R}$, respectively. For case 4 and case 6, $f^{V,R}$ has negligible MAE. However, for $f^{D,R}$, the biggest MAE value was observed, representing 78% and 267% of NMD and NSTD in case 6, respectively. For case 4, the MAE for $f^{D,R}$ was measured as 48% and 123% of NMD and NSTD, respectively. On the contrary, as expected, removing the dummy fasteners dominates the changes in the objective metrics in the squeak plane. Thus, in the first phase, the objective only includes the terms in the rattle direction. As a conclusion, for the variation metric in the rattle direction, the effect of constraints from the squeak plane group is of a secondary order, compared to the constraints from the rattle direction group. For the deviation metric in the rattle direction, the same conclusion can be made for most of the studied geometries. However, in cases 4 and 6, this effect was shown to have almost the same order for the constraints from both groups. Therefore, for assemblies belonging to these categories, in the objective metric, the weighting of the deviation can be decreased in the first phase of the optimisation.

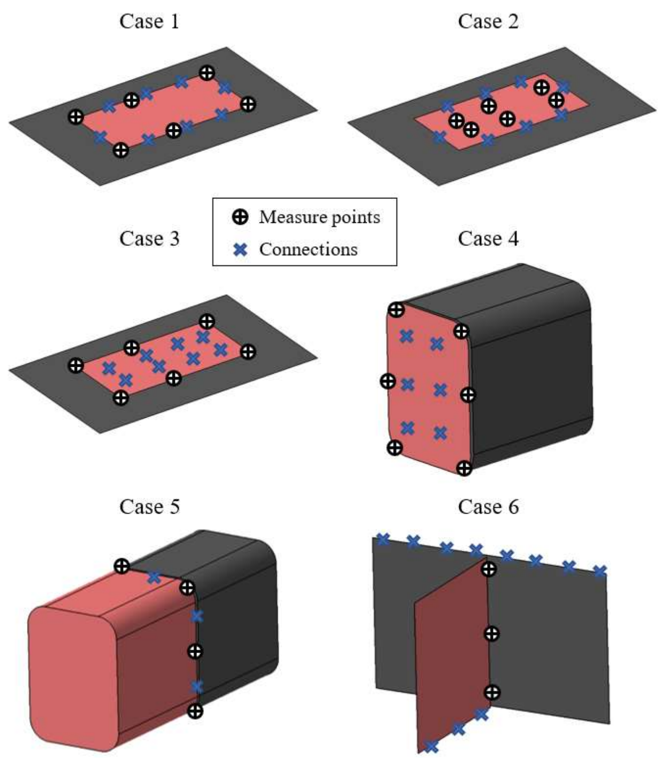

Figure 22: Simplified connection concepts for the geometry cases used for falsifying the method assumption.

Another measure that was taken to speed up the optimisation process, was the assumption made to apply all the fasteners simultaneously in the assembly, as was also done by Cai [75]. Therefore, the sequence of the fasteners in a design is considered not to influence the results considerably. To reject the repeated designs, disregarding the sequence of the fasteners, a mathematical constraint was added to the optimisation formulation as described in [77]. The optimisation method employed in this work was the Multi-Objective Genetic Algorithm (MOGA) as introduced by Fonseca and Fleming [46], using an elite pool. The initial generation in the optimisation process was a DOE set generated by the genetic algorithm version of the Incremental Space Filler (ISF) method [79].

Table 2: Variation and deviation results for the simplified geometries from Figure 22, with and without including the dummy fasteners.

Difference %	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
$f^{V,R}$, MAE[1]	24	47	12	3	7	0
$f^{V,R}$, NSTD[2]	44	97	30	33	31	20
$f^{V,R}$, NMD[3]	102	538	104	105	135	40
$f^{D,R}$, MAE	34	58	29	43	6	80
$f^{D,R}$, NSTD	56	144	68	35	40	30
$f^{D,R}$, NMD	182	860	321	90	172	103
$f^{V,S}$, MAE	569	71	90	623	47	0
$f^{V,S}$, NSTD	50	10	12	1	12	21
$f^{V,S}$, NMD	209	61	52	1	34	39
$f^{D,S}$, MAE	453	67	48	626	41.3	148
$f^{D,S}$, NSTD	42	8	19	3	12	19
$f^{D,S}$, NMD	178	51	70	12	14	26

[1]MAE is the mean absolute error in percentage.
[2]NSTD is the normalised standard deviation in percentage.
[3]NMD is the normalised max difference in percentage.

Outcome: The main outcome of this work was the developed framework for the optimisation of connectors configuration in an assembly with the aim of minimising the risk for the generation of S&R in critical interfaces. By employing the proposed method, the most robust designs respecting the geometric variation and tolerance propagation in critical interfaces can be found. The method was used to find the connection configuration for a side door inner panel assembly and a decorative panel assembly in the instrument panel of a passenger car. For details of the optimisation workflow and the model setup please refer to [77]. In both cases, designs were achieved that performed better compared to the baseline design, considering the geometric variation and tolerance stack-up in the selected critical interfaces for S&R.

Scientific and industrial contribution: The main scientific contribution of this research is the descriptive study done on the assumption for decoupling the constraints in two groups effecting the geometric variation results in the rattle direction and the squeak plane and the involvement of these in the stepwise optimisation. The study performed on the generic simplified geometries fully supported this idea for the proposed geometric variation objective. For the geometric deviation objective, the assumption holds true for most of the cases. However, for some geometrical categories it was observed that the effect of constraints from the squeak plane group has almost the same order as the constraints from the rattle direction group. Therefore, to use the proposed method in such categories one provision can be to weigh the geometric variation objective considerably higher compared to the geometric deviation metric in the first stage of the optimisation.

The main industrial application of this work is the proposed optimisation framework to reduce the risk for S&R by geometrical variation management. The application of the method for two industrial assemblies was demonstrated and the details for the optimisation setup were discussed.

5

DISCUSSION

In this chapter, the research questions are answered by referring to the outcomes of the studies presented in the results section. The contribution of the outcomes to scientific knowledge and their industrial application are summarised. The quality of the presented work is also discussed by referring to the validation and verification criteria.

The studies conducted so far have resulted in partially answering the research questions. Nevertheless, the prospect of planned future studies and the foreseen outlook of the research is that the answers to the research questions will evolve more in later phases of the PhD work. The answers to the research questions, to the extent that the conducted study results allow, are given below.

5.1. ANSWERING THE RESEARCH QUESTIONS

RQ1: *To objectively evaluate squeak and rattle sounds, what elements are needed to establish a robust simulation framework?*

So far, all of the conducted literature studies and field studies have yielded the S&R prediction framework, presented in the form of a cause and effect diagram in Figure 13. The cause and effect diagram shown in Figure 13, introduces the essential elements that need to be considered as contributors to the prediction of S&R in the automotive industry. The three main domains in this diagram include the system input definition, the modelling and simulation, and the evaluation metrics. These domains are discussed in section 4.1 and the identified contributors to each element are introduced in Figure 13. In studies I, II, III and IV, some of the assessment criteria used in the physical verification process were studied in detail. In studies I and III, some of the methods used for developing objective sound quality metrics for S&R sounds were reviewed and an enhanced method for this purpose was proposed. In studies III and VI, physical vibration data from the system response were collected to be used to further study the structural dynamics response in virtual analysis in future. The physical simulation of S&R events was mainly covered by study II, where different tools used for physical verification of S&R events were compared. In this study, the system input was also compared among different physical simulation methods. The virtual modelling and simulation methods were addressed in studies IV and VI. In study IV, the parameters involved in the contact modelling and simulation for rattle events were investigated. In study VI, the implementation of geometric variation analysis in the prediction process of S&R was reviewed. Furthermore, as discussed in section 4.1, the modelling process and the interaction between different virtual and physical models are summarised in Figure 14.

RQ2: *How to improve the current status of the available tools and methods for inclusion of elements involved in the squeak and rattle prediction framework?*

As stated in the delimitations section (1.2.4), the identified cause and effect diagram involves contributing elements from different domains and disciplines. This makes it impossible to thoroughly cover all these elements within the scope of a single PhD work. However, an attempt to explore some of these contributing elements and further develop methods for involving them in the prediction process has been made. The available tools and methods for predicting and dealing with the S&R problems are briefly reviewed in section 2.2. As far as the assessment criteria area is concerned, study III describes an enhanced method for designing sound quality metrics for evaluation of S&R sounds. It also introduces a sound quality metric by employing new statistical measures to better capture the perceived annoyance level of rattle sounds. The parameter study conducted in study IV describes the best correlating output parameters, with reference to the experimental data, to be used in future for dynamic response metrics in virtual simulations. Study VI proposes objective measures for quantifying the geometric variation simulation results in the prediction of S&R problems. Concerning the modelling and simulation domain, study IV presents the method for nonlinear modelling of rattle events and the parameters involved in the simulation process. The conducted parameter study gives useful information for model tuning when an accurate response is needed in terms of output parameters contributing to the generation and severity of rattle events. Study V describes the employment of a model reduction approach in the nonlinear simulation of S&R problems. It was shown that simulation cost can be reduced considerably while the quality of the system response can be maintained at an acceptable level. Study VI introduces an optimisation methodology for better involvement of geometric variation as an important contributing factor to S&R generation in the design phase of the product.

RQ3: *How can the proposed framework be used in the new product development process prior to the pre-design-freeze phase?*

The application of the proposed methods is described in studies IV to VI. In study IV, it is shown how the parameter study results can be used as a reference for model tuning to improve the accuracy of system response in terms of parameters contributing to the severity of rattle sounds. The model reduction approach employed in study V shows the sensitivity of the simulation results to some of the parameters involved in the modelling method. The influence of interface definition between linear and nonlinear parts of the model and the resulting computation cost gain and response accuracy loss is discussed. In study VI, the proposed optimisation method was employed in the design of a side door inner panel assembly and a decorative panel assembly in the instrument panel of a passenger car. The details of the application of the method and the modelling and optimisation setup details are given and the improvement in the results, compared to the baseline designs, is discussed.

5.2. SCIENTIFIC AND INDUSTRIAL CONTRIBUTION

The scientific and industrial relevance of the studies conducted in this work is discussed in detail in chapter 4 under each study topic. Overall, the cause and effect diagram presented in Figure 13, a brief review of the available methods and tools given in section 2.2 and study II and the improvements for simulation methods introduced in studies III-VI all have industrial application in predicting the S&R sounds. The studies (studies II and III) performed on the parameters to better describe the nature of rattle sounds, the effect of temperature on the perceived annoyance of different rattle sounds (studies I and II), the proposed method for subjective listening testing (study III), the parameter study on the modelling parameters in the nonlinear simulation of S&R (study IV), the impact of interface definition for a model reduction on the S&R simulation results (study V), and the study on the dependence level of the geometric variation simulation results in the S&R coordinates on the constraints in various degrees of freedom (study VI), have all added to the knowledge about predicting and evaluating nonstationary sounds such as S&R.

5.3. REFLECTION ON THE RESEARCH OUTCOMES BASED ON THE SUCCESS CRITERIA

The outcomes of this work, with reference to the prescribed success criteria in section 3.2.3, are briefly reviewed hereinafter.

- *Acceptance by experts*: this criterion is reflected by the number of peer-reviewed publications originating from this work as appended to this thesis. The papers have been presented in relevant conferences and peer-reviewed by experts within the field, or submitted for review to pertinent journals.
- *Accuracy of the proposed methods*: this criterion was measured differently in the various studies. In study III, the statistical error values between the experimental

observations and prediction have been used to calculate the confidence level of the outcome. It was shown that the proposed fit function resulted in accurate predictions within the 95% confidence intervals obtained from the observation data. In study IV, the accuracy of the simulation method was improved by predicting the contact force and the transient response of the system using nonlinear models compared to linear models. In study V, system response after applying the model reduction was compared to the baseline non-reduced model using statistical measurements, including the normalised root-mean-squared error, mean absolute error and modal assurance criterion (MAC) [68]. It was concluded that the accuracy of the system response was ensured by monitoring the aforementioned metrics. In study VI, it was observed that the proposed optimisation method resulted in optimised designs that outperformed the baseline design with regard to the defined variation and deviation objective metrics. This conclusion was made by comparing the objective values for the designs in the scatter plot of the optimisation results.

- *Generalisability and robustness*: with regards to generalisability, in studies I and III sound stimuli were collected from a rattle producing machine under laboratory conditions and in various test setups, to make the study valid for a wide variety of rattle sounds. The finite element model of the same test apparatus was used in study IV in the nonlinear simulation of impact events. However, to further investigate the generalisability of the outcomes of these studies, descriptive studies need to be conducted to judge whether the findings hold true when the methods are applied to different assemblies from the car or other similar products. For collecting the S&R sound database in study II, cars from different segments were included and various test conditions were used. Thus, the outcomes are considered valid for a wide range of applications in the automotive industry. In study VI, the assumption made for decoupling the optimisation problem was falsified for a set of simplified generic geometries. This was done to enhance the generalisability of the method. In study II, the robustness of the proposed subjective listening test method was examined by calculating quality metrics such as self-consistency and concordance.
- *The efficiency of the proposed methods*: in study VI, the simulation time was the efficiency criterion and, in comparison to the baseline non-reduced model, the required computational time was reduced drastically, by 98%. In study VI, it was shown that for a large assembly with a complicated connection configuration, such as the side door assembly, by using the proposed two-stage optimisation method, the computational effort needed to find an optimised connection configuration was made affordable.
- *Applicability in the industry*: In all of the conducted descriptive and prescriptive studies included in this thesis, the models were either taken from the automotive study, such as in studies II and V, or tuned to replicate industrial models, such as in studies I, III and IV, or both, such as in study VI. Studies V and VI, present the proposed methods and illustrate the findings for industrial cases and describe the simulation setup. In study IV, the parameter study table can be used as a modelling guideline for nonlinear simulation of impact when studying the rattle events. The proposed sound quality metric in study III can be used to objectively evaluate the rattle sounds in the automotive industry. Nevertheless, the usefulness of the outcomes of studies III and IV need to be judged for industrial application by carrying out descriptive studies using industrial cases. The significance of considering temperature when physically evaluating S&R sounds was stressed in studies I and II. The outcome of study II can also be employed for comparing different test methods when planning for a physical

S&R evaluation.

5.4. QUALITY OF THE RESEARCH OUTCOMES

Validation and verification are defined differently when referred to in different contexts. However, in design research, validation is done to check if the product serves the purpose it was intended for. While by verification, one judges the credibility of the outcomes [50], [80].

5.4.1. Verification of the work carried-out

As Buur and Anderson [81] proposed, one important fold of checking the research quality is logical verification. Logical verification is about if the implemented approach in the research consistently, completely and coherently examining results in falsifying a theory. There shouldn't be conflicting elements within the research and established methods need to be implemented to secure coherency and completeness. All the studies performed in this work lie within the S&R prediction framework depicted in Figure 13. It was planned to address some of the elements contributing to each of the main three domains in this framework. By using this framework as a high-level description of the problem and by following the DRM research methodology it was attempted to maintain coherency among the different studies. Studies I, II and III were made in sequence to understand the phenomenon, identify the improvement potentials and propose solutions to address the identified gaps. The results of these studies complement and complete each other, and the stream of the studies lies under the first three stages of the DRM framework. The findings of these studies are not contradictory and support each other. The effect of temperature in studies I and II showed a similar pattern and also showed the significance of using the statistical measures and the psychoacoustic metrics for S&R classification. Studies IV and V both targeted the nonlinear simulation of S&R events. The witnessed drawback of using nonlinear simulations in study IV was addressed in study V. Study VI introduces a new application for geometric variation analysis in S&R prediction. This method can be combined with the common structural dynamic analysis methods to enrich the simulation process as outlined in the S&R prediction framework.

5.4.2. Validation of the findings in this work

For the research to be valid, it needs to address what it is intended to address. The other fold of the research quality, as Buur and Anderson [81] discussed, is validation by acceptance. The theories and outcomes are accepted and can be used by the industrial community and the scientific society within the field. The studies performed to date are either published in the form of peer-reviewed conference papers or are under-review for journal publication. The results have been presented at the conferences and forums and have been discussed with the experts within the field. Both in planning and conducting the research studies, experts from the industry were involved to ensure the relevance of the work to the needs within the industry. The results of the studies, their industrial application and relevance have been presented and discussed with the relevant stakeholders from the industry and the academic research group.

Winter [82] proposed validation be categorised as internal validity, external validity and construct validity.

- Internal validity deals with the matter that the causes of the outcome are studied correctly. It indicates that the parameters and variables within the boundaries of the study have a causal relationship. In most of the conducted studies, statistical measures were used to compare the results with other available methods or designs. The results were graphically presented in the form of different types of bar charts, contour plots and graphs. For studies I, III and IV, the experimental data were collected under laboratory conditions to have the contributing parameters under control and reduce the uncertainties. When virtual models were used (studies IV-VI), these were either validated with reference to the experimental data, or already validated virtual models were picked, to ensure that the system behaviour was as intended.

- External validity addresses the generalisability of the outcomes of the research beyond the setup of the studies. In the conducted studies, different measures were taken to ensure the generalisability. In studies I, III and IV, a generic representation of an assembly in a car was used. Thus, the problem under study was not limited to a specific part or assembly from a car. Rather, the results and conclusions can be extended to products possessing similar mechanisms. In study II, the test subjects were picked from different segments of the product portfolio and a comprehensive test plan was picked. Therefore, the conclusions made are valid over a wide range of products in a wide span of verification methods, and are not limited only to a specific car model in a specific verification method. Although study V demonstrates the application in a specific sub-system in a car, the conclusions hold true at least for all the subsystems with mechanical properties within the same range. Most of the in-cabin subsystems, possess components and connection configurations, conceptually similar to the studied case. In study VI, the method was initially developed using generic simplified geometries and the hypothesis was falsified for these generic geometries. This makes the findings extendable not only for a wide range of assemblies in the car but also to other products with geometrical assemblies belonging to the studied simplified categories. When specific subsystems were selected to conduct a study, this selection was always based on field studies and interviews with experts to pick a relevant subsystem that could be a good representative of the phenomenon under study.
- Construct validity concerns the generalised claims made as the outcome based on the theoretical concepts governing the problem and if the claims relate to the intended purpose of the research. While checking the construct validity of the research work, the delimitations of the research are therefore the key threatening elements to be considered. In studying S&R problems, special consideration should be taken for different contributing parameters in the phenomenon under study, otherwise the authenticity of the outcomes might be endangered. Using controlled laboratory conditions was one of the measures to minimise this risk and enable enhanced control over the contributing parameters. Measurements were always made more than once, to reduce the effect of unknown parameters on the results. Measurements were always screened for presence of noise and uncertainties and the conclusions were made knowing this risk or taking measures to eliminate them. When subjective tests were carried out, consistency and concordance measures were monitored to estimate the confidence level in the findings.

Sargent [80] proposed a validation and verification plan for simulation models in design research, with defined boundaries between activities done in the real world and the simulation world. In short, the credibility of a simulation model is reflected in the degree of confidence in using a model and in the information retrieved from it. This stepwise approach was followed wherever simulation models were used in this research, to ensure the credibility of the results.

5.5. POSITIONING THE RESEARCH OUTCOMES WITHIN THE FIELD

The elements included in the S&R cause and effect diagram, in Figure 13, have been identified through literature, field and descriptive studies. A simplified depiction of the interactions among different S&R modelling and simulation activities is given in Figure 14. By including the outcomes from the descriptive and prescriptive studies that were conducted and are planned to be conducted during this PhD, the proposed framework needs to be evolved into the form of a prediction process diagram. This prediction process diagram will include different analysis methods and for use in industrial applications and remains as future work.

One of the contributing elements to the generation of S&R from the cause and effect diagram is the geometric variation. This was addressed in this thesis. In this work [77], a method for the involvement of geometric variation analysis in the design phase for reducing the risk for S&R generation is proposed. As opposed to the passive use of the geometric variation analysis data in CPA analysis in the pre-design-freeze phases, as described in [31], or to adjust the gap criteria as suggested in [83], or employed in [84], the proposed method in this work can be actively employed during the design phase for attribute balancing in optimisation loops. A future work topic may then be to study the S&R risk by analysing the system response in terms of structural dynamics and geometric variation as a result of the connection configuration changes using the proposed optimisation approach.

With regard to the research conducted in the assessment criteria domain, the employment of the proposed subjective listening test method [28] for designing a rattle sound quality metric yielded experimental data with high self-consistency and concordance levels. In contrast, the use of available subjective test methods [27], as employed in a descriptive study [30] by the author, did not produce robust results. Compared to the commonly used standard acoustic and psychoacoustic metrics [19]–[21], it was shown in the literature that the use of other psychoacoustic metrics [23], [24] and statistical measurements of these [22] improves the S&R evaluation process. In this thesis, the use of a new statistical measure [28] to adjust the standard psychoacoustic metrics showed successful prediction, lying within the 95% confidence intervals of the observation data. However, both the proposed subjective listening test method and the psychoacoustic metric require to be further evaluated through descriptive studies for industrial applications and generalisability.

As suggested in previous studies [9], [37], [38], [85], to increase the accuracy of the prediction process of S&R events, structural response kinetics and kinematics need to be included in the S&R evaluation metrics. Thus, the modelling setup and the influence of the modelling parameters on the response accuracy of the system in a nonlinear simulation of rattle events was investigated in [57], but as observed in [57], nonlinear simulation of S&R demands high computational resources. Nevertheless, this drawback was not addressed in previous studies [36] on the nonlinear simulation of S&R events. In this research, it was shown [70] that by substructuring the model to linear and nonlinear regions and applying the standard CMS method of Craig-Bampton [61], satisfactory results can be achieved. Previous applications of the Craig-Bampton CMS method in nonlinear problems have mainly been limited to geometric nonlinearities [63]–[67]. Although in previous studies [63]–[67] this application for models with a large number of interface DOFs or when nonlinearities appear in the vicinity of the interfaces has not appeared promising, in study V [70] it was shown that in S&R nonlinear simulation, the boundary for substructuring the model can be defined close to the nonlinear region for the sake of computational efficiency.

6

CONCLUSIONS

This chapter summarises the research work conducted to date and the outcomes of the work, as well as briefly providing an outlook for the continuation of the work.

6.1. CONCLUSIONS

As for all other product attributes, the employment of more quantified prediction approaches and verification assessment methods to treat S&R sounds has grasped the attention of the automakers. However, the insufficient knowledge available about the mechanisms behind the generation of these annoying noises, in addition to the technical hurdles to efficiently integrate the proposed methods in the industry, have been the significant stoppers to achieve this goal. Thus, determination of a framework to support the exploration of the causes of the phenomenon and capturing their impact remains a necessity in the industry. The objective of this research was to address this problem by identifying the framework for predicting S&R sounds in the automotive industry, to further investigate and improve the elements in different domains of the framework and to show the applicability of the proposed methods in the industry.

To date, a prediction framework in the form of a cause and effect diagram, encompassing the three domains of the assessment criteria, modelling and simulation and system excitation and the contributing elements in each domain has been identified in this research work. Some of the available methods have been further explored and enhanced through the conducted studies. These include:

- A subjective listening test method to be used for designing sound quality metrics has been proposed. The method aims at enhancing the confidence level of the subjective testing methods in eliciting the users' perception of the quality of the product. The method was used to design a rattle sound quality metric by employing new statistical measures of the psychoacoustic characteristics of the sound.
- Rattle sound is caused by impact events. To better capture the kinetics and kinematics of the event, a nonlinear modelling approach for the impact events has been studied. The parameters involved in the nonlinear model were studied for their effect on the rattle events.
- The previous study, in agreement with the prevailing notion among the engineers regarding the virtual simulation, supports the fact that increased modelling complexity demands increased computational cost. To overcome this drawback, the application of a model order reduction method in nonlinear S&R simulation was studied. It was shown that for the sake of increased efficiency, the substructure boundaries between linear and nonlinear regions can be defined in the vicinity of the nonlinear regions where S&R events happen.
- An optimisation strategy was introduced to involve the geometric variation analysis in determining the connection configuration in an assembly to minimise the risk for the generation of S&R. The proposed optimisation method involves a two-stage optimisation for the rattle direction and then fully restraining the degrees of freedom among the parts in an assembly. This method decreases the optimisation time, therefore making it affordable for large assemblies inside the car cabin. The method was employed to optimise the connection configuration in a side door assembly as well as a panel in an instrument panel of a passenger car.

In some of the descriptive and prescriptive studies, generic models and samples were used, such as the sound samples from the rattle producing machine, the single beam model used in the nonlinear rattle simulation or the generic geometries used through the development of the optimisation method for the geometric variation analysis. Although this can be interpreted as a limitation to the real application in the industry, it supports the generalisation of the outcome. The findings are not bound to a specific case and are less influenced by the uncertainties in the modelling and the limitations imposed by the specific setup. In contrast, in the other studies, where the subject under study was a subsystem of a car, the cases were taken from the known problematic subsystems. Thus, the worst cases or common areas where the phenomenon happened in the product, or is expected to happen in similar products in future were studied.

6.2. FUTURE WORK

To continue the work, further explorative studies are planned to investigate other elements in the identified cause and effect diagram for S&R prediction. These planned studies are briefly listed below and are illustrated together with the already conducted studies in Figure 23.

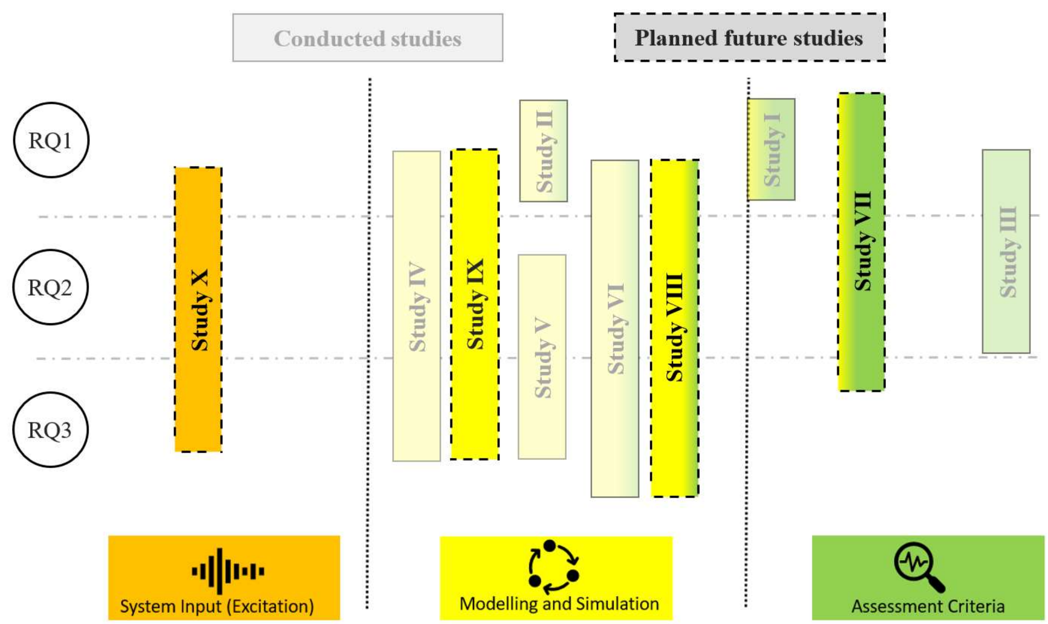

Figure 23: Planned studies as future work to be covered during the PhD together with the finished studies presented in this thesis.

- Study VII: Enhanced structural dynamics metrics for S&R quantification based on the collected kinetic and kinematic parameters from the system response.
- Study VIII: Inclusion of the dynamic response of the system together with the geometric variation in the proposed optimisation framework. This work demands a method to quantify the dynamic response of the system and then use it to study the interacting effects of the two properties of the assembly in a multi-disciplinary optimisation process.
- Study IX: Nonlinear modelling of stick-slip events for squeak simulation and prediction.
- Study X: Investigation of a method for enhancing the efficiency of the system excitation signals for S&R evaluation.

REFERENCES

[1] K. Stylidis, C. Wickman, and R. Söderberg, “Defining Perceived Quality in the Automotive Industry: An Engineering Approach,” *Procedia CIRP*, vol. 36, pp. 165–170, 2015.

[2] M. Trapp and F. Chen, *Automotive buzz, squeak and rattle : mechanisms, analysis, evaluation and prevention*. Butterworth-Heinemann/Elsevier, 2012.

[3] A. Sprenger, “Customer Perception of S&R Noises,” in *International Squeak and Rattle Forum*, 2017.

[4] Alistair Charlton, “Read while you drive: Volvo Concept 26 is the autonomous car interior of the future,” *International Business Times*, 2015.

[5] F. Kavarana and B. Rediers, “Squeak and Rattle - State of the Art and Beyond,” in *Noise & Vibration Conference & Exposition*, 1999.

[6] M. Harrison, *Vehicle Refinement: Controlling Noise and Vibration in Road Vehicles*. Warrendale, PA: Elsevier Ltd on behalf of SAE International, 2004.

[7] X. Wang, Ed., *Vehicle noise and vibration refinement*. Cambridge: Woodhead Publishing, 2010.

[8] M. J. Crocker, *Handbook of Noise and Vibration Control*. New Jersy, 2007.

[9] A. Akay, “A review of impact noise,” *J. Acoust. Soc. Am.*, vol. 64, no. 4, pp. 977–987, 1978.

[10] Karl Ulrich, Steven Eppinger, and Maria C. Yang, *Product Design and Development*, 7th ed. New York: McGraw-Hill, 2020.

[11] R. G. Cooper, “Stage-gate systems: A new tool for managing new products,” *Business Horizons*, vol. 33, no. 3. Elsevier, pp. 44–54, 01-May-1990.

[12] Ken W. Collier, *Agile Analytics: A Value-Driven Approach to Business Intelligence and Data Warehousing*, 1st ed. Addison-Wesley Professional, 2011.

[13] E. L. Peterson and M. Sestina, “Using Rumble Strips for Buzz, Squeak and Rattle (BSR) Evaluation of Subsystems or Components.” SAE International, 2007.

[14] R. S. Brines, L. G. Weiss, and E. L. Peterson, “The Application of Direct Body Excitation Toward Developing a Full Vehicle Objective Squeak and Rattle Metric.” SAE International, 2001.

[15] “hällered proving ground Facilities & Safety Regulations.” Volvo Car Corporation, 2017.

[16] “SSP 04 Stick-Slip Test Bench Manual.” Ziegler-Instruments GmbH, p. 73, 2016.

[17] C. Mercer, “Acceleration, Velocity and Displacement Spectra – Omega Arithmetic,” 2006.

[18] H. (Hugo) Fastl and E. Zwicker, *Psychoacoustics : facts and models*. Springer, 2007.

[19] M. Jay, Y. Gu, and J. Liu, “Excitation and Measurement of BSR in Vehicle Seats,” in *SAE Technical Paper*, 2001.

[20] G. C. Grenier, “The Rattle Trap,” in *SAE Technical Paper*, 2003.

[21] H. H. Na, H. Park, H. Lee, and B. Choi, “A Study on the Rattle Index from a Vehicle Door Trim under Audio System Inputs,” in *SAE Technical Paper*, 2013.

[22] J. Lee, S. Lee, Y. Kwak, B. Kim, and J. Park, “Temporal and spectral characteristics of BSR noises and influence on auditory perception,” *J. Mech. Sci. Technol.*, vol. 29, no. 12, pp. 5199–5204, Dec. 2015.

[23] M. A. Trapp and K. K. Hodgdon, “An evaluation of friction and impact induced

acoustic behaviour of selected automotive materials, Part II: impact induced acoustics," *Int. J. Veh. Noise Vib.*, vol. 4, no. 1, 2008.
[24] S.-H. Shin and C. Cheong, "Experimental characterization of instrument panel buzz, squeak, and rattle (BSR) in a vehicle," *Appl. Acoust.*, vol. 71, no. 12, pp. 1162–1168, Dec. 2010.
[25] U. Widmann, "A psychoacoustic annoyance concept for application in sound quality," *Acoust. Soc. Am. J.*, vol. 101, pp. 3078-, 1997.
[26] J. Starck and J. Pekkarinen, "Industrial impulse noise: Crest factor as an additional parameter in exposure measurements," *Appl. Acoust.*, vol. 20, no. 4, pp. 263–274, Jan. 1987.
[27] N. Otto, S. Amman, C. Eaton, and S. Lake, "Guidelines for Jury Evaluations of Automotive Sounds," in *Noise & Vibration Conference & Exposition*, 1999.
[28] M. Bayani, C. Wickman, and R. Söderberg, "Analysis of sound characteristics to design an annoyance metric for rattle sounds in the automotive industry," *Int. J. Veh. Noise Vib.*, vol. (submitted, 2019.
[29] N. Kousgaard, "The application of binary paired comparisons to listening tests," in *Symposium on Perception of Reproduced Sound*, 1987, pp. 71–80.
[30] M. Bayani, C. Wickman, and R. Söderberg, "Effect of temperature variation on the perceived annoyance of rattle sounds in the automotive industry," in *23rd International Congress on Acoustics*, 2019, pp. 4397–4404.
[31] H. Daams, "Squeak and Rattle Prevention in the Design Phase Using a Pragmatic Approach," in *SIAT 2009*, 2009.
[32] H. Viktorsson, "Digital Pre Assembly number six, DPA[6], Proprietary," Gothenburg, 2019.
[33] J. N. Reddy, *An introduction to the finite element method*, 2nd ed. New York: McGraw-Hill, 1993.
[34] J. Weber and I. Benhayoun, "Squeak & Rattle Correlation in Time Domain using the SAR-LINE^{TM} Method," *SAE Int. J. Passeng. Cars - Mech. Syst.*, vol. 5, no. 3, pp. 1124–1132, Jun. 2012.
[35] E. Caamaño, I. Lama, A. Rousounelos, and J. Viñas, "Improved methodology for squeak & rattle analysis with Abaqus and correlation with test results," in *SIMULIA Customer Conference*, 2011.
[36] E. M. Kreppold, "A Modern Development Process to Bring Silence Into Interior Components," in *SAE Technical Paper*, 2007.
[37] J. Her, S.-R. Hsieh, W. Li, and A. Haddow, "Quantitative Prediction of Rattle in Impacting System," in *SAE Noise and Vibration Conference and Exposition*, 1997.
[38] J. M. Choi, S. J. Lyu, Y. S. Seol, I. K. Jun, and C. Yi, "A BSR Analytical Evaluation Method Considering the Sound Quality Perception," in *SAE 2013 Noise and Vibration Conference and Exhibition*, 2013.
[39] Z. Shen, G. Ameta, J. J. Shah, and J. K. Davidson, "A comparative study of tolerance analysis methods," in *Journal of Computing and Information Science in Engineering*, 2005, vol. 5, no. 3, pp. 247–256.
[40] R. Söderberg and L. Lindkvist, "Computer aided assembly robustness evaluation," *J. Eng. Des.*, vol. 10, no. 2, pp. 165–181, 1999.
[41] J. Gao, K. W. Chase, and S. P. Magleby, "Generalized 3-D tolerance analysis of mechanical assemblies with small kinematic adjustments," *IIE Trans.*, vol. 30, no. 4, pp. 367–377, 1998.
[42] W. Cai, S. J. Hu, and J. X. Yuan, "Deformable sheet metal fixturing: Principles, algorithms, and simulations," *J. Manuf. Sci. Eng. Trans. ASME*, vol. 118, no. 3, pp.

318–324, Aug. 1996.
[43] S. Charles Liu and S. Jack Hu, “Variation simulation for deformable sheet metal assemblies using finite element methods,” *J. Manuf. Sci. Eng. Trans. ASME*, vol. 119, no. 3, pp. 368–374, Aug. 1997.
[44] C. A. Coello Coello, G. B. Lamont, and D. A. Van Veldhuisen, *Evolutionary algorithms for solving multi-objective problems*. Springer, 2007.
[45] J. Ölvander, “A Survey of Multiobjective Optimization in Engineering Design,” Linköping, 2000.
[46] C. M. Fonseca and P. J. Fleming, “Genetic Algorithms for Multiobjective Optimization: Formulation, Discussion and Generalization,” in *Proceedings of the Fifth International Conference on Genetic Algorithms*, 1993, pp. 416–423.
[47] D. E. Goldberg, *Genetic Algorithms in Search, Optimization and Machine Learning*, 1st ed. Boston: Addison-Wesley Longman Publishing Co., Inc., 1989.
[48] C. M. Eckert, M. K. Stacey, and P. J. Clarkson, “The spiral of applied research: A methodological view on integrated design research,” in *Proceedings of the 14th International Conference on Engineering Design (ICED’03)*, 2003.
[49] L. Blessing, “What Is This Thing Called Design Research?,” in *Proceedings of ICED 03, the 14th International Conference on Engineering Design*, 2003.
[50] L. T. M. Blessing and A. Chakrabarti, *DRM, a Design Research Methodology*. London: Springer London, 2009.
[51] M. Cantamessa, “Design research in perspective - a meta-research on ICED 97 and ICED 99,” in *13th, International conference on engineering design*, 2001, pp. 29–36.
[52] Y. K. Kim, H. Kwon, W. J. Choi, C. S. Woo, and H. S. Park, “Environmental considerations of plastic behaviors for automobile applications,” *Procedia Eng.*, vol. 10, pp. 1029–1034, Jan. 2011.
[53] M. Trapp and R. Pierzecki, “Squeak and Rattle Behavior of Elastomers and Plastics: Effect of Normal Load, Sliding Velocity, and Environment,” in *SAE 2003 Noise & Vibration Conference and Exhibition*, 2003.
[54] A. Svensson and J. Hasselström, “Fundamental physical testing of rattle - Design and evaluation of a rattle producing test rig,” Chalmers University of Technology, Göteborg, 2017.
[55] V. Kulkarni and S. M. Nairy, “Squeak and Rattle Sound Database and Acoustic Characterisation,” Chalmers University of Technology, 2019.
[56] A. K. Sen and M. S. Srivastava, *Regression analysis : theory, methods and applications*. Springer-Verlag, 1990.
[57] M. Bayani, A. P. Székely, N. Al Hanna, H. Viktorsson, C. Wickman, and R. Söderberg, “Nonlinear modelling and simulation of impact events and validation with physical data,” in *ISMA 2018, International Conference on Noise and Vibration Engineering*, 2018, pp. 4299–4313.
[58] A. P. Székely and N. Al Hanna, “Nonlinear Modelling and Simulation of Impact Events and Validation with Experimental Test,” KTH ROYAL INSTITUTE OF TECHNOLOGY, 2018.
[59] W. C. Hurty, “Vibrations of Structural Systems by Component Mode Synthesis.” 1960.
[60] R. R. Craig and M. C. C. Bampton, “Coupling of substructures for dynamic analyses,” *AIAA J.*, vol. 6, no. 7, pp. 1313–1319, 1968.
[61] R. R. Craig, “Coupling of substructures for dynamic analyses: An overview,” in *Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, 2000, vol. 5, pp. 3–14.
[62] D. J. Rixen, “A dual Craig-Bampton method for dynamic substructuring,” *J. Comput.*

Appl. Math., vol. 168, no. 1–2, pp. 383–391, Jul. 2004.
[63] L. Wu, "Model order reduction and substructuring methods for nonlinear structural dynamics," TU Delft, 2018.
[64] P. M. A. Slaats, J. de Jongh, and A. A. H. J. Sauren, "Model reduction tools for nonlinear structural dynamics," *Comput. Struct.*, vol. 54, no. 6, pp. 1155–1171, Mar. 1995.
[65] J. Barbič and Y. Zhao, "Real-time Large-deformation Substructuring," *ACM Trans. Graph.*, vol. 30, no. 4, pp. 1–8, Jul. 2011.
[66] P. Tiso, E. Jansen, and M. Abdalla, "Reduction method for finite element nonlinear dynamic analysis of shells," *AIAA J.*, vol. 49, no. 10, pp. 2295–2304, Oct. 2011.
[67] O. Weeger, U. Wever, and B. Simeon, "Nonlinear frequency response analysis of structural vibrations," *Comput. Mech.*, vol. 54, no. 6, pp. 1477–1495, 2014.
[68] T. Abrahamsson, *Calibration and Validation of Structural Dynamics Models*, First. Gothenburg: Chalmers University of Technology, 2012.
[69] "MATLAB R2018a Documentation." Mathworks, 2018.
[70] M. Bayani, A. Basheer, F. Godborg, R. Söderberg, and C. Wickman, "Finite Element Model Reduction Applied to Nonlinear Impact Simulation for Squeak and Rattle Prediction," in *11th International Styrian Noise, Vibration & Harshness Congress: The European Automotive Noise Conference*, 2020.
[71] P. J. Hughes, W. Scott, W. Wu, R. J. Kuether, M. S. Allen, and P. Tiso, "Interface Reduction on Hurty/Craig-Bampton Substructures with Frictionless Contact," in *Nonlinear Dynamics, Volume 1: Proceedings of the 36th IMAC, A Conference and Exposition on Structural Dynamics 2018*, 2019, pp. 1–16.
[72] R. Söderberg, K. Wärmefjord, L. Lindkvist, and R. Berlin, "The influence of spot weld position variation on geometrical quality," *CIRP Ann. - Manuf. Technol.*, vol. 61, no. 1, pp. 13–16, Jan. 2012.
[73] S. S. Gosavi, "Automotive Buzz, Squeak and Rattle (BSR) Detection and Prevention," in *SAE Technical Papers*, 2005, vol. 2005-January, no. January.
[74] R. Söderberg, L. Lindkvist, K. Wärmefjord, and J. S. Carlson, "Virtual Geometry Assurance Process and Toolbox," *Procedia CIRP*, vol. 43, pp. 3–12, 2016.
[75] W. Cai, "Fixture optimization for sheet panel assembly considering welding gun variations," *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.*, vol. 222, no. 2, pp. 235–246, Feb. 2008.
[76] S. Dahlstrom and L. Lindkvist, "Variation simulation of sheet metal assemblies using the method of influence coefficients with contact modeling," *J. Manuf. Sci. Eng. Trans. ASME*, vol. 129, no. 3, pp. 615–622, Jun. 2007.
[77] M. Bayani, C. Wickman, L. Lindkvist, and R. Söderberg, "Squeak and rattle prevention by geometric variation management using a two-stage evolutionary optimisation approach," in *Proceedings of the ASME International Mechanical Engineering Congress and Exposition*, 2020.
[78] "RD&T Software Manual." RD&T Technology AB, Molndal, Sweden, 2019.
[79] E. Rigoni and A. Turco, "Metamodels for fast multi-objective optimization: Trading off global exploration and local exploitation," in *8th International Conference on Simulated Evolution and Learning, SEAL*, 2010, vol. 6457 LNCS, pp. 523–532.
[80] R. G. Sargent, "Verification and validation of simulation models," *J. Simul.*, vol. 7, no. 1, pp. 12–24, Feb. 2013.
[81] J. Buur, "A theoretical approach to mechatronics design," Technical University of Denmark, 1990.
[82] G. Winter, "A Comparative Discussion of the Notion of 'Validity' in Qualitative and

Quantitative Research," *Qual. Rep.*, vol. 4, no. 3, pp. 1–14, Mar. 2000.
[83] B. P. Naganarayana, S. Shankar, V. S. Bhattachar, R. S. Brines, and S. R. Rao, "N-hance: Software for identification of critical BSR locations in automotive assemblies using finite element models," in *SAE Technical Papers*, 2003.
[84] I. Benhayoun, F. Bonin, A. de Faverges, and J. Masson, "Simulation and Optimization Driven Design Process for S&R Problematic - PSA Peugeot Citroën Application for Interior Assembly," in *Noise and Vibration Conference and Exhibition*, 2017.
[85] M. Fard, A. Subic, L. Lo, and F. K. Fuss, "Characterisation of vehicle seat rattle noise from seat structural dynamics," *Int. J. Veh. Noise Vib.*, vol. 10, no. 3, pp. 226–240, Jan. 2014.