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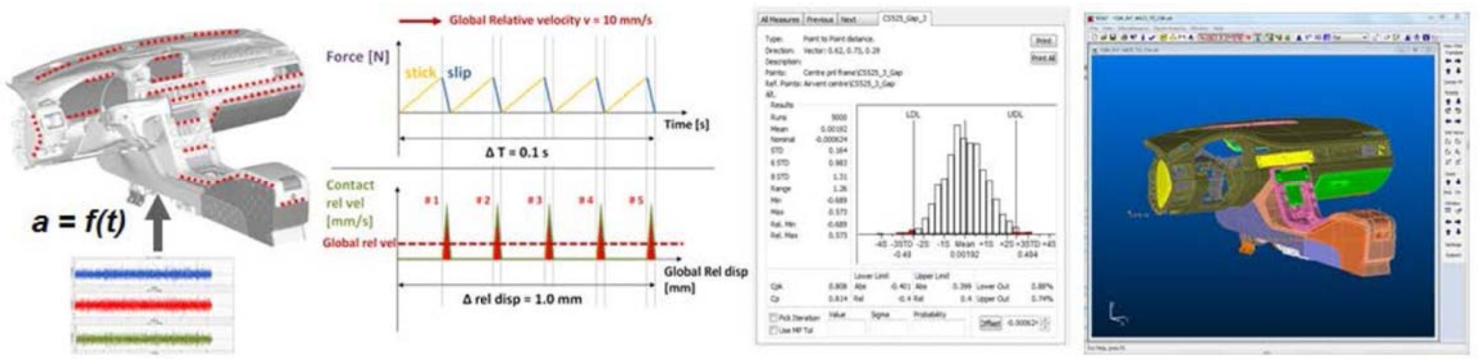

Heat dependent squeak & rattle simulation using the E-line method in combination with variation simulation

Master's Thesis in Product Development

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Technical report

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ABSTRACT

This is the report of a thesis work performed at Volvo Cars Corporation together with Chalmers University of Technology. The purpose is to investigate whether varying temperature affects squeak and rattle. The centre stack of a Volvo V40 car was chosen as the critical system to be investigated in this thesis.

The primary objective of this master thesis work has been to develop a methodology with different software interface. This is to analyse the impact of temperature and vibration load on different components that affects the Perceived Quality in cars. This method should make the development process efficient by identifying critical Rattle & Squeak areas in new design cars. The simulation and analysis work is realistic as it involves original components and functioning environment. Thus it can decrease the number of physical prototypes. To perform the complete analysis, this thesis work has a connection between variation analysis in RD&T with the modal transient analysis in Nastran. The entire method can be conducted at different temperatures for different thickness materials including composites. Also all possible areas can be analysed to good effect.

The variations due to manufacturing were analysed for different components in the software RD&T. Next the variations due to vibrations were analysed in the software Nastran. Both of these have been conducted before at VCC but they have been only for verification of requirements mainly at room temperature. It was assumed that if the methods could be combined and results are analysed, the designers could have an idea about squeak and rattle conditions in the designs. It was presumed that the properties of the components vary with temperature and humidity. The temperature range expected when the car is in use during its entire lifetime is -40°C to 80°C. Therefore the selected components were simulated for this range. However, humidity has not been considered in this thesis work.

The results obtained from the simulations for the selected critical system were analysed. From the observations it has been concluded that temperature does affect squeak and rattle for this case. Several verifications have been conducted to check the robustness of the method and have been mentioned. But no experimental validation was done and could be considered as future scope of work.

The software packages RD&T and Nastran are considered to be efficient tools for representing reality and have been considered as reliable for analysing and verifying automotive components.

Keywords:
Squeak, Rattle, RD&T, Nastran, Static displacement, Dynamic displacement, Mean Peak to Peak, Relative Displacement, Stick-Slip measurement.

PREFACE

This thesis work was carried out during spring 2014 at the Ergonomics & Craftsmanship department, 91300, at VCC (Volvo Cars Corporation in Torslanda), Gothenburg in collaboration with Chalmers University of Technology. The thesis work corresponds to 30 credits and is a conclusion to the masters in Product development for the authors.

For the entire duration of the thesis work, our industrial supervisors Dr Casper Wickman and Jens Weber have been valuable sources of information and knowledge at VCC. Both our supervisors encouraged us through regular meetings and guided us to conduct various verifications tasks in the thesis. The various facets of the project could only be investigated because we had continuous support from our supervisors who shared their experience and the expertise when it was required. We would like to thank you for our association and the time spent with you at VCC.

We would like to thank our examiner, associate professor and RD&T expert Lars Lindkvist, for providing us the guidance and technical knowledge on various occasions. Without his technical expertise and RD&T knowledge the implementation of the project would not have been possible. On many occasions he inspired us with quick responses and user friendly solutions for problems which seemed rather complex.

Further we would like to thank our supervisor Samuel Lorin for helping us understand the basics, providing us support whenever we desired, discussing the progress of the project and providing feedback on the work. It would have been difficult to meet the planned schedules and project targets without his help.

We would also like to thank Tommy Johansson for providing us the time and support for the experimental part which was necessary for the project.

We are also thankful to Christer Nilsson, Honarpardaz Madhi and Fabio for helping us with valuable inputs and answering our questions which has been of great help.

Finally, we would like to thank our families and friends for their love and support which made the entire time at VCC and at Chalmers memorable.

Gothenburg, June 2014

Ardhendu Prasad Nanda and Sebastian Mannfolk

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1 INTRODUCTION

Volvo Cars Corporation is one of the world's most prominent automotive manufacturer and developer with focus on high quality and dependability. It is important for the quality to be perceived as good as even the smallest squeak can impair the image of the vehicle, no matter how good the structural and functional qualities are. The department responsible for the visual, haptic and auditory experience is called Perceived Quality.

While some aspects can be simulated today, Volvo Cars Corporation mainly relies on experience of employees and tests on prototypes when it comes to designing for perceived quality. The more accurate the simulations can be made the more errors can be identified early on, when changes are cheaper and easier to implement. This is called a simulation driven design process and it aims for reducing lead time and cost. This master thesis focus on one area needed in order to achieve such a design process by identifying if and how squeak and rattle are affected by varying temperature.

Squeak and rattle are two phenomena handled in the Solidity department, a subdivision of Craftsmanship and Ergonomics at Volvo Cars. At Chalmers Squeak & Rattle are included in Perceived Quality. Rattle is the sound from the impact of adjacent parts that are normally not in contact, due to external loads such as vibrations. Squeak occurs when two parts in contact slide against each other with sufficient velocity and normal force. Generally, squeak and rattle simulations have been conducted at room temperature only. There is currently no developed method to analyse the effect of thermal changes on squeak and rattle in components. In this thesis, squeak and rattle conditions due to thermal change are investigated. Thermal expansion and changes in elasticity have both been considered when simulating with finite element models. This has been done in several software packages, such as RD&T, Ansa, Nastran and Matlab, in order to identify the squeak and rattle.

1.1 Background

Variation during manufacturing is not desired, the precision and reliability of tools and fixtures will never be perfect and thus all produced parts will not be identical. When specifications are set tolerances are given to the geometry to dictate allowed limits for the variation. The software RD&T, developed by Lars Lindkvist and Rikard Söderberg at RD&T Technology, allows for simulation of such variations and is used by Volvo Cars Corporation.

Squeak and rattle at room temperature have previously been simulated at Volvo Cars Corporation. It uses a method called E-line which identifies the variation due to external loads such as vibrations. The E-line is created on the model in the pre-processor software Ansa, run in the processing software Nastran and then the result is post-processed in Matlab. Similar to E-line, a feature called Seam has also been developed in RD&T and in this master thesis they have been used together for the first time. In order to determine squeak and rattle, both variations due to manufacturing and external loads are combined.

Components expand at elevated temperatures and compress at lowered temperatures (Stratasys 2008). The amount of expansion or compression depends on the thermal expansion coefficient of the materials. For an assembled product consisting of several components with different material, subsequently with different thermal expansion coefficients the relation and position between adjacent parts can be affected. In addition to a change in size the temperature also affects Young's modulus.

1.2 Hypothesis

When simulating for squeak and rattle, is it necessary to consider the temperature range in the user phase, the user phase considers the temperature range from -40 °C to 80 °C?

1.3 Purpose

Perceived Quality of a product is high if the performance is good and remains the same irrespective of user temperature conditions. In order to improve the Perceived quality of automotive components at different temperature and achieve a good simulation driven design process it is necessary to know whether to factor in temperature or not. This thesis is performed in order to investigate if it is needed or not to include temperature when simulating for squeak and rattle.

1.4 Delimitations

In this project the centre stack of a Volvo V40 is investigated to understand if temperature has any significant effect of squeak and rattle. A positive response to the hypothesis would confirm it to be true in similar cases as well. On the other hand, a negative response would not indicate that temperature variations should be ignored completely for other similar cases. The temperature range analysed is limited to -40 °C to 80 °C since this is the estimated service temperature of the vehicle and is a requirement of the vehicle.

1.5 Objectives

Academic objective

- To test the hypothesis and understand whether variation in temperature range (from -40°C to 80°C) should be considered when evaluating squeak and rattle in automotive systems.

Industrial objective

- Define technical requirements/ specifications that are necessary for squeak and rattle simulation at different temperatures.

2 THEORY

This section includes the theory of geometry assurance which is needed for maintaining optimum perceived quality. Therefore robust design and tolerance management has been described. Next, the finite element method (FEM) theory and variation simulation theory has been addressed. The basic concept of the project that is "squeak and rattle" has been outlined along with the theory at the end.

2.1 Quality

Quality is one of the factors that is important for a product to meet the customers' expectations. In fact, the recent developments have been to focus on how the products are perceived by the customers. A term used by Garvin for the first time called perceived quality, has been the result of this development (Garvin 1984). The perceived quality takes into account visual, haptic feedback, sound, smell and external factors. The main focus of this research has been to address the sound quality by analysing squeak and rattle. It is important for the customers that they have the same pleasant experience with the products under different conditions. Temperature is a parameter which can affect perceived quality. As quality needs to be assured in the temperature span of use, all terms associated with analysing temperature impact have been described in this chapter.

2.2 Robust Design

In order to ensure that the product quality meets the customers' expectations, the audible effects due to manufacturing variation, environment and user conditions should be minimized. When products are produced in mass, the manufactured parts are not identical. But the focus on minimizing variation can increase developmental and later manufacturing costs significantly which is undesirable. Therefore robust design is one of the practices, where the product provides the same experience to the user in spite of variation, environmental effects or user conditions. (Forslund 2011). This is done by reducing the effect of variation and other conditions by simulating the product in design and concept phase even before manufacturing. To minimize the performance loss with fluctuating everyday conditions, robust design is generally followed in automotive companies and the conditions suitable for robust design has been shown in figure 1 below.

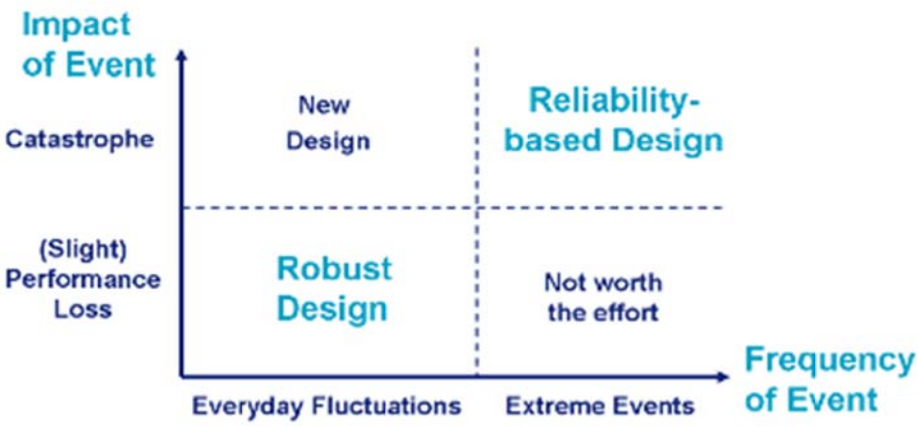


Figure 1: Conditions for Robust design **(Forslund 2011)**

The process of simulating a product, with the help of Computer Aided Engineering software packages to develop a robust product, generally saves material and money for the Original Equipment Manufacturer (OEM). Some of the advantages of using Computer aided Engineering are mentioned below (Johanson 1993).

1. It helps to refine designs based on simulated results.
2. Simulation results and test results can be compared to validate the performance of the simulation process.
3. A single server can store all the data, processes and models which can be accessible to designers and engineers working in different areas. In this way they can work together in creating a masterpiece without necessarily coming into physical contacts with one another
4. It allows engineers and designers to make changes in their designs during early stages, without affecting the manufacturing or prototyping costs.
5. It reduces cost of production.
6. It reduces the lead time of production.

2.3 Geometry Assurance & Tolerance management

Geometry Assurance is the field of studies which aims at reducing the effect of variation by increasing the precision of different functional attributes of the product. It includes a set of activities in the concept phase, verification and production phase to minimize the effect of geometrical variations. (Söderberg et al. 2006)

In products, geometrical variation occurs due to variation in the tooling during manufacturing processes and also due to part variations because of different positioning systems (Söderberg et al. 2006). In order to obtain the manufactured products as desired, requirements are set on the parts and fixtures in form of limits called tolerances.

2.3.1 Tolerance

A tolerance is defined as the range of variation that is allowed in a component with specified dimension or locating system. This is without affecting the structural integrity, operating capability or impinging components (Ariyo 2004). When limits are applied on the dimensions of the parts, they are called dimensional tolerances and when applied on the orientation or location of the parts in a subassembly, they are called geometrical tolerances (Huang 2008). Generally tighter tolerances increases the manufacturing cost of the product and should be avoided.

2.3.2 Variation Simulation Theory

Variation simulation in the design phase is an important tool to predict the properties of different design parameters. The variation, due to part tolerance and positioning tolerance, is simulated to assure that requirements are fulfilled in the final product.

2.3.3 Rigid and non-rigid simulation

In a rigid body simulation, the parts are assumed not to deform. This is because the rigid body simulations can be performed in less time and do not depend on the material properties of the parts. Considering part and assembly variations in the assembly, points are chosen on the parts to be observed. These sets of points are assigned a property (e.g. gap, flush etc.) to be measured which are called *measures*. RD&T provides a platform where rigid bodies can be imported as VRML files. The variation simulation analysis and contribution analysis can be performed on these parts by selecting various measures like flush and gap measures. A contribution analysis is conducted in order to find out how large impact various tolerances have on measures.

Contribution for the Measure: Seam 1_Gap_1070

Type: Point to Point distance.
Direction: Vector: 0.00, 0.00, 1.00
Description:
Points: CS_Inner\Node12409043
Ref. Points: CS_Ring\Node18602493
Alt. Asbl.:

Part	Point/Arc	Tolerance	Range	Contr.	Tol. Dir.SubSystem
#Tolerance Group#	[1_I_T]	1_I_T_Tot	1.0	49.7%	0.1, 0.1, 1.0
#Tolerance Group#	[1_R_T]	1_R_T_Tot	1.0	49.7%	0.1,-0.1, 1.0
CS_Inner	Node12409043	1_I_T_Rel	0.1	0.2%	0.0, 0.0, 1.0
CS_Ring	Node18602493	1_R_T_Rel	0.1	0.2%	0.0, 0.0, 1.0
Fixture02	SubAssy01_Node12412559_2	Fixture02_SubAssy01_Node12412559_2_1	5.3	0.0%	0.0, 0.0, 1.0

Figure 2: Contribution analysis

In case of thin plastic components and effect of temperature, non-rigid or compliant models are selected as they are assumed to deform. The compliant models in form of FE meshes have nodes and elements (Check FEM theory section 2.4). Each element has the same property that is characteristic to the part. In case of compliant models, deformation or bending of the models can occur along any direction which is close to the material behaviour in reality. In RD&T compliant models can be imported as Abaqus or data bulk files and thus non-rigid simulation can be performed. The rigid simulation can only handle locating scheme with 6 degrees of freedom while non-rigid simulation handles locating scheme with more than 6 degrees of freedom.

2.3.4 Locating Schemes

The purpose of a locating scheme is to locate one part on another part in an assembly or on a fixture. This is done by locking a rigid body in six degrees of freedom in space. There are 6 points chosen along 3 linearly independent directions to locate the part in space. There are different locating schemes that can be used depending on the kind of parts. They can be orthogonal locating schemes (3-2-1 and 3-point as can be seen in figure 3 and 4) and non-orthogonal locating schemes (3-directions and 6 directions as can be seen in figure 5 and 6). In orthogonal locating schemes, the locating directions are perpendicular to each other whereas in non-orthogonal locating schemes, the locating directions are not perpendicular to each other. The most commonly used locating scheme for rigid components is 3-2-1 locating scheme where a plane is first defined by 3 points locking three degrees of freedom, the next 2 points define a line orthogonal to the first plane locking two degrees of freedom and finally 1 point locking the final degree of freedom (Söderberg et al. 1999).

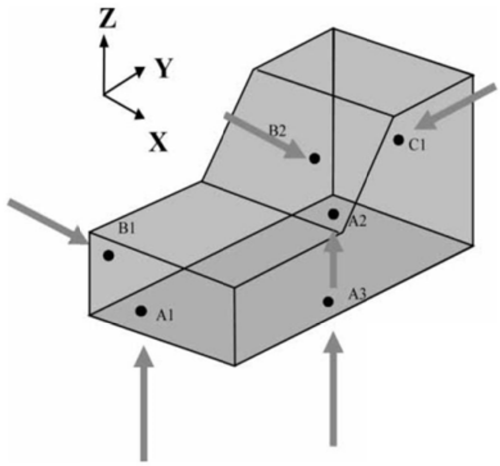


Figure 3: 3-2-1 locating scheme
(Söderberg et al. 1999)

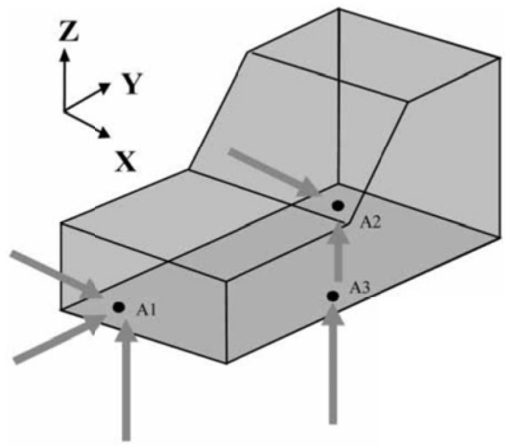


Figure 4: 3-point locating scheme
(Söderberg et al. 1999)

In case of 3-direction locating scheme the first 3 points define the primary locating direction where the points may not be in the same plane, the next 2 points defines the secondary locating direction that may be non-orthogonal to the primary direction, and finally 1 point defines the tertiary locating direction which may not be orthogonal to either of the primary or secondary locating directions.

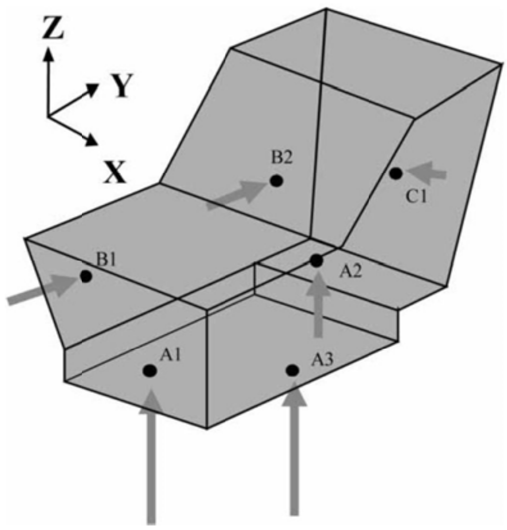


Figure 5: 3 directions locating scheme
(Söderberg et al. 1999)

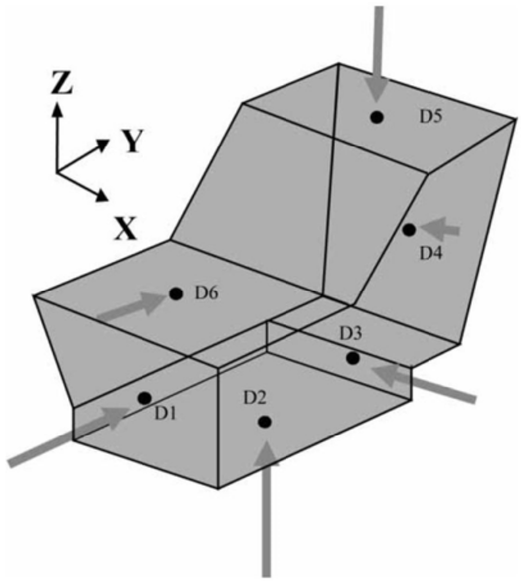


Figure 6: 6-directions locating scheme
(Söderberg et al. 1999)

In case of thin components and parts with low Young's modulus like the plastic parts, non-rigid bodies should be used. In these cases non-rigid (also called compliant) parts should be used with 6 locating points. When the compliant parts are located in space, it can be over-constrained by additional support points to counteract for effects of gravitation and for variations in parts and fixtures. In addition to the defined positioning system the support point is assigned on nodes and always lock only one direction. When it is required to lock a particular node in more than 1 direction, multiple support points is needed to be defined on that particular node. The locating scheme points are denoted by black flags and support points are denoted by white flags as shown in figure 7.

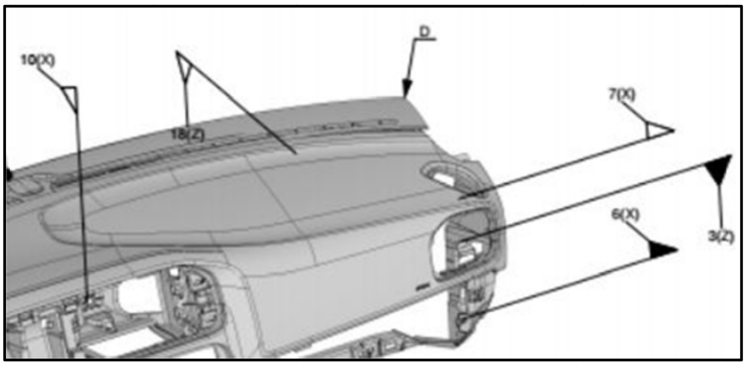


Figure 7: IP Part with Support points

2.3.5 Subassemblies, fasteners, weld points

In order to assemble multiple parts, the subassembly feature should be used. It ensures the parts are positioned in the simulation process in correct order. The subassembly is used to assemble two or more parts together and then position them on to a fixture with different input tolerances. The subassembly feature allows two compliant parts to be attached with the help of fasteners and weld points.

A Fastener in RD&T refers to a physical structure which joins two compliant parts together. The fastener feature as shown in figure 8 is used in RD&T models where screw or pin is present in reality. The parts are fastened together by forcing nodes into contact in desired directions during simulation. The factors which can be taken into consideration when a fastener is to be created is the geometrical shape of fastener. the size of the fastener, the directions in which nodes should be forced into contact, mating surface distribution and loading direction of the fastener.

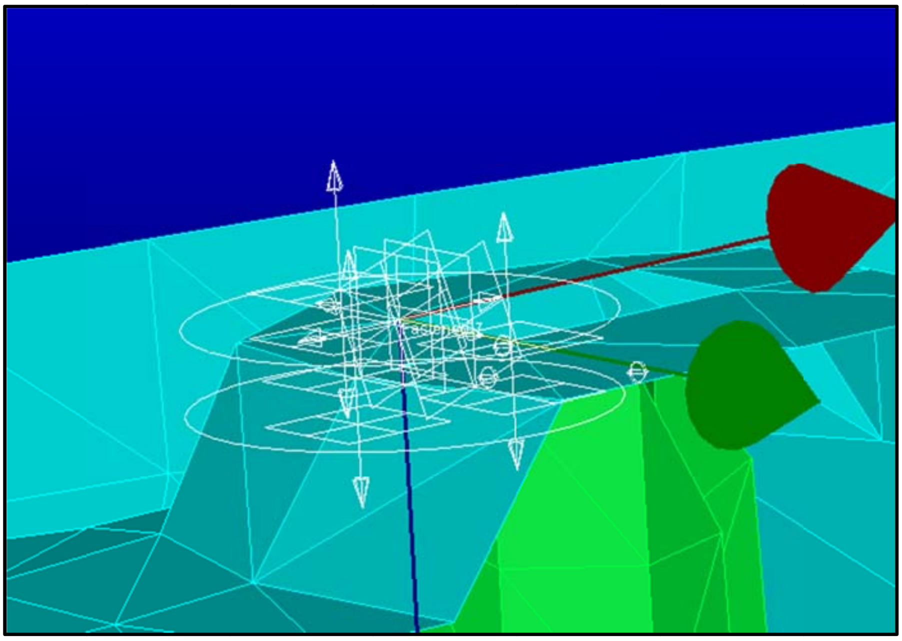


Figure 8: Screw feature in RD&T

A weld point is used between two parts to simulate spot weld. A weld point feature connects two different parts at the selected nodes. For surface meshes a weld point locks all six degrees of freedom and only one weld point is necessary.

2.3.6 Influence of temperature

When components are assembled, there can be assembly variations due to deviation from nominal dimensions and also due to geometrical variation. Most of the assemblies are done at normal temperature. But with increase and decrease in temperature during product usage the components can undergo changes due to variable expansion and compression. This will lead to thermal stresses and deformed parts, which can have different variations in comparison to the variations at normal temperature (Lorin 2012).

In automotive industries, focus has been on using lightweight materials for different parts to improve efficiency and engineering characteristics (Lorin 2012). Polymers are the lightweight materials which have been attractive because of its mechanical properties. But with change in temperature, their mechanical properties, like Young's modulus, vary. E.g. polymer material like M30 ABS has Young's modulus varying from approximately 2300 at -40°C to 1400 at 80°C. With increase in temperature the stiffness decreases which can have varying effects on the components depending on its locating system (see figure 9).

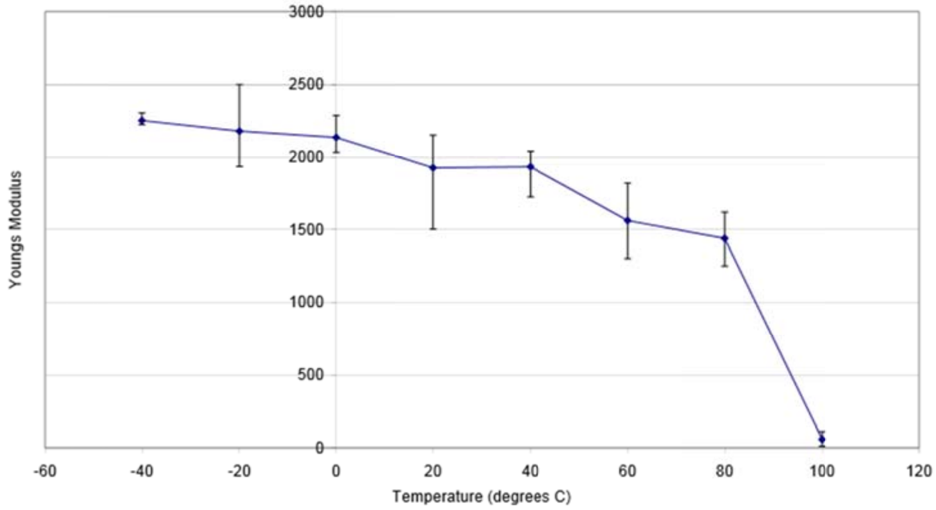


Figure 9: Young's modulus vs Temperature, ABS (Stratasys 400m Inc. 2008)

In order to observe the effect of temperature on the deformation of parts with a particular positioning system, RD&T provides a feature where parts can be thermally expanded or compressed under the influence of temperature change. The assembly as a whole undergoes changes after it has been fastened or welded at the desired positions. Thus the variation simulation conducted after the thermal expansion on the components can be used to analyse the effect of temperature on the variation in the assembly.

2.3.7 Analysis Methods

The variation simulation results can be analysed in RD&T with methods like variation analysis, contribution analysis and stability analysis.

Variation Analysis

The variation analysis tool analyses the critical dimensions in the models using the Monte Carlo technique (Grossman, 1976). The dimensions to be analysed are set by defining measures which typically corresponds to requirements. Here it is possible to study the range, 6 sigma, 8 sigma distributions, mean and capability *(Cpk)* of the simulation process. *Cpk* is defined what a process can produce assuming that the process is not centred between the specification limits. The number of iteration is defined by the user and the result is observed in a normal distribution curve see figure 10.

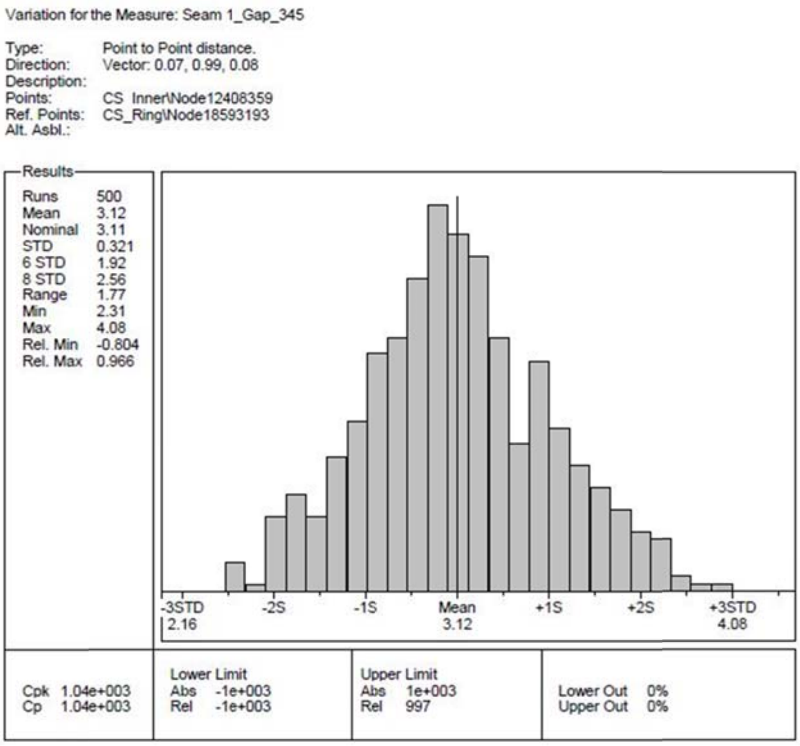


Figure 10: Variation analysis result sheet

Contribution Analysis

The contribution analysis is the tool used to analyse the contribution of various factors that adds up to the variation in each of the measures. For each of the measures the different factors can be specific or group tolerances on parts and locating schemes which adds up to 100 %. This tool helps to analyse the distribution of the causes of variation that affects the measures. The results are used to set tolerances so that requirements are fulfilled.

2.4 Nomenclature

Nominal Gap

The distance between two points for a particular measure is defined on the split line gap in such a way that all product properties are fulfilled (such as Perceived Quality requirements, swing clearance, dynamic movement, etc.) and that is referred to as the nominal gap which is then represented on the CAD model. It is not affected by variations or deformations.

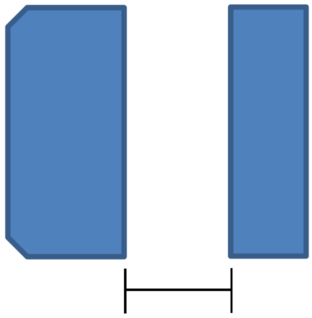


Figure 11: Nominal gap between components

Seam

A seam is also known as a surface strip which is created on a split line between two rigid models in RD&T. A split line is the visible gap between two components when they are located next to each other. The seam consists of a set of points which is used to define a set of measures. Thus it maintains the direction of the measure from one part to the other part between the two measures.

E-line

The E-line is created as a 3D line along the split line and is created between two parts. One is a master and other is a slave surface (Weber et al. 2013). Between one node on each part a spring element is created where the z-direction in the local coordinate system for this element points towards the slave surface. One such spring element corresponds to a measure in RD&T and a desired amount of these can be created using the E-line script.

Measures are created on the E-line which are represented by spring elements and is used to measure the relative displacement in the Gap see figure 12.

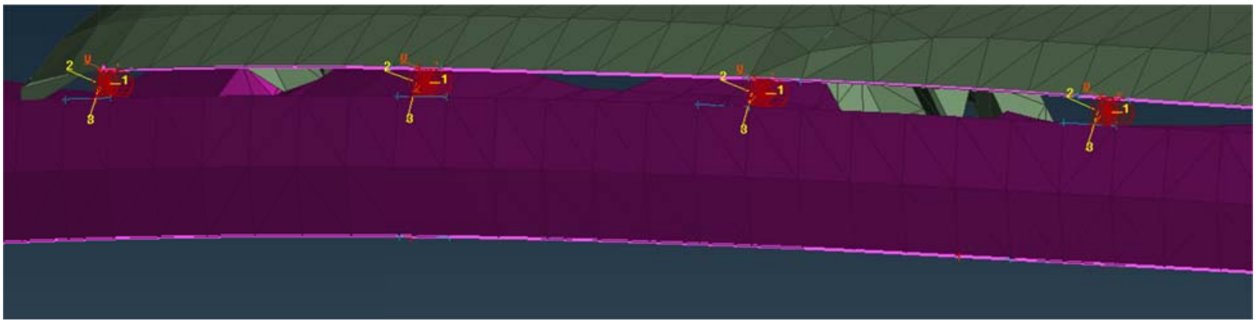


Figure 12: Measures on E-line

2.5 Static and Dynamic displacement

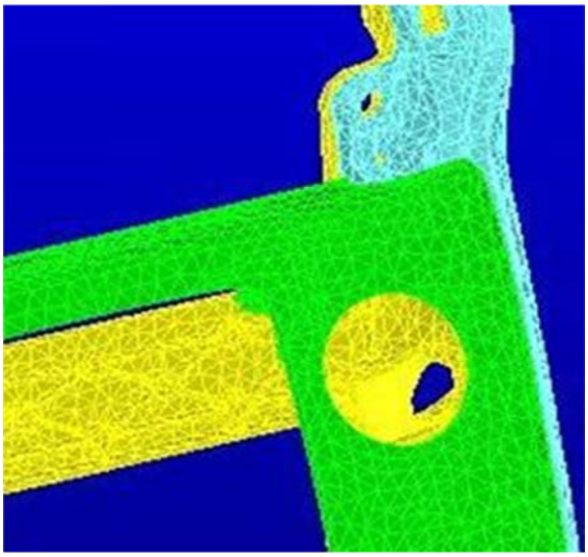
Static displacement is the value of the output variation on each of the individual measures when the model is analysed on a stationary fixture only with the tolerances. The value of the probability distribution (6 sigma and 8 sigma) is considered for the static displacement value where the measures have the same direction as the original set of points in the nominal gap.

Dynamic displacement refers to the output value in each of the defined measures when the models are subjected to transient vibration load. The values are measured in the same direction as the set of points considered for the nominal gap.

2.6 FEM Theory

Finite Element Method is used for analysing a virtual model with boundary conditions quite similar to the one in reality. In FEM, the physical part is approximated by a simplified model consisting of a finite number of *nodes* and *elements*. The *elements* are connected to the *nodes* and the variables such as displacement; temperature is evaluated on these nodes considering the behaviour of the assumed load on each of these elements (Lakshmi 2008).

In order to simplify the physical part into a model with nodes and elements, the geometries are meshed and is considered to be the pre-processing stage. The part can be modelled as a solid or as a mid-surface mesh, see figure 13 and 14. The solid, volume meshes contains a set of nodes and connected elements in the entire volume of the mesh and generally consists of longer simulation time. However, in mid-surface mesh the property of the solid is modelled by approximating the solid by a surface in the middle of the thickness. The mid surface mesh which generally has fewer nodes has lesser simulation time than the volume mesh and is generally preferred for complicated systems. It is also used to analyse geometries that are much slimmer in one direction compared to the other in order to avoid the problems with aspect ratio.



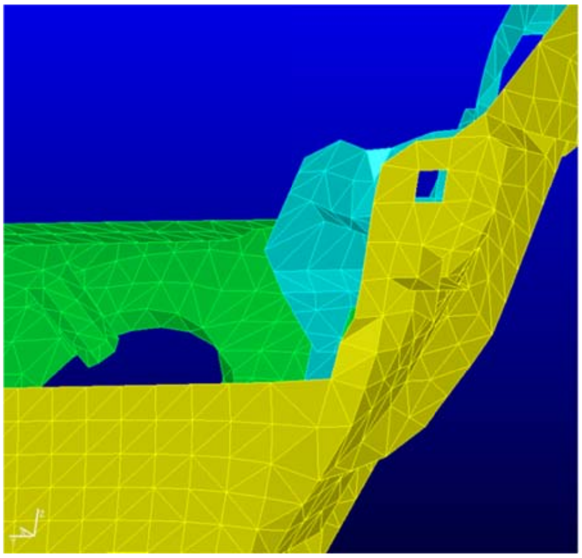


Figure 13: Solid, Volume meshed

Figure 14: Mid-surface meshed

2.7 Squeak and rattle Theory

The issue of squeak and rattle occurs only when there is relative displacement between two components which are adjacent to each other. The squeak and rattle are issues which are generally audible and decrease the perceived quality of the products. Since squeak and rattle are undesirable, it is required to predict them in assemblies and avoid their occurrence through design changes and engineering considerations.

Rattle can occur in two cases. First, if the two parts have a gap initially when in rest and collide with each other due to external load. The second case is when the two part just touch each other but leave contact when exposed to an external load and repeatedly impact each other to produce rattle. It is defined as the noise which occurs when the relative displacement due to static and dynamic displacement is more than the nominal gap. This can be avoided by considering tolerances on the parts and positioning systems which ensures that the nominal gap is more than the relative displacement.

The squeak occurs when the parts are in contact and they rub against each other continuously due to external vibration load. The squeak is defined as the noise which occurs in the contact plane between two components when maximum principal peak to peak is more than the relative displacement. The relative displacement is defined as the inverse of impulse rate which is the output of stick-slip measurement and the maximum simulated distance moved in one direction in the squeak plane is called maximum principal Peak to Peak, mpP2P. The mpP2P is the response of the random load in the squeak plane along x and y directions. The z-direction is normal to the squeak plane and is the rattle direction.

2.7.1 Rattle Simulation

This series of steps are followed to analyse rattle between components with a gap:

1. The variation simulation is carried out in RD&T with consideration to heat expansion. Simulation will result in static displacement *Ds(t)* as the output where *Ds* is a static geometric displacement and *t* is temperature. The seam feature is used for defining measures. The static displacement is the half of the value of probability distribution from the results e.g. 8 sigma divided by 2

$$Ds(t) = -Mean\ shift + \frac{8\ sigma(t)}{2} = -\big(Mean(t) - Mean(20)\big) + \frac{8\ sigma(t)}{2} \quad (1)$$

2. The dynamic displacement is calculated between components using E-line and Young's modulus *E(t)*.The dynamic displacement is the displacement value obtained from Matlab when the results from Nastran are plotted in displacement vs. nodes in the time domain.

3. Rattle is calculated by the difference of the values of static and dynamic displacement from nominal gap which are obtained from previous steps. The higher the difference, the greater are the chances of occurrence of rattle.

$$\text{Rattle} = \text{Nominal Gap} - \text{Static Displacement} - \text{Dynamic Displacement}$$

$$R(t) = Nominal\ Gap - Ds(t) - Dd(t) \quad (2)$$

Where *(t)* = values obtained at particular temperature t.

In equation (2), Rattle condition can be ascertained only if difference of nominal gap and static displacement is not equal to or less than zero. In such cases, the occurrence of squeak should be investigated instead as the components are in contact due to variation even before the application of the vibration load.

$$Nominal\ Gap - Ds(t) \leq 0 \quad (3)$$

4. The simulations are performed in (1) and (2) at room temperatures t=20°C. The simulations can be performed at higher and lower temperatures.

5. The change in rattle between two different temperatures, *R(t)* and *R(20)* where *R(t)* is the rattle at t°C and *R(20)* is the rattle at 20°C, is calculated to observe the magnitude of change in rattle, ΔR.

$$\Delta \mathrm{R} = R(t) - R(t = 20) \quad (4)$$

2.7.2 Squeak Simulation

The following steps are followed to analyse the squeak between two components initially in contact:

1. The contact force is estimated from the models by considering thermal expansion of the components. The necessary parameter to determine the output contact forces is the Young's modulus of the components, how it change with temperature and also the expansion of the component itself.

   Contact force *F(t)* is the output here for input *E(t)* where t is the temperature

2. The dynamic relative displacement is calculated between the components using the E-line method and a temperature dependent Young's modulus *E(t)*. The simulation is run in Nastran which gives a result of movement path in squeak plane from which the *mpP2P* is acquired. The maximum and minimum velocity (*vmax(t)* and *vmin(t)*) is also approximated from the graphs which are obtained from squeak plane during movement. This graph is obtained as an output from the Matlab results.

3. The stick-slip testing is performed in stick-slip machine at VCC with input parameters *F(t)*, *vmax(t)* and *vmin(t)* for each of the temperature t.

4. The value obtained from slip stick measurement is the Impulse rate *(IP)* and this output is used to calculate relative displacement per pulse for squeak, *SQmax.*

$$SQmax = 1/\ IP \quad (5)$$

5. The occurrence of squeak is evaluated by calculating the difference between maximum principal peak to peak and relative displacement. If *S(t)* is negative there is an occurrence of squeak.

$$S(t) = SQmax - mpP2P \quad (6)$$

6. The simulations are performed at room temperature, t=20°C, and can also be performed at higher and lower temperatures.

7. The change in squeak between two different temperatures, ΔS, is calculated to observe the change in magnitude of squeak for different points on the split lines.

$$\Delta S = S(t) - S(t = 20) \tag{7}$$

3 METHODOLOGY

In this chapter the research methodology used in this project is described. Furthermore, the application of the methodology and its significance is explained.

3.1 Methodology theory

Overall research plan

In order to evaluate the performance of the research method and monitor the intended outcomes of the project, the "Aims against Stages" concept is used. Using this framework various questions are listed which contribute to the deliverables of the project. The questions are assigned to the stages and at the end of each step in a particular iteration, the answers are sought to those questions to understand the performance of the process. An example has been mentioned in Figure 15 (Eriksson 2007).

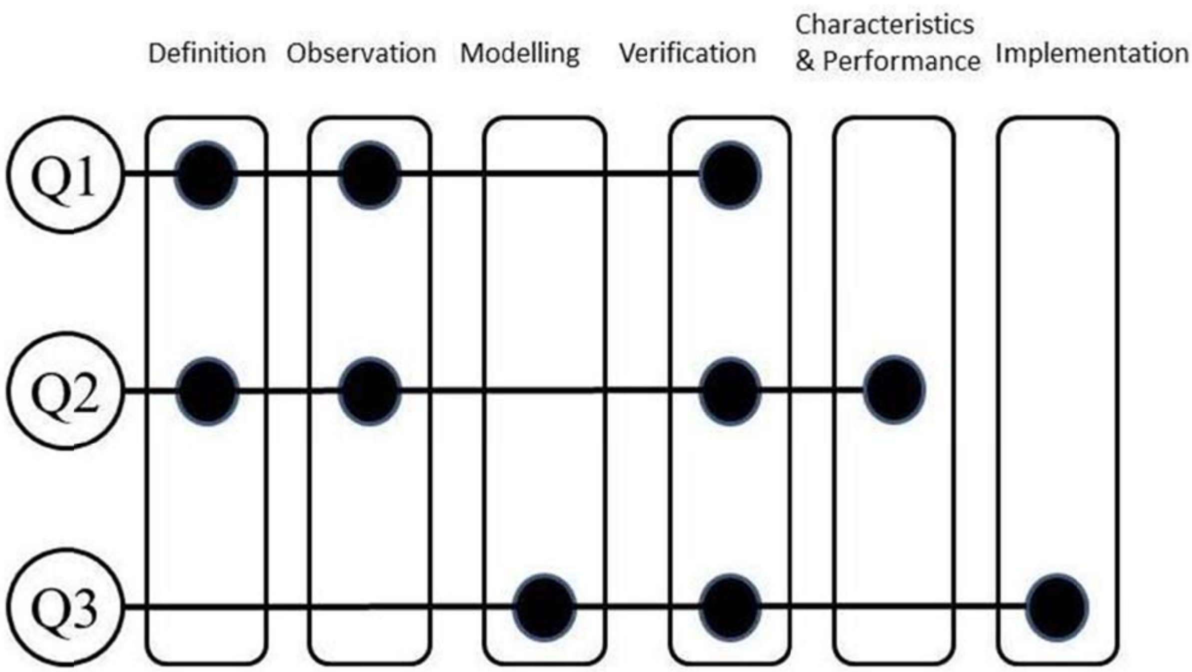


Figure 15: Aims against Stages

Problem oriented iterative research method

The problem oriented iterative research method framed here is iterative in nature and takes into account a number of possible outcomes and consequences. It is a combination of two different methodologies-Problem oriented research methodology and Design development methodology. The first methodology strives to create an understanding of the problem by estimating and measuring the error in the model (Hulten, 1998). The other method is iterative by trial and error approach and focuses on understanding the problem and not by solving the actual problem through linear planning as in traditional problem solving methods (Blessing et. al. 2009). The methodologies are combined in order to have a flexible approach to make improvements at each level again and again. It is shown in figure 16. This combination is efficient as it enables to implement, the improvements and the gained knowledge, in previous levels. This approach of understanding the problem and the various scientific properties associated with it is considered to be successful and is being widely used in developing new products.

The various steps in the research method have been described below:

1. Defining the problem
2. Observing the problem
3. Modelling
4. Verifying the model
5. Characteristics and Performance
6. Implementing the process

1. Defining the problem

The problem either falls into the category of product/performance/functionality failure of a product or further improving the functionality and performance of the product.

2. Observing the problem

This helps to understand the problem and the parameters that are important for the problem which may be linked to architecture, design or manufacturing processes. This is done to increase the knowledge on the key parameters so that they can be used to model and verify the problem in later stages. Generally it is done by literature studies, experiments or by experience.

3. Modelling

The problem is modelled with the key parameters so that it is a representation of the product in reality. It can be mathematical, visual or any other model depending upon how it is used. The process is highly iterative as it requires modifications, improvements and redefining the problem to improve performance. Addition of new parameters relevant to the model can lead to higher accuracy of the model, increased knowledge but can increase the complexity of the problem

4. Verifying the model

In order to understand the influence of the key parameters, the problem is simulated as close to reality as possible. The results obtained are verified by mathematical calculation, experimentation, experience or logical confirmation. All the phases until the verification stage are generally iterative since more understanding of the problem is acquired throughout the usage of the method. The iterations do not only occur within one step of the method but changes in all steps can be done at any time, thus later steps are affected.

5. Characteristics and Performance

This stage is essential to analyse the impact on the process when a parameter is changed or to understand how to control and avoid the effect of the problem

6. Implementing the process

The significance and effect of implementing the process in product development process is analysed and various benefits or damages are observed before taking a decision

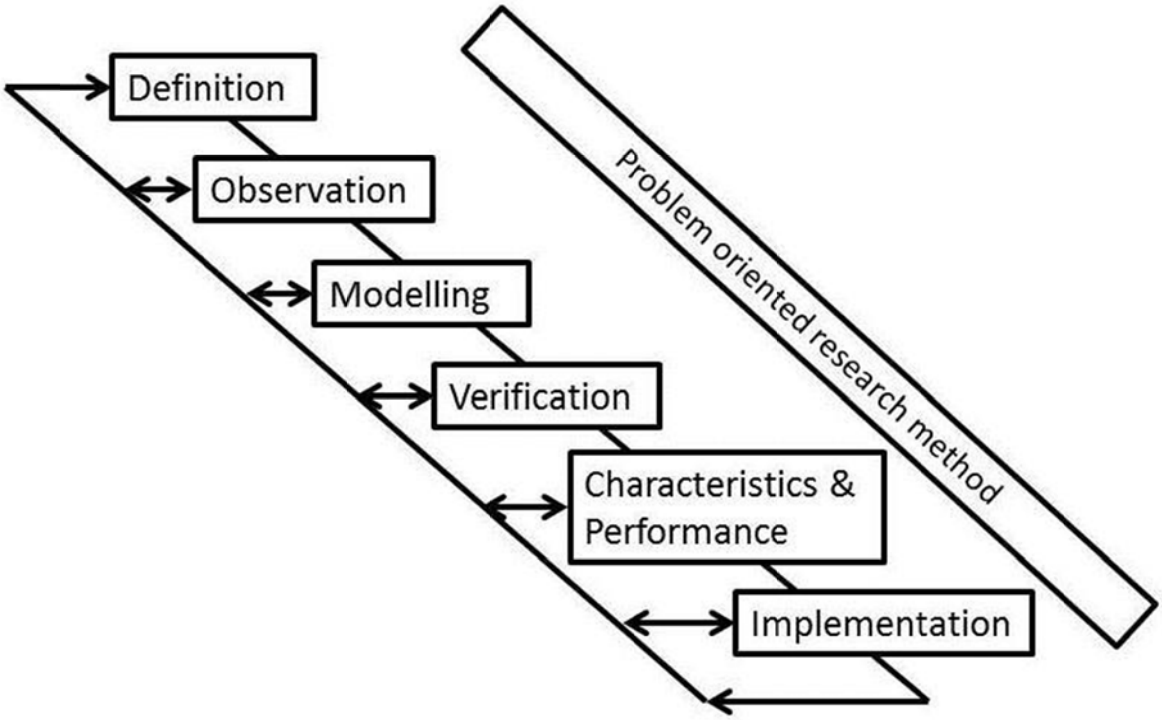


Figure 16: Problem oriented research method

3.2 Implementation of research methodology in project

Overall research plan

To monitor the deliverables and develop the knowledge, the following questions were listed against different stages in the project:

Q1- what are the key parameters affected by temperature for the model and how do the parameters vary with varying temperature?

Q2- What is the performance of the E-line method and variation simulation in the software packages when the temperature is varied and material properties are changed accordingly?

Q3- Is it possible to work out the entire problem on a single model that is used for both transient modal analysis with the E-line method and variation simulation for varying temperatures?

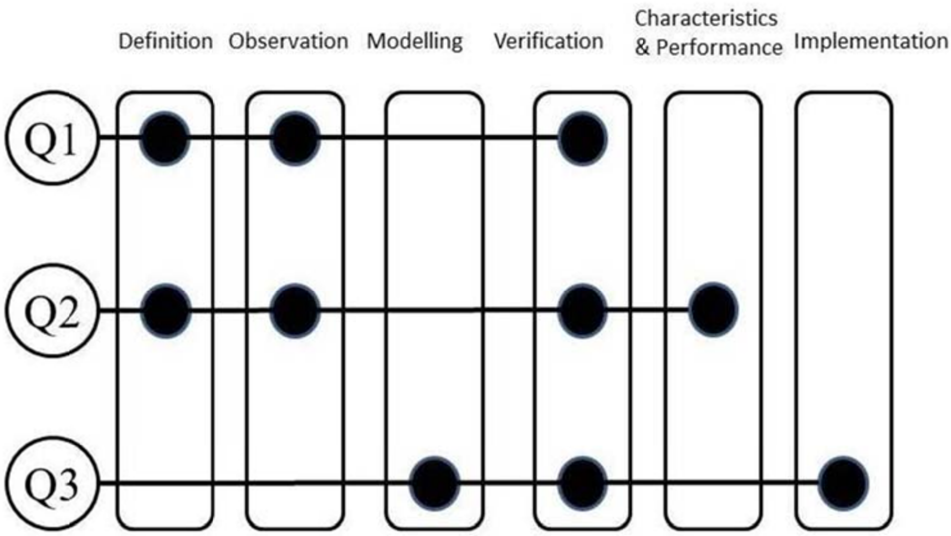


Figure 17: Aims against stages for current research work

In this project, the *problem was defined* to improve the concept of identification of squeak and rattle in Centre Stack components while working at different temperatures (from -40 to 80) in order to be able to reduce the occurrence of these issues. The *problem was observed* by investigating the various parameters (e.g. split line conditions) and requirements (tolerances, location of screws and positioning). The problem was *modelled* in RD&T and Ansa separately but the parameters that are similar for the models and which provide the results (measures) are kept the same. The *models were verified* by simulating them for different runs at different temperatures. Finally the *characteristics and performance* of the models were analysed from the results obtained from the static and dynamic simulations.

The entire process was performed iteratively and also in a repetitive manner as it needed improvements at each level, along with the progress of the thesis. In the first iteration after trying out different types of meshes it was in *observation phase* where the usage of both triangular and tetrahedral element mesh in RD&T could be tried. In the *modelling* and *verification* phase, more iterations were conducted to improve simulation time even when volume meshes were replaced by mid-surface meshes and also when the contact modelling parameters were decreased. To increase the *performance* the entire process was repeated a number of times to observe what improvements would reduce the modelling time. Taking into account these observations, some of the new features were implemented by Lars Lindkvist which enabled to reiterate the models and simulation with less time. These improvements included features such as Gap to Mesh (selecting the nearest nodes in the compliant models for the measures), maintaining same direction of the measures and use element sets for different thickness of the materials. Later it was observed that the Seam could not be changed once the modelling was completed fully. This problem was solved by a new version of the software RD&T which saved a lot of time remodelling the whole problem from scratch.

The problem was defined initially with one case and during the project improvements were done on the same case, which lead to redefining the case twice later. All the steps were followed for each of the cases. The performance of the process was assured by comparing the results of the simulations on these three different cases.

4 CASE DESCRIPTION

This thesis involves the procedure for how to identify the amount of squeak and rattle and how it is affected by temperature. It was improved upon using existing research and development methods as well as research work while working on three specific cases, all of them on the centre stack of a Volvo V40. The centre stack was chosen because it was a critical system from Squeak and Rattle point of view. The first case was simple and used to develop the simulation method. Following cases had more complexity added to more correctly represent reality. The centre stack is attached to two other parts; the instrument panel towards the front of the vehicle and the tunnel console which is located below the centre stack.

Figure 18: Centre stack of Volvo V40

4.1 Case I

The centre stack is susceptible to squeak which easily can be heard if the driver presses his or her leg against it. It consists of several plastic components which are connected with screws and snap fits. The components that were investigated for the first case were CS inner, CS frame and CS outer. The temperature span between -40°C and 80°C was of interest since these represents the expected extreme operating temperatures. Seven temperatures; -40°C, -20°C, 0°C, 20°C, 40°C, 60°C and 80°C were chosen at an equal interval in order to investigate the entire range and observe the gradual change. Furthermore two possible areas for rattle or squeak were investigated as seen in figure 19, one split line between CS inner and CS frame and another one between CS frame and CS outer.

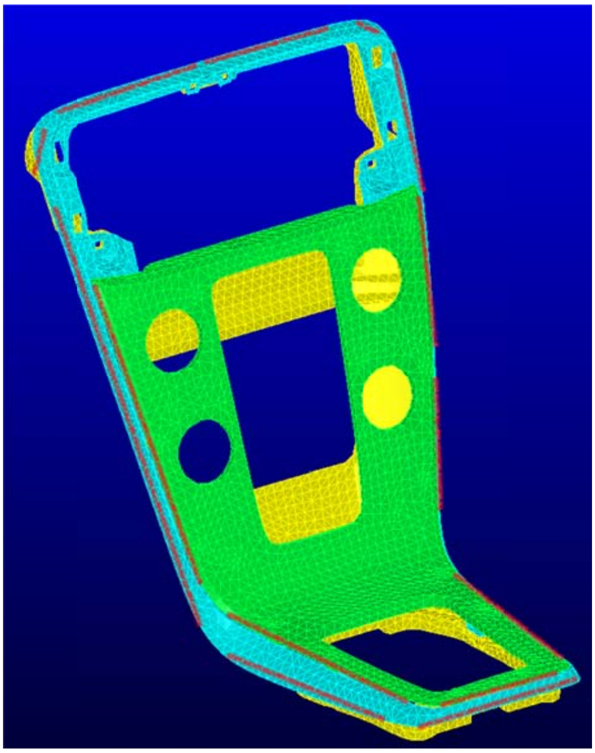


Figure 19: Case 1 with the two selected split lines

In figure 20 and 21 the number of the measures can be seen and are referred to in the result section.

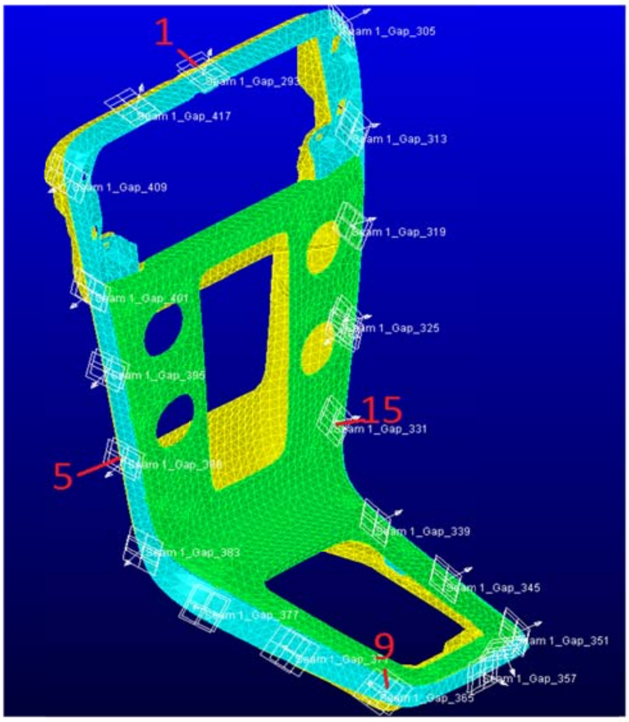


Figure 20: Seam 1

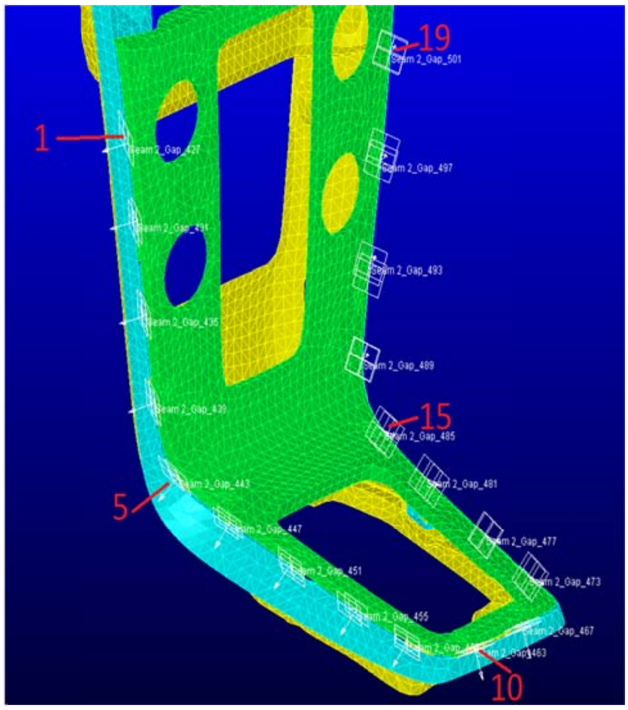


Figure 21: Seam 2

4.2 Case 2

Additional parts were added for the second case to provide a more correct representation of mass and stiffness. They were air vent panel, two vent ducts, radio panel and the radio with point masses on the nodes see figure 22. An additional split line was investigated, this time between the newly added air vent panel and CS frame.

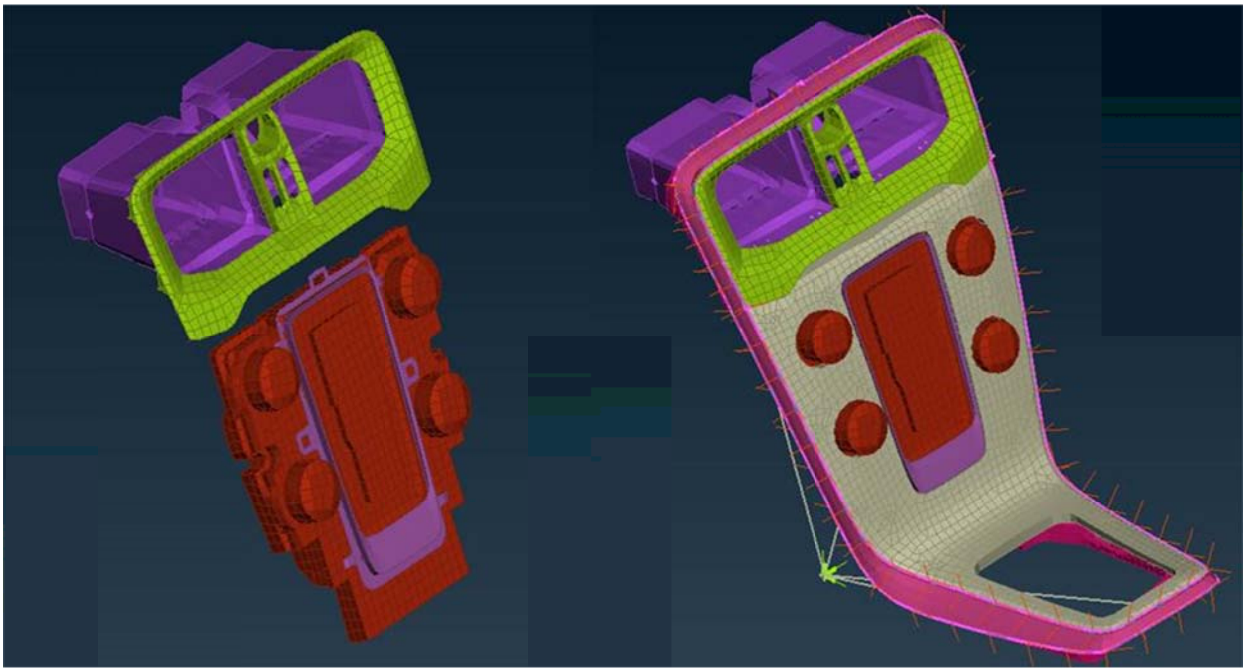


Figure 22: Case 2 with new parts

It was important to represent the components, measures and connections between them correctly and as close to reality as possible. They should also be represented similarly in RD&T and Ansa. RD&T is used to simulate the static displacement due to manufacturing tolerances and while Ansa is used to prepare models for simulations with the goal to identify how external loads, such as vibrations causes dynamic displacement. Additional measures were added on each E-line in case 2 in order to get a better resolution in the results see figure 23.

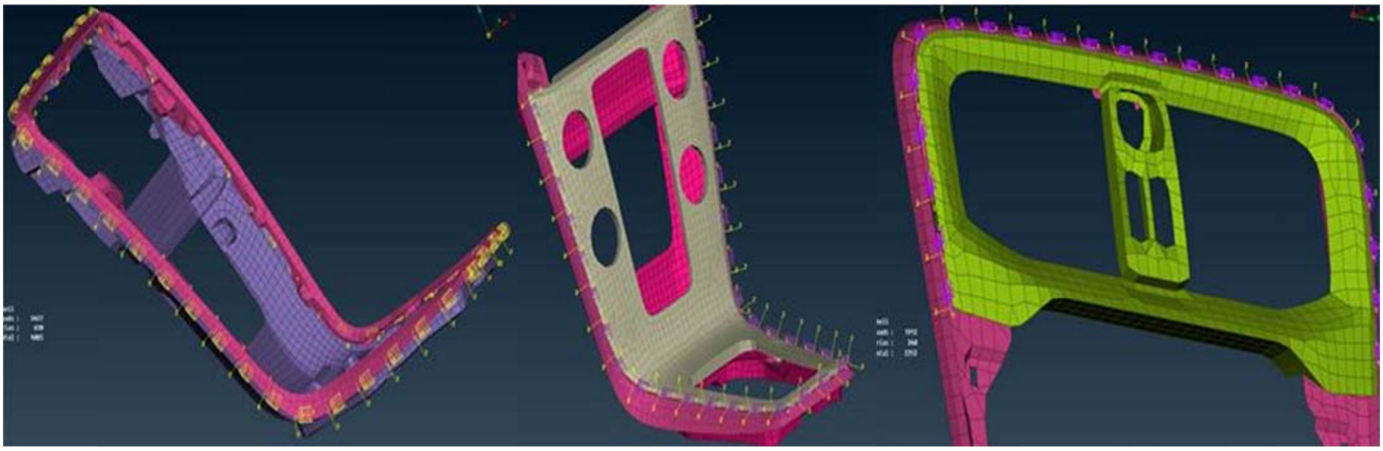


Figure 23: Case 2 with E-line 1, E-line 2 and E-line 3

4.3 Case 3

The third case included everything that was considered in case 2 with the addition of tolerances on the fasteners see figure 24. According to drawings at VCC, tolerances were placed in the plane normal to the direction of the screws.

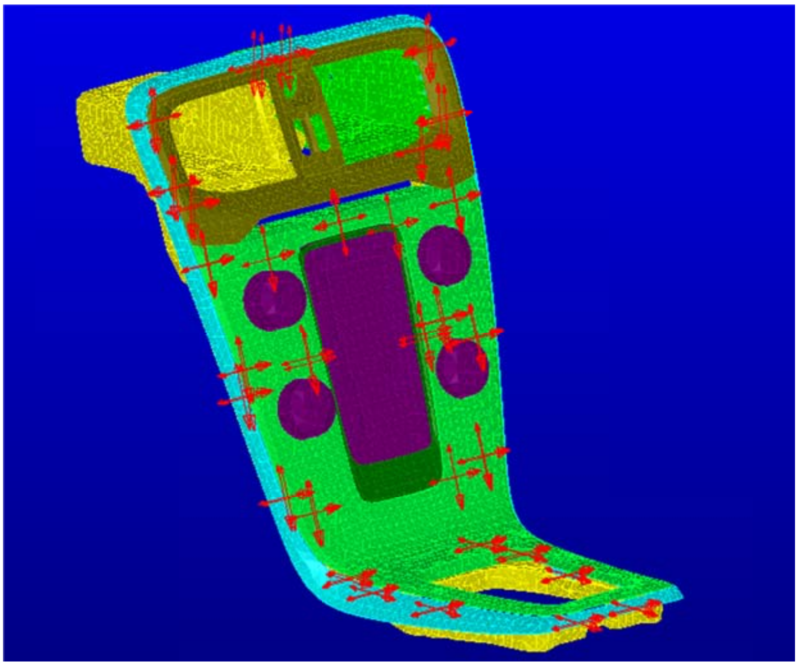


Figure 24: Fastener Tolerance with direction

5 WORK PROCESS

In this chapter the work flow for the three cases is explained in detail. It includes both, how the static displacement was simulated in RD&T and how Ansa, Nastran and Matlab were used to acquire the dynamic displacement. The process described in this chapter will first treat the entire process, developed while case 1 was being worked on, and followed by improvements done while case 2 was treated.

The nominal gap between two parts in a split line is acquired from Catia models and is used as a starting point when simulating squeak and rattle. To describe the entire process in reality for static displacement, the centre stack parts were first located on each other using the locating scheme within the subassembly and released only after it is screwed. The release causes spring back but is restrained in position by the screws. It is then positioned on the instrument panel and tunnel console. The deviations occur due to the tolerances in the parts and the assemblies. At different temperatures, the parts change in shape and deformation occurs when they are in use at the customers place, much after the product has been assembled. But in this simulation the thermal changes occur before they are assembled and screwed. This implies the entire process with the assembly, spring back and the fasteners are performed after the parts change their shape. It is assumed that both the conditions are quite similar and would have same effect with the change in temperature.

The dynamic displacement in the real process is observed when the components are assembled together and is attached to the car which is then subjected to various loading conditions. The loading data was recorded previously at VCC on a test track with the help of accelerometers located at different strategic positions. In this simulation it is assumed that the entire assembly is connected to a single point below it. The load is then applied onto this point, as if it is located on a shaker table.

5.1 RD&T

RD&T was the software used to simulate the part variation that occurred due to dimensional and geometrical tolerances, each Monte Carlo run represent one centre stack being manufactured and assembled. There are two types of models which can be used in RD&T; rigid and flexible models see figure 25. Only the flexible ones can be used to simulate with deformations of components.

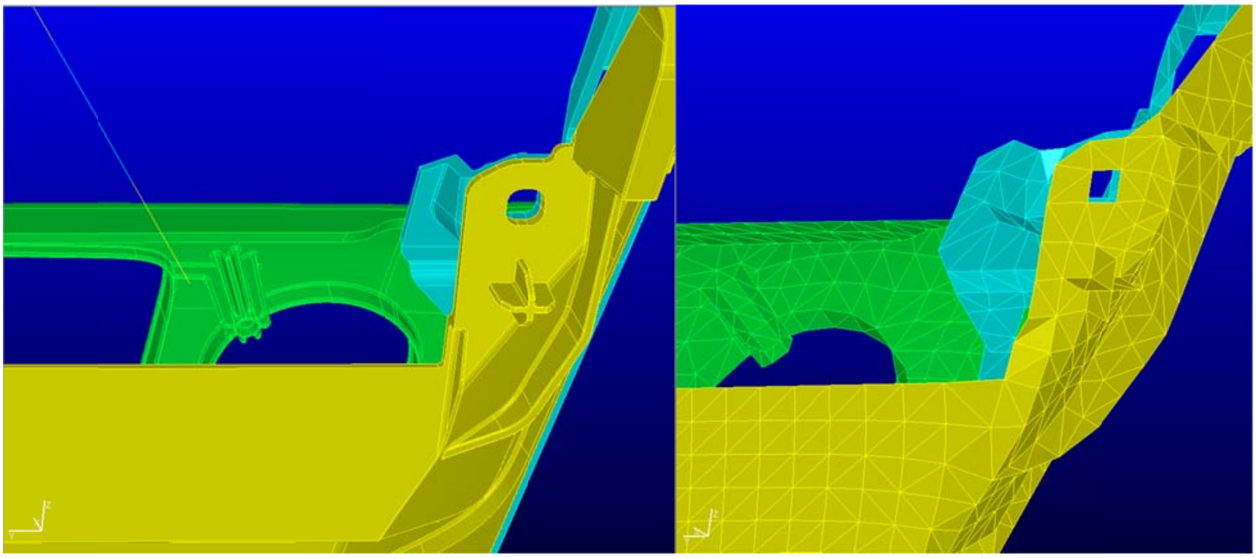


Figure 25: Rigid body model (left) and Compliant model (right)

The components were loaded into RD&T in VRML (Virtual Reality Modelling Language) format and were therefore completely rigid. While components in this format cannot be used for simulating flexible behaviour, they can be used to create a series of measures along the split lines of interest using the seam feature.

5.1.1 Seam feature

The seam feature is used to create a surface strip (pink in figure 26) and measures between two components. One component is always chosen as the local part (the green part in figure 26) and the surface strip will by default be in touch with that part while the other part becomes the target. A chosen amount of gap and flush measures can then be created along the seam using the normal of the surface strip as direction. Geometrical data, such that is contained in VRML files, is required to create the seam and have fulfilled their purpose once the measures are created. The geometrical data was replaced by mesh representation. The usage of both volume meshes and mid surface meshes was investigated. While volume meshes resembled the rigid model closely, it was observed that the mid surface ones were significantly faster to simulate with as it contained less elements.

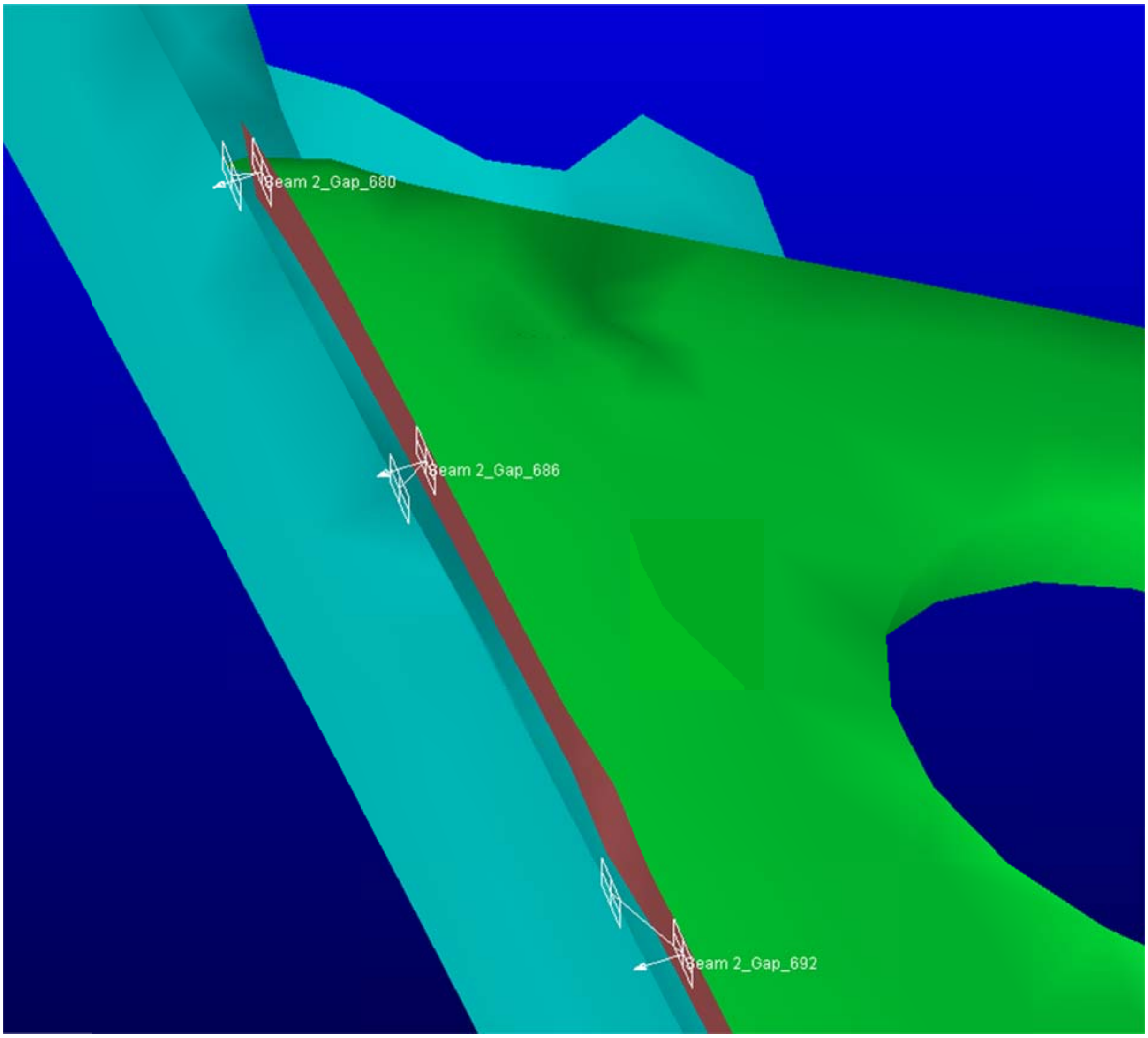


Figure 26: Seam with measures

Measures in RD&T take place between two points or nodes. Points are geometrical data that is contained in rigid models while nodes are non-geometrical data. Nodes are part of meshed models that are used in simulation with flexible components. To begin with, the seam feature generates points for the generated measures. When the meshed parts were imported the measures were not connected to the model anymore. So they had to be moved from the points of the rigid model to nearby nodes of the meshed model using the feature “Move to Gap” (See figure 27 and figure 28) The “Move to Gap” feature in RD&T performs this task automatically but keeps the direction of the original measures which is crucial to acquire correct results. This improvement of the Seam feature was suggested during the development of the project and implemented by Lars Lindkvist.

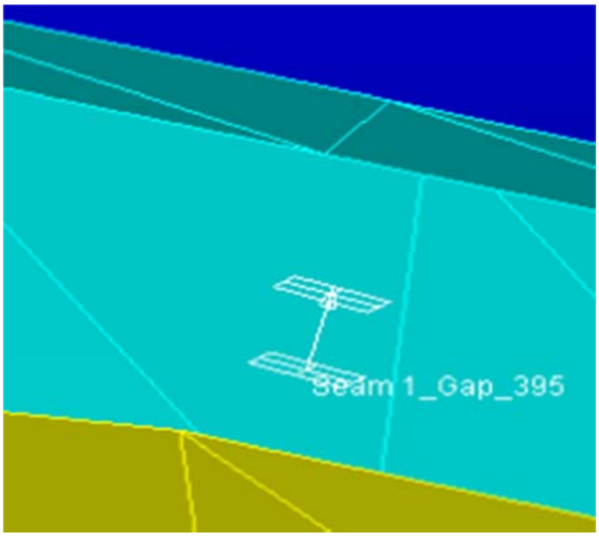


Figure 27: Measures from the seam

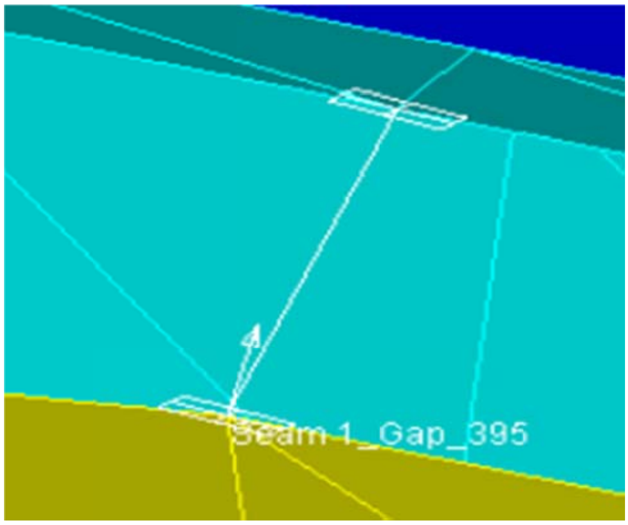


Figure 28: Measures with move to gap feature

It was crucial to match up the amount and positions of measures created in RD&T to the ones created in Ansa with the E-line feature. This was difficult due to the difference in shape between the rigid part, on which the seam feature was used, and the mid surface meshed part on which the E-line was created on. To solve this a large amount of measures were created in RD&T (see figure 29). All of these measures that were not relating to one in Ansa were then deleted.

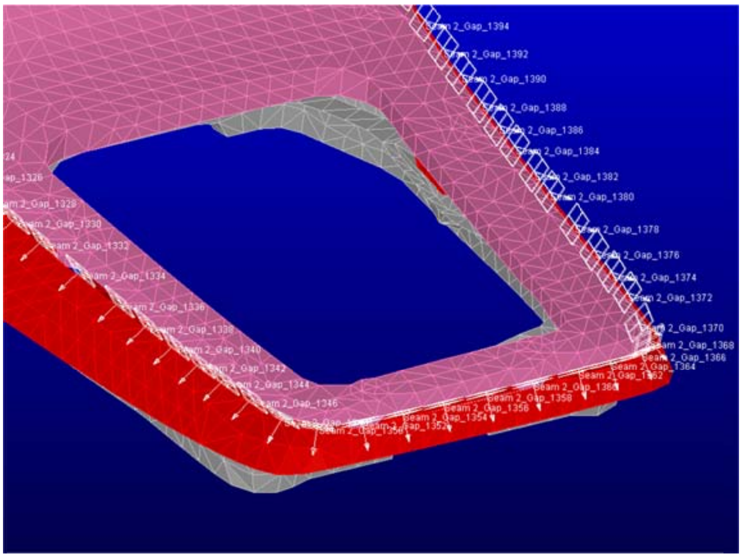


Figure 29: Seam with more created measures

5.1.2 Fasteners

With the measures corrected, the screws and snap fits were realized as fasteners which were created with the fastener feature in RD&T. Additionally three weld points were used between two parts in contact to lock the degrees of freedom. Although one weld point locks all 6 DOF, however three weld points were used for all the iterations. The number of weld points was kept the same as more weld points does not really affect the simulation.

The locating schemes for the individual parts were needed to be able to run Monte Carlo simulations but using them to represent screws would result in the parts being put together in the wrong order during simulation. The locating points were therefore positioned so that they would not interfere with measures or fasteners.

For this project, not all properties of the fasteners were considered. Only the geometrical shape of the fastener, the direction of it, the dimension, the distribution of mating surfaces and the degrees of freedom locked.

5.1.3 Applied tolerances

In reality the centre stack (yellow in figure 30) is a component between the two front seats of the car. It is connected to two different parts. One is the tunnel console which is located below the centre stack inner and the other is the instrument panel. Both of these are in turn connected to other parts creating two series of parts that are connected.

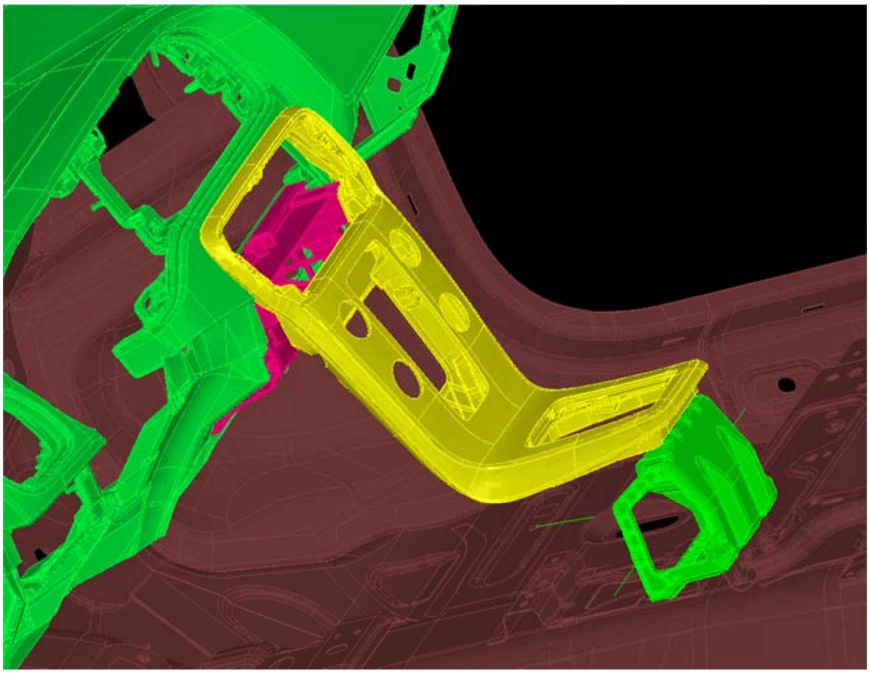


Figure 30: Centre Stack connected to Instrument panel and tunnel console

Between the two series of parts tolerances are defined and both series are eventually attached to a common part, the body in white (depicted as dark pink in figure 30). In order to have a realistic model, all part to part tolerances in the two series which together resulted in the variations of the centre stack had to be joined together and applied directly on the meshed centre stack. This removed the need for any other meshed part to be included.

In order to identify the tolerance values that are assigned on the centre stack a simulation with rigid models was run in RD&T. It is preferable to use rigid parts over non-rigid ones because the simulation time would be too long otherwise. It included all parts between the centre stack and the body in white. The rigid models and tolerances between them were already in use at VCC and thus already placed as per specifications. Measures of the type "point-self" were used. They measured how far a point moved in a certain direction during simulation. Three simulations, one per axis, were run with four different points of the centre stack defined as point-self measures. These were the points where the centre stack was connected to other parts in the two series.

Furthermore, the gap along the investigated split lines varies during manufacturing due to set tolerances. In RD&T these tolerances were applied according to specifications on every split line which was investigated. The factors that directly affected the results in RD&T were the tolerances on the fasteners and the split lines. Furthermore fasteners constrained the parts, thermal expansion changed the size of them and material data dictated how the individual parts would behave.

5.1.4 Material data

The parts that make up the centre stack consist of different materials. The behaviour of a part in RD&T is affected by several material attributes like Young's modulus, Poisson's ratio, the thermal expansion coefficient and the density. The materials used in the centre stack were ABS/PC and ABS. While they have similar characteristics, ABS has slightly lower density and thermal expansion coefficient but higher Young's modulus.

According to figure 31 Young's modulus for ABS vary due to temperature. While a range of values are given per temperature, specific values were chosen and those can be seen in table 1 and 2. The value for 20°C was taken from the models used at VCC and the other ones were interpolated using the figure 31 as a base.

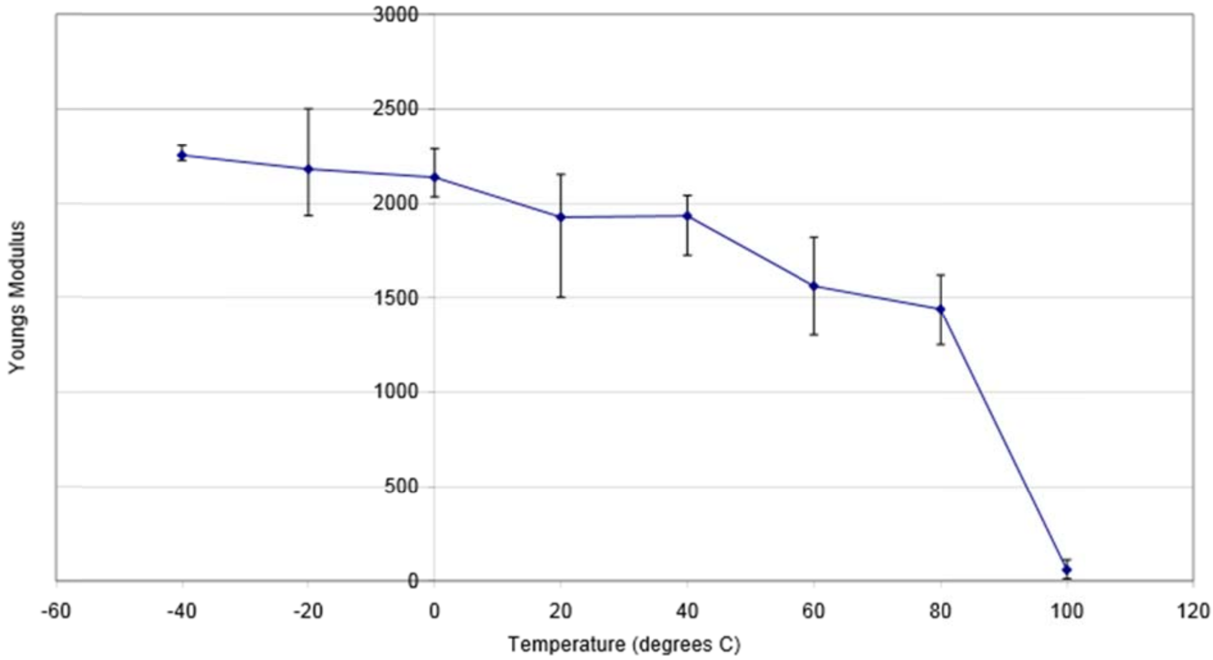


Figure 31: Young's modulus depending on temperature (Stratasys 400m Inc. 2008)

The data for how Young's modulus vary due to temperature for ABS/PC was not found. It was instead presumed to follow the same characteristics as ABS, this assumption was supported by experts at VCC. From the same model as before the Young's modulus at 20°C was taken. ABS/PC has a Young's modulus 100 MPa lower than ABS and that offset was assumed for all the temperatures investigated. The different material properties in the range of -40°C to 80°C for all the components have been listed in the table 1 and 2. The parts made up of ABS/PC are the CS Outer, the CS Frame, the Radio, the Radio frame and the Vent ducts. The CS Inner and the Air vent consists of ABS.

Table 1: Material properties for ABS/PC

ABS PC	-40°C	-20°C	0°C	**20**°C	40°C	60°C	80°C
E (Young's modulus)	2500	2200	2250	**2100**	2150	1750	1550
ρ (Density)				**1100**			
P (Poissons ratio)				**0,3**			
Thermal expansion coefficient				**85**			
Shear modulus	962	846	865	**808**	827	673	596

Table 2: Material properties for ABS

ABS	-40°C	-20°C	0°C	**20**°C	40°C	60°C	80°C
E (Young's modulus)	2600	2300	2350	**2200**	2250	1850	1650
ρ (Density)				**1050**			
P (Poissons ratio)				**0,3**			
Thermal expansion coefficient				**73.8**			
Shear modulus	1000	885	904	**846**	865	712	635

5.1.5 Element Thickness

Depending on how thick the model is in reality, every element in the mid surface mesh has a thickness assigned to it. A single complex part can thus have elements with different thicknesses, which is the case with the parts in the centre stack. To be able to identify thicknesses in RD&T it is required that the files containing the flexible models are structured the correct way, which was done in Ansa. In order to realize the thicknesses in RD&T there is a feature which was developed by Lars Lindkvist to be use with composite materials. It makes it possible to define different characteristics for different sets of elements that still are in the same part. Since one part only contained one material the only property that was changed was the thickness.

5.1.6 Simulation process

It was important to have all parts assembled in the correct order during the simulation. To achieve this all parts of the centre stack were put into a subassembly which in turn was connected to a fixture via a locating scheme.

During the simulation the parts are placed and held together due to the locating scheme and they vary due to manufacturing tolerances on the positioning system. In the next step they are locked together with fasteners and later released from the hold of the locating schemes which gives spring back to the components. The spring back is the condition where a component tries to fall back to its original shape after it is released from the locating scheme. In this case the components are restrained by the fasteners. Eventual expansion due to temperature change was to be applied before the Monte Carlo runs started.

5.2 Ansa and Nastran

The pre-processor Ansa was used to prepare the models for modal transient analyses in Nastran. The results were then input to a Matlab script and the dynamic displacements were acquired. The entire centre stack was connected to a single point which then was vibrated according to a signal which was recorded on a test track in a real life scenario.

The centre stack was provided by the NVH department at VCC. It was represented by mid surface meshed components, with materials and properties included. Several steps were necessary in order to prepare the models for Nastran. The individual parts had to be connected to each other, nodes where the dynamic displacement would be measured had to be defined and boundary conditions had to be set.

5.2.1 Connections and boundary conditions

The parts had to be connected to each other in the same positions in Ansa as in RD&T. All these positions were identified and rigid elements were used to connect several nodes of different parts forcing them to act as if they were screwed together see figure 32.

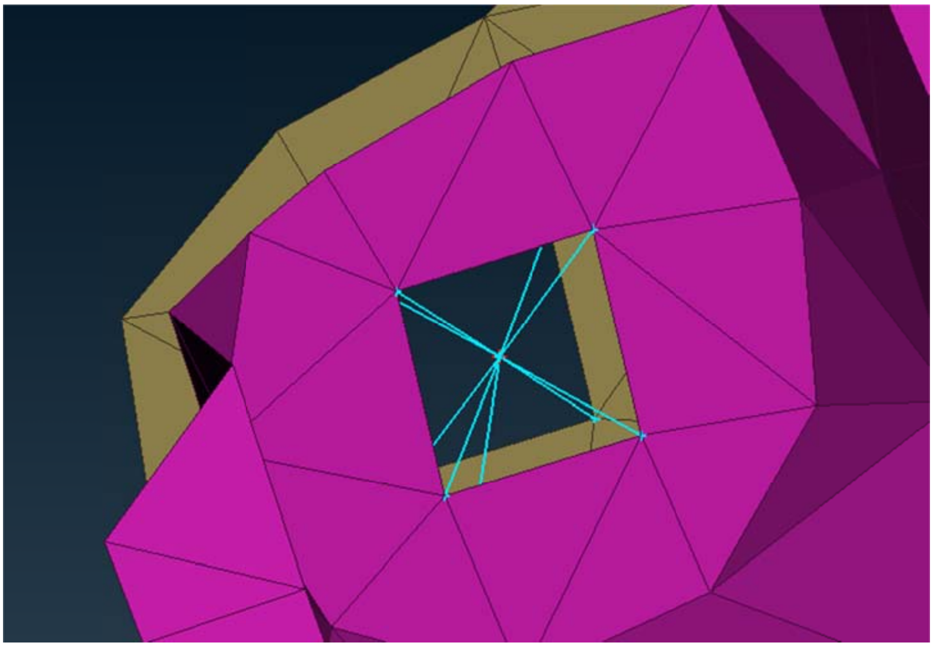


Figure 32: RBE2 element

When created, the rigid elements have one master and several slave nodes. This was used to set the required boundary condition. In RD&T there were several connections to parts other than the centre stack see figure 30. Nodes corresponding to these connection points were connected by a rigid element in Ansa, with these nodes as slaves. The master node was then moved below the centre stack (as shown in figure 33) and was specifically set as a boundary condition on which a load was applied when simulated in Nastran.

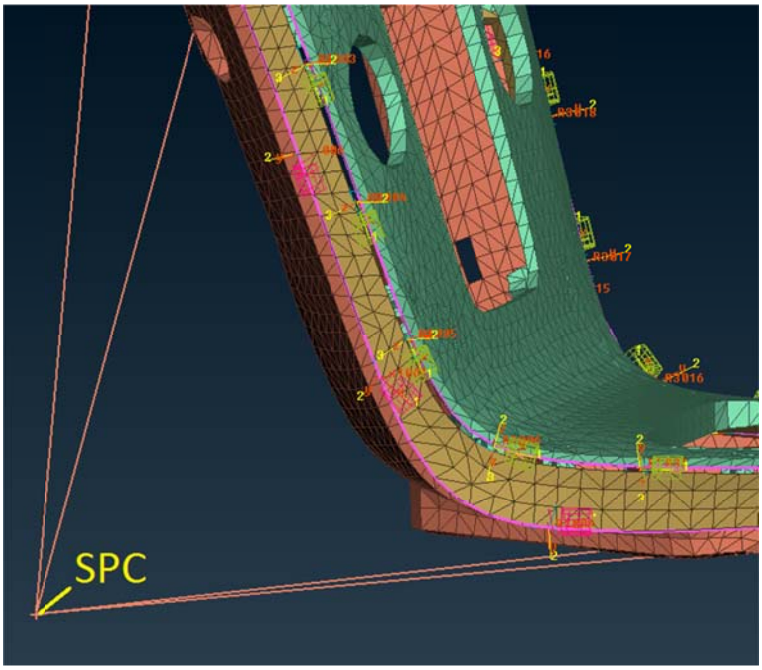


Figure 33: SPC

5.2.2 The E-line

The E-line method was used to identify the dynamic displacement along the split lines. It can be compared to the seam feature in RD&T, it relates two nodes, one node on each part, and the relative displacement between these nodes is measured in the desired direction see figure 34.

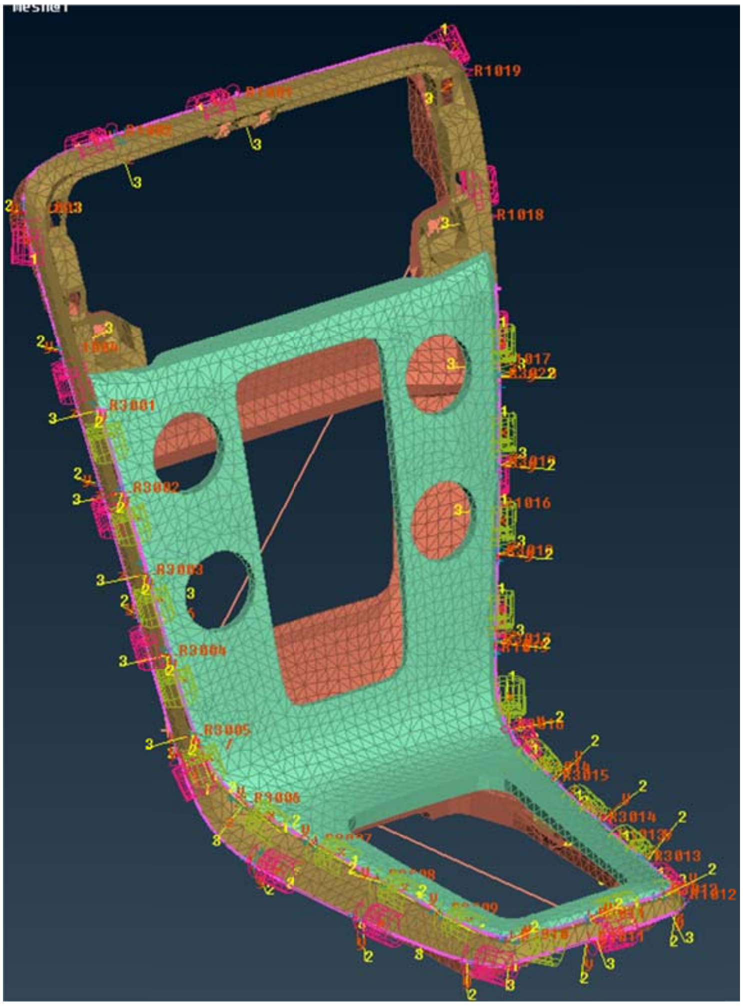


Figure 34: E-line and Seam with equal number of measures

Besides new nodes, spring elements are created between each node pair. Depending upon the stiffness these elements have in the direction between the parts, the rattle direction, rattle or squeak is investigated. Having no stiffness allows the nodes to move unaffected by the spring elements, thus displacement in rattle direction and subsequently rattle is investigated. Having a high stiffness however prevents movement in the rattle direction. Forcing the displacement to occur in a plane, the squeak plane, to which the rattle direction is normal. Thus the displacement in the squeak plane is of interest and squeak can be investigated.

5.2.3 Text file preparations

Nastran is the software developed by NASA and is used to for structural analyses. The type of analysis that was used for this project was a modal transient analysis. It indicates that displacement of nodes is simulated with boundary conditions for a set amount of time, in this case the time was 20 seconds. The boundary conditions were accelerations in x, y and z direction which were acquired by VCC on a real life test track.

Nastran handles text based files. For this project specifically, five files were needed in order to run the modal transient analysis. When all preparations were done in Ansa a Nastran (*.nas) file was output. It contained information about the centre stack, all nodes, elements and properties needed in Nastran. Additionally the boundary conditions were in form of three *.bdf files and contained the acceleration over time in x, y and z direction respectively. The last file needed was an *.ecd file which acted as a header file. It contained all specifications necessary to run the files in Nastran as well as joined the other files together.

5.2.4 Matlab

As a result of the modal transient analysis in Nastran a punch file (*.pch) was acquired. To derive the result from this file a Matlab script that was developed as a part of the E-line method was used. While the punch file contained the relative displacement for all the node pairs on the E-line the geometry for these nodes were not included. That had to be input into the Matlab script as a text file and it only contained data about the E-line, not anything else on the centre stack. With these two files it was possible to visualize the squeak and rattle in Matlab.

At one instance either rattle or squeak could be chosen and also for only one temperature. In case of rattle it was the relative displacement that was the result from the *.pch file, and in case of squeak it was maximum principal peak to peak (mpP2P). Once the files were loaded in Matlab the results were displayed in plots and in colour coded 3D graphs where the colour indicated the severity of rattle or squeak. Finally a text file containing the maximum relative displacement was output. In order to make the result more trustworthy it was chosen to ignore all values above 90% of max since these were very likely to only be a few stray values. The stray values only occur rarely and thus the squeak and rattle they produce would be very brief and negligible for the listener.

5.2.5 Stick-slip measurement

The only real life experiment conducted in this thesis was with the stick-slip machine at VCC (see figure 35). The stick-slip measurement provides the impulse rate between two components when they are in squeaking condition. In the machine one piece of a certain material is pressed against another with a force specified by the user. The pieces were then slid back and forth against each other with a velocity also specified by the user. It was desired to measure the contact force in RD&T and use that as an input to the stick-slip machine. However it was discovered that it could not be acquired so the machine was run for various values chosen to cover most its range.

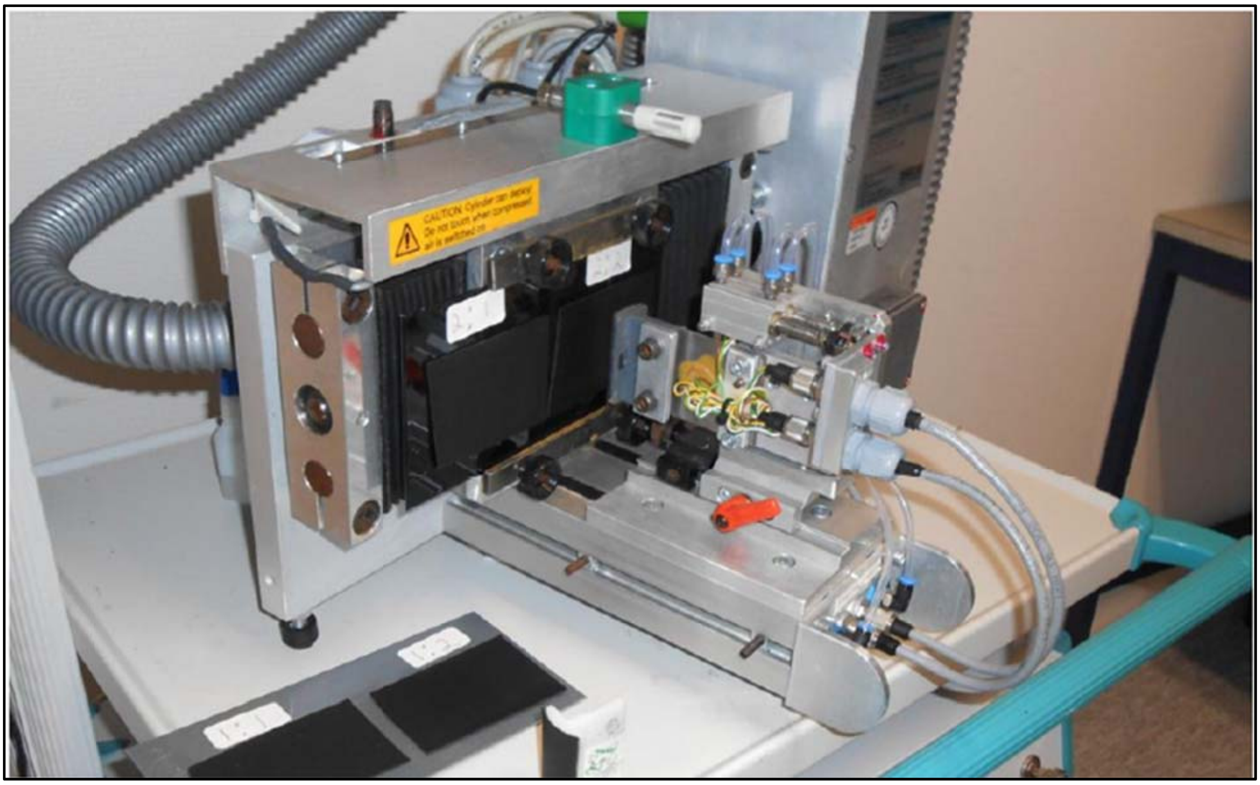


Figure 35: Slip stick measurement machine

Due to friction during the usage of the stick-slip machine the parts stuck together and afterwards slipped due to the distance moved, the slip indicated one occurrence of squeak. The CS inner consists of ABS and CS outer of ABS/PC. The CS frame, while consisting of ABS/PC, was chromed which gave a different result than pure ABS/PC did. Thus the two pairs of materials that were tested were ABS against chromed ABS/PC along with ABS/PC against chromed ABS/PC.

The output of interest was the impulse rate which indicated how many occurrences of squeak there was per millimetre. The inverse of this, the distance required for a squeak to occur, was then used to compare the mpP2P result from Matlab which is the simulated movement in the squeak plane. If the simulated mpP2P was larger than the inverse of the impulse rate from the stick-slip experiments squeak occurred.

The results acquired were however not satisfactory. The geometry of the parts were not taken into consideration, only flat plates were used. Additionally a heating element was used for the experiments at higher temperatures. This is not only inaccurate but also reduces humidity rather than increasing it, as it usually is more humid in warmer areas where the vehicle is used. Due to time constraints, additional experiments were not conducted and values used were instead found in an already created database. Data for material and temperatures not in the database were approximated.

5.2.6 Case 2

When the first case was completed it was decided to add additional parts and make the simulations closer to reality (see figure 36). The air vent panel (in green), two air vent ducts (in purple), the radio (in red) and a radio frame (in bright purple) between the radio and CS outer.

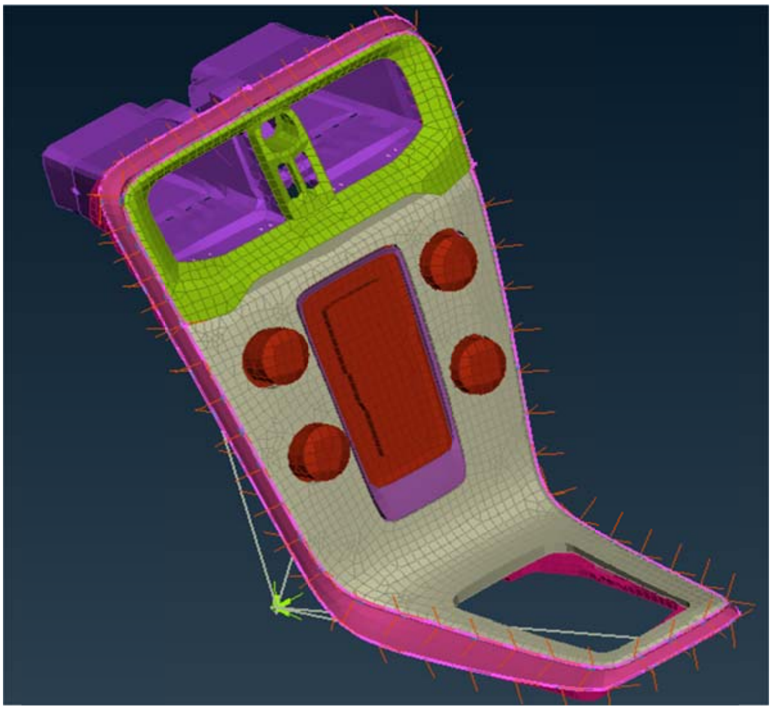


Figure 36: Case 2

These parts allowed a more realistic representation of stiffness and inertia, there were also a distributed mass on the radio to reach the correct mass of the part see figure 37.

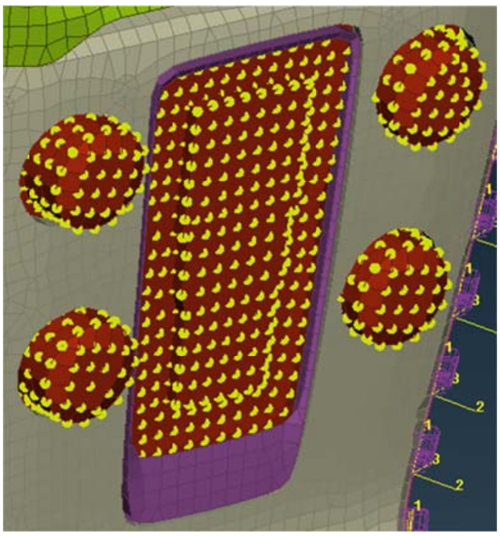


Figure 37: Radio with distributed point mass

A third split line was investigated, between CS frame and the newly added air vent panel (see figure 38). All split lines also were given a greater amount of measures in RD&T than before, subsequently more spring elements were created in Ansa. This was done in order to acquire a higher accuracy around critical areas of the split lines.

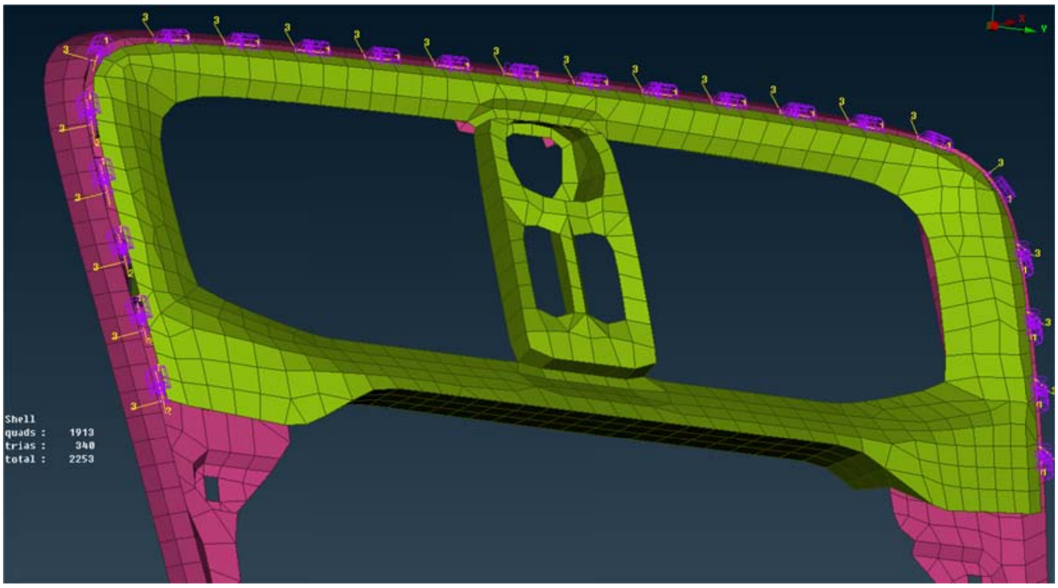


Figure 38: Case 2, E-line 3

5.2.7 Case 3

The same parts and fasteners used in case 2 were also used in this case. Tolerances on the fasteners however were first added in this case. The values were taken from drawings at VCC though some had to be approximated since the revisions of some of the parts used in this case did not correspond to any drawings.

5.3 Verification

Several behaviours have been verified throughout the course of the project.

5.3.1 Contact force in RD&T

It was planned to obtain the contact force between two parts from the RD&T simulation, which then would be used as an input for the stick-slip machine. To verify that the simulation result was correct, it was compared with the results calculated separately on paper. Two simple bars were created and meshed in Catia. One side of the first bar was in contact with the other bar, nine nodes from one part coinciding with corresponding nodes on the other see figure 39. These 18 nodes were assigned contact force measures and were also set as contact points. It is important to remember that nodes not set up for contact force measurement would still interfere with the measurement and therefore it was required to have values of all nodes of interest.

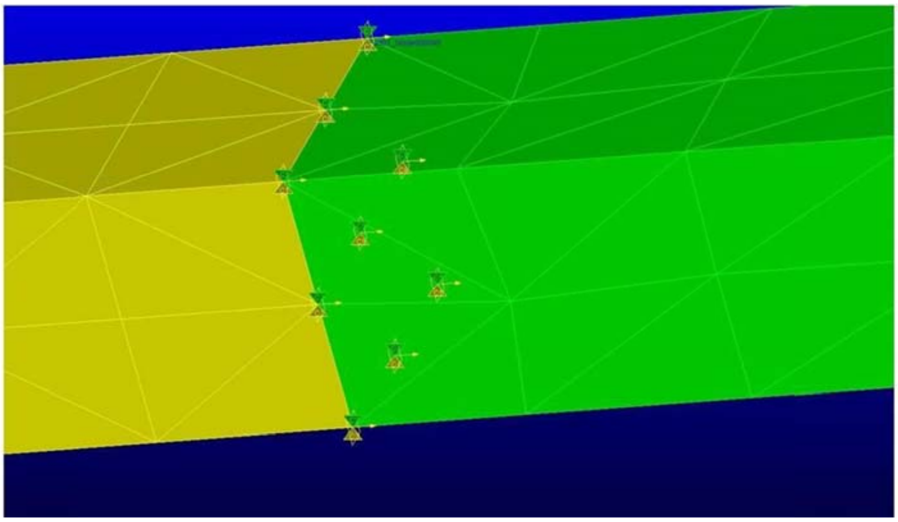
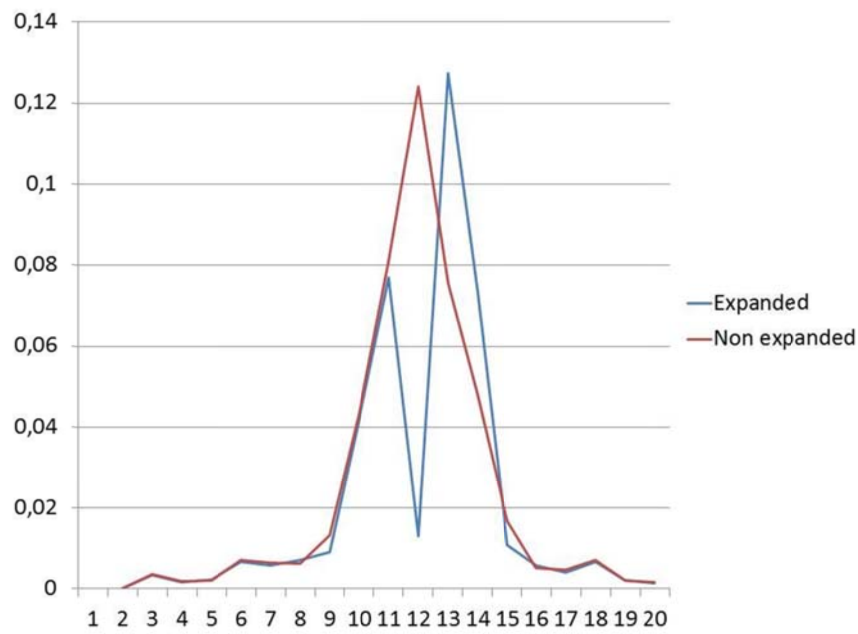


Figure 39: 9 nodes on bars for contact force

The parts were forced into each other by applying a forced offset on all nine nodes of one of the parts. By running a variation analysis with one iteration, the contact forces for each of the nine pair of nodes could be calculated. The values of the forces were added together and were compared to the manually calculated value for the force. It was found that the value of the force could be simulated correctly although it only worked if the mesh was set as linear. Alternately quadratic elements had nodes not assigned as contact points and thus gave an inaccurate result. It was found later in the project that if parts are placed in a subassembly it is not possible to calculate the contact force the desired way and thus it was not used further in the project.

5.3.2 Expanded models in Ansa

There were two possible factors that were considered to be changed in Ansa when simulating for different temperature; Young's modulus and the size of the parts. If the size would be taken into consideration they would be expanded in RD&T and then imported into Ansa. Whether this was needed or not was verified by comparing the results from modal transient analyses. It was done with one non-expanded model and one expanded for 80°C, the E-lines were created to match each other as well as possible.



Graph 1: Dynamic displacement of Expanded vs Non-expanded models

After simulations it was observed that for the E-lines the dynamic displacement for both the models had the same progression as depicted in Graph 1. For E-line 1 the graphs were almost same except for few points which were sensitive to rattle. For E-line 2 the graphs were different but they had the crests and troughs at the same points see appendix C. It was observed that the expanded models had triangular mesh elements and the non-expanded had tetrahedral mesh elements. The increase in stiffness due to triangular mesh elements was considered to be the cause of variation. Also the spring element locations were different for the sensitive points in both the models. Therefore it was concluded that non-expanded models can be used for the simulations and is reliable as it has less stiffness.

5.3.3 Mesh type

Whether volume or mid-surface meshed parts was to be used in RD&T were investigated in the thesis. A volume meshed part is a more accurate representation of reality than a mid-surface meshed one. On the other hand, it was much faster to simulate with the mid-surface meshed parts and the models used in Ansa were already of that format making it easier to correlate measures in RD&T to spring elements in Ansa if mid-surface meshed parts were to be used.

It was observed that the volume meshed models took longer simulation time, whereas the mid-surface meshed model could be simulated within approximately two hours. As the result were same for both the cases, so lower simulation time for mid-surface meshed models was advantageous as a number of simulations were performed. Since the duration of the thesis was limited, the preference for mid-surface meshed models for the simulations was quite obvious.

5.3.4 Element type.

When using a mid-surface mesh in RD&T all quadrilateral elements in a model are automatically converted into triangles. These elements are automatically linear, only connected to three nodes. It is however possible to convert linear elements to parabolic using a setting within RD&T.

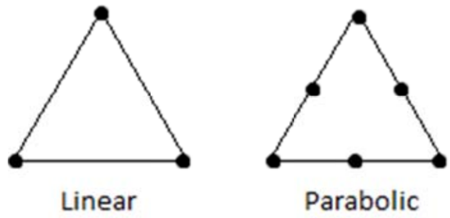


Figure 40: Linear and parabolic elements

The quadratic (parabolic) analysis setting converts linear elements to parabolic automatically by creating an additional node between two original nodes decreasing the stiffness of the model see figure 40. The quadratic simulation is considered for flexible models and is supposed to increase the accuracy of the results.

Whether this was needed or not was investigated by conducting one simulation with linear elements and one with parabolic (quadratic analysis). If the results would be identical or close to identical it could be concluded that simulating with linear elements were sufficient. Simulation with linear elements was desirable since it was much faster than the simulations with models with parabolic elements.

After simulations of the static displacement the results were compared between linear and parabolic elements, it was observed that it was almost same. But the simulations time was much longer for parabolic element analysis and almost thrice in time than the linear elements.

5.3.5 Contact modelling

When simulating with fasteners in RD&T all contacts are represented by one node on each part. These two nodes are forced into contact by randomly moving them until they come within a certain distance from each other, the contact equilibrium. The greater this value is the faster it is to simulate but the accuracy of the result is worse.

Table 3: Contact modelling characteristics and output

Model containing	Contact Equilibrium	Contact Max Iterations	No of Run	OUTCOME
All Screws	0,0001	10^4	1	ERROR
	0,001	10^5	1	ERROR
	0,001	10^6	1	RESULT

Therefore it was observed that models with contact equilibrium 0,001 and contact max iteration value of 10^6 gives result with no error see table 3.

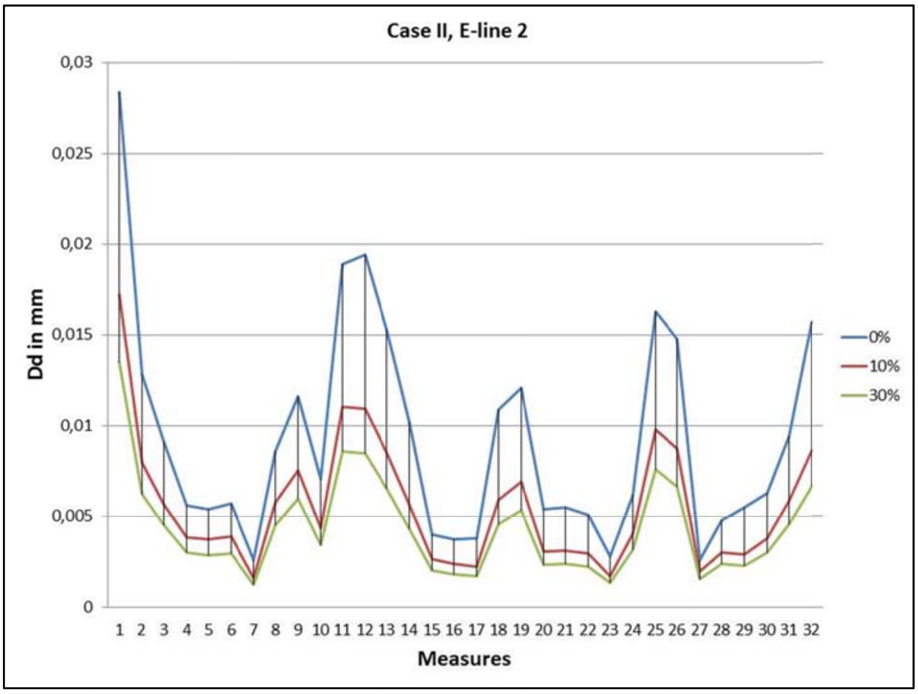
5.3.6 Contact optimization

The time it took to simulate static variation in RD&T was drastically reduced at the end of the project when an optimization routine for calculating contact equilibrium was implemented with a new RD&T version. To verify that the results were the same with the new RD&T optimization routine in comparison to the old RD&T version without it, a single case variation simulation for 60°C was conducted with the new routine and one with the old software. The result shows that it only differs at the second decimal place, one hundredth of a millimetre.

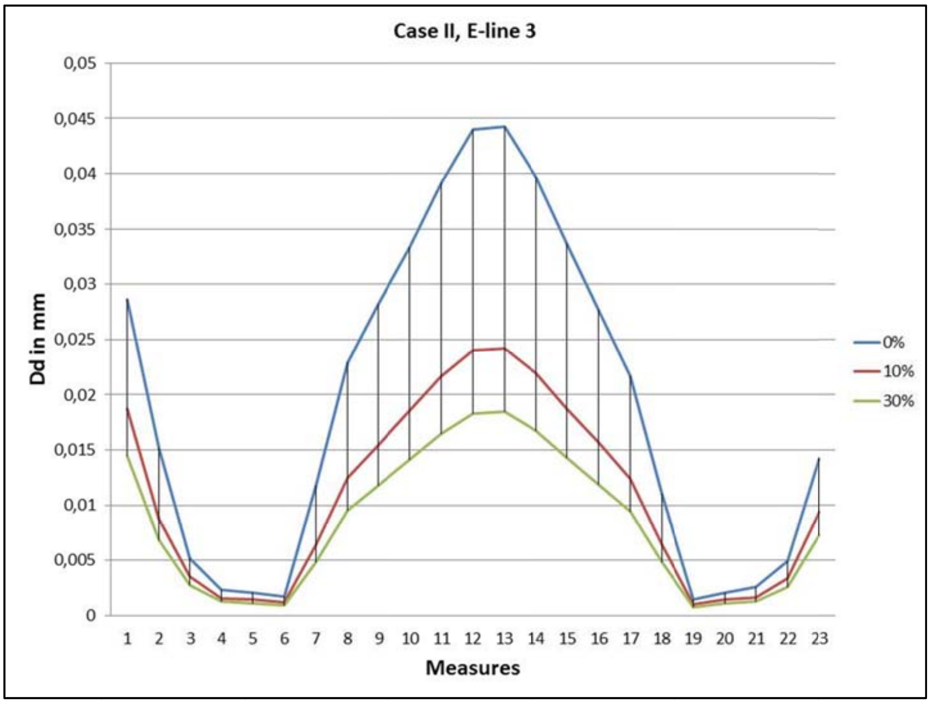
5.3.7 Statistical Evaluation Parameter

The results of the dynamic displacement were interpreted in Matlab which contains a parameter called the statistical evaluation parameter. This parameter cut off the upper most values of the entire plot depending upon the selected percentage cut-off. It was necessary to understand the difference of results for different percentages (0, 10 % and 30 %) and also to determine an optimum value for the analysis of the results.

The results have been plotted for E-line 2 and E-line 3 in graph 2 and graph 3. It was observed that with decrease in statistical parameter the dynamic displacements increased significantly. But the values at 10% was close to the ones at 30% and the graphs followed the same pattern. Thus it was concluded that the value at 10% for statistical evaluation parameter gives us better results and it was chosen for all the simulations conducted in this thesis work.



Graph 2: Case 2, E-line2



Graph 3: Case 2, E-line 3

6 RESULTS

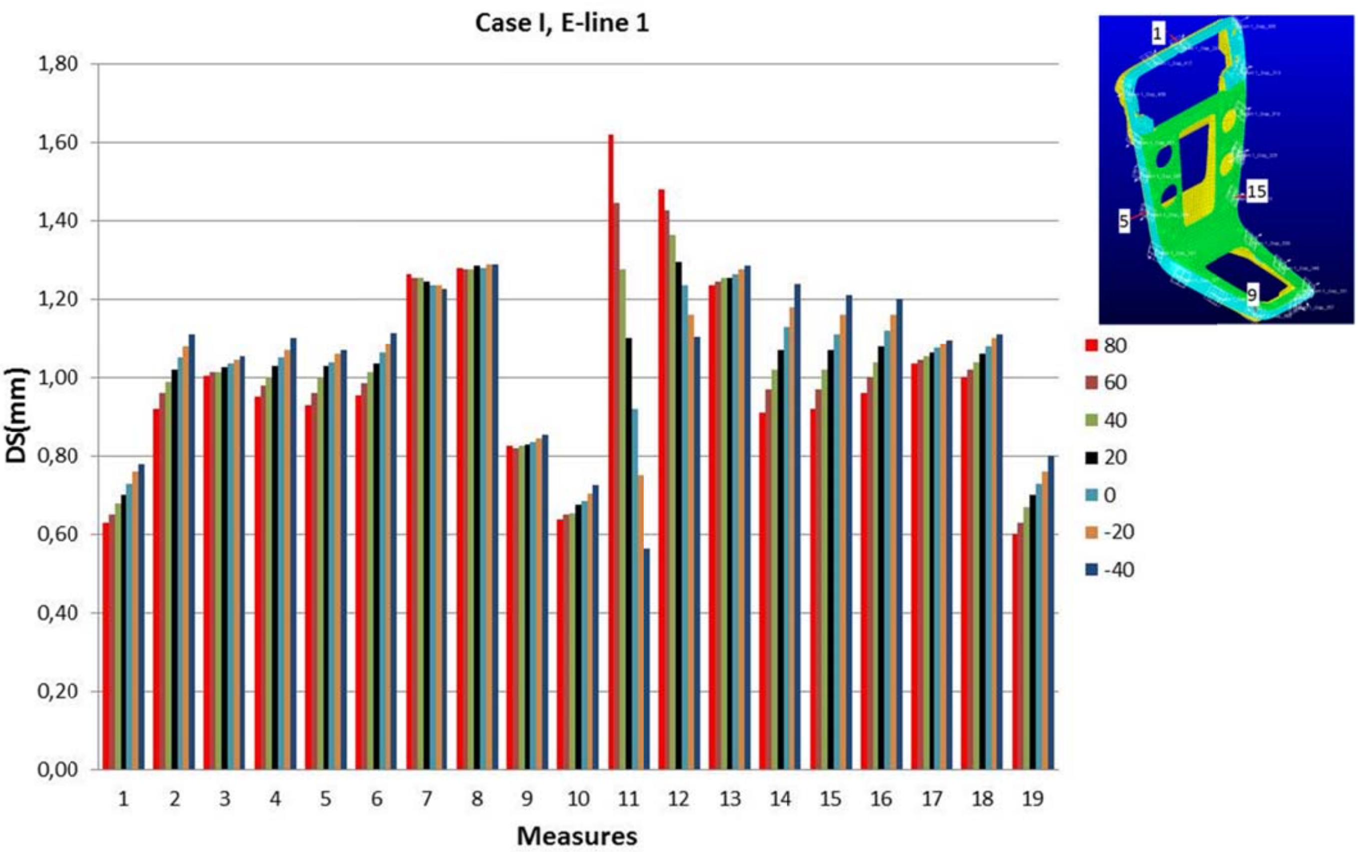
Results from the variation simulations, the contribution analyses and the modal transient analysis are shown in this chapter.

6.1 Case I

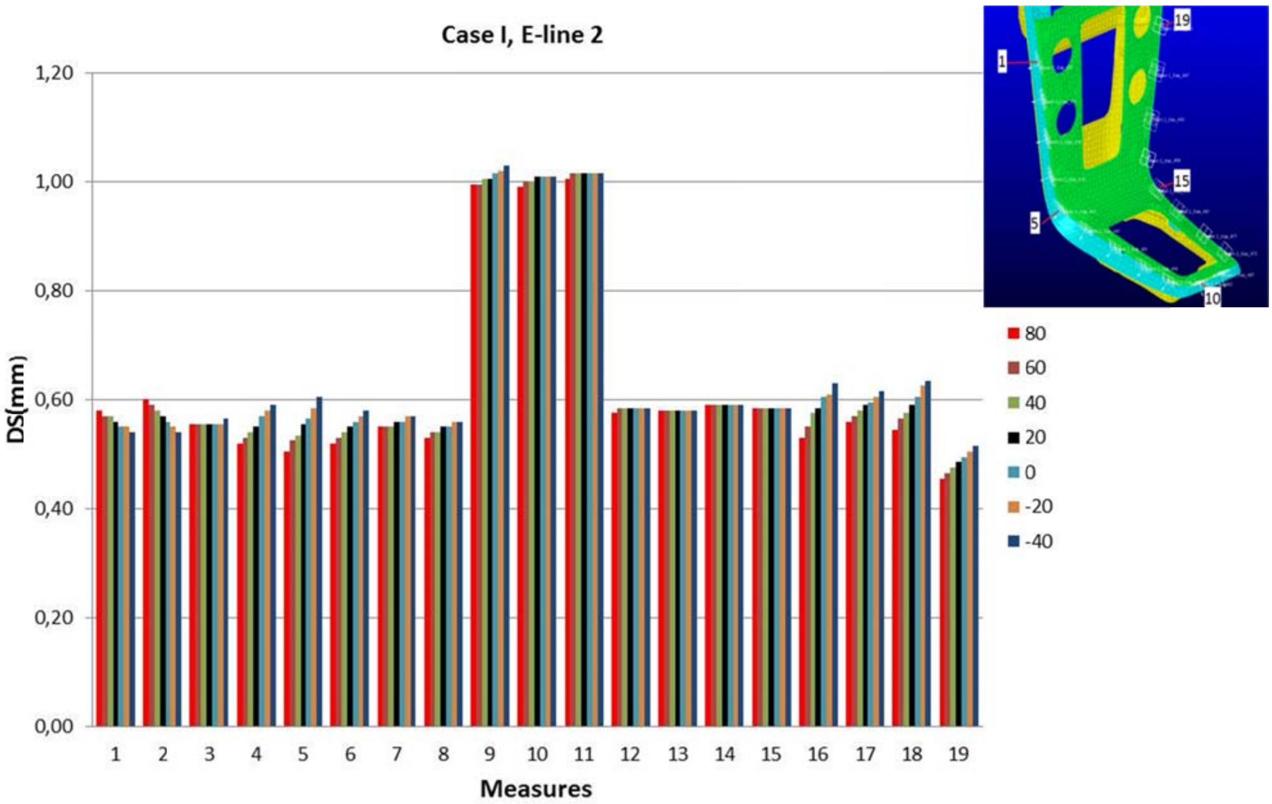
The result for case 1 is with only two E-lines and at different temperatures.

6.1.1 Variation analysis

It was observed in Graph 4 for E-line 1 and Graph 5 for E-line 2 with 19 points each, the static displacement for the components have different values at different temperatures. It can be seen that for points 11 and 12, *Ds* has 1.6 mm at 80°C and 0.6 at -40°C. But for point 19, the value of *Ds* is 0.6 at 80°C and 0,8 at -40°C.



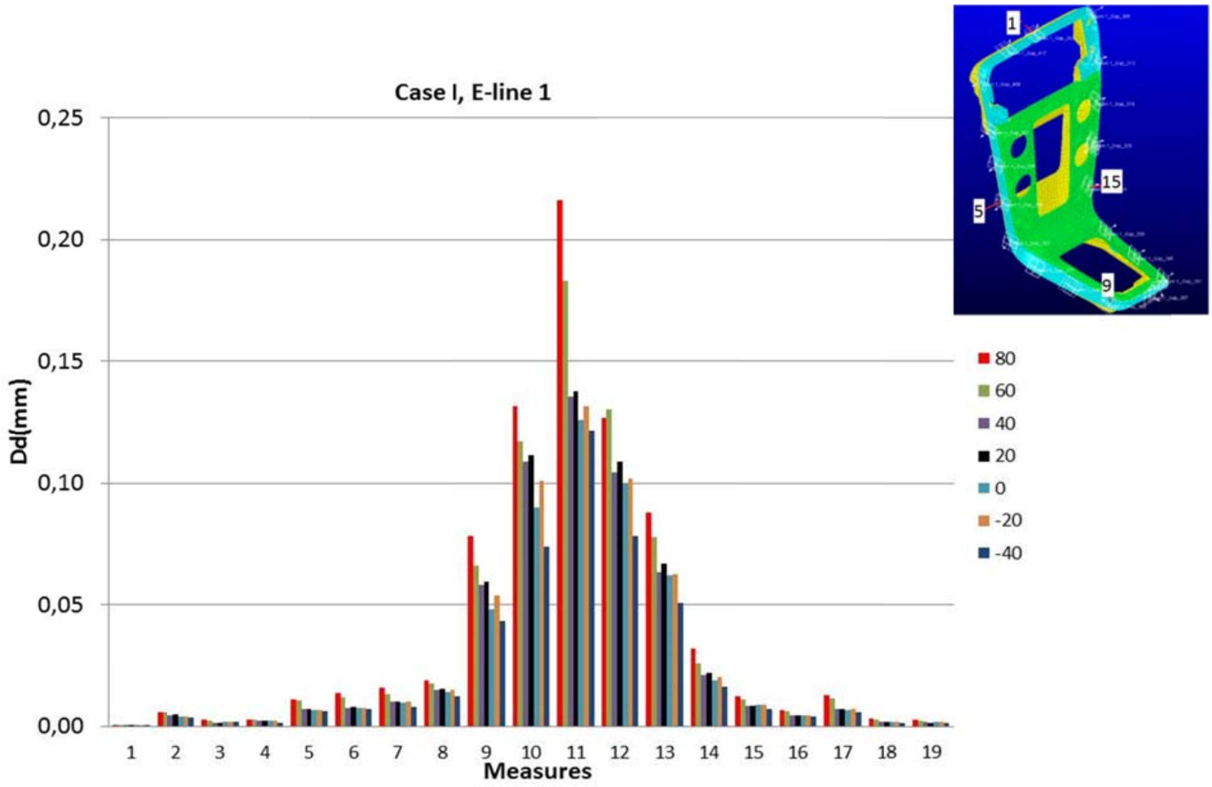
Graph 4: Static displacement , Case I, E-line 1



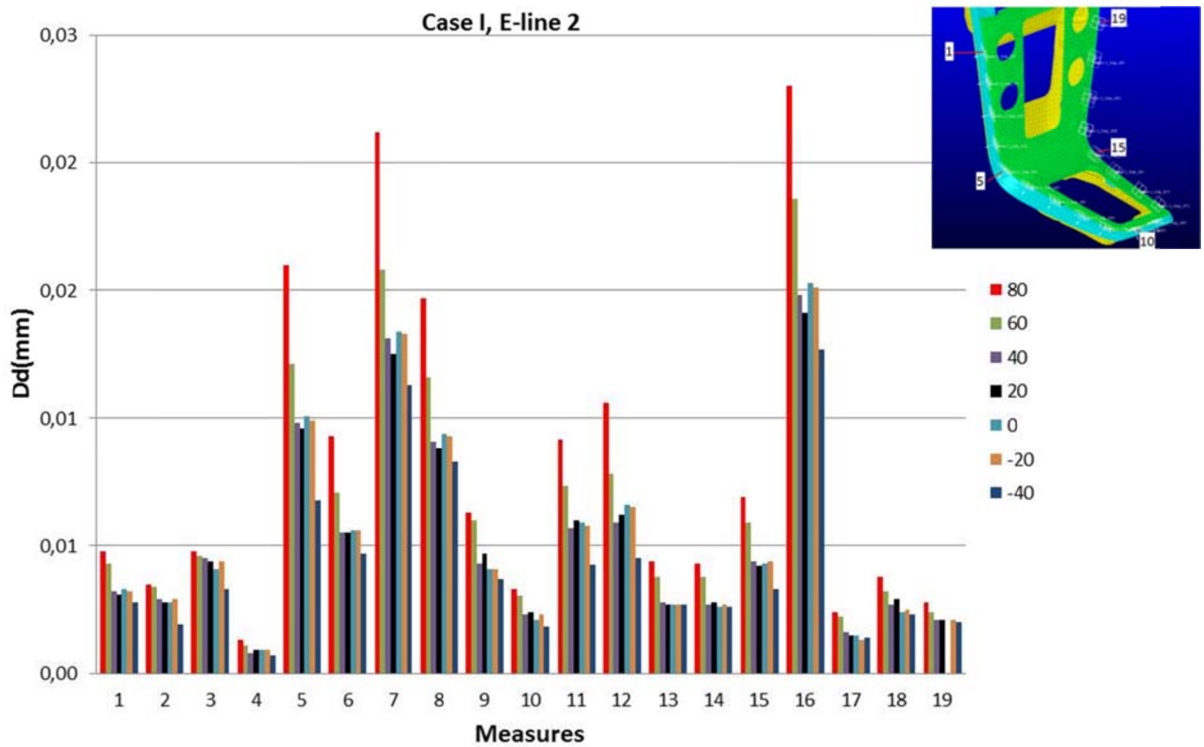
Graph 5: Static displacement , Case I, E-line 2

6.1.2 Modal transient analysis

The value of the dynamic displacement has been tabulated in graph 6 and 7 for different temperatures. It shows that there is difference in the values as temperature changes but it in the second order decimal place. The graphs 6 and 7 depict that for E-lines 1 and 2, the higher the temperature the greater is the value of *Dd*. For 80°C, Measure 11 has higher values of *Dd* for E-line 1 and measures 7, 8 and 16 have higher values for E-line 2.



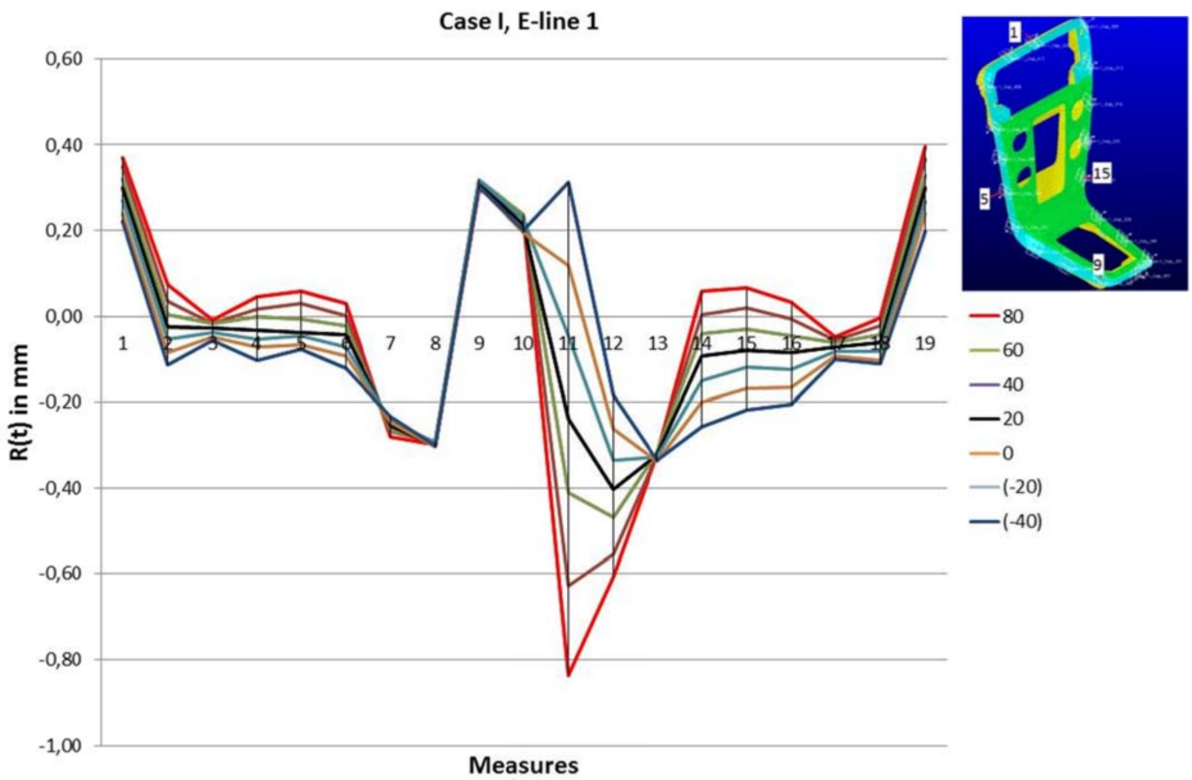
Graph 6: Dynamic displacement, Case I, E-line 1



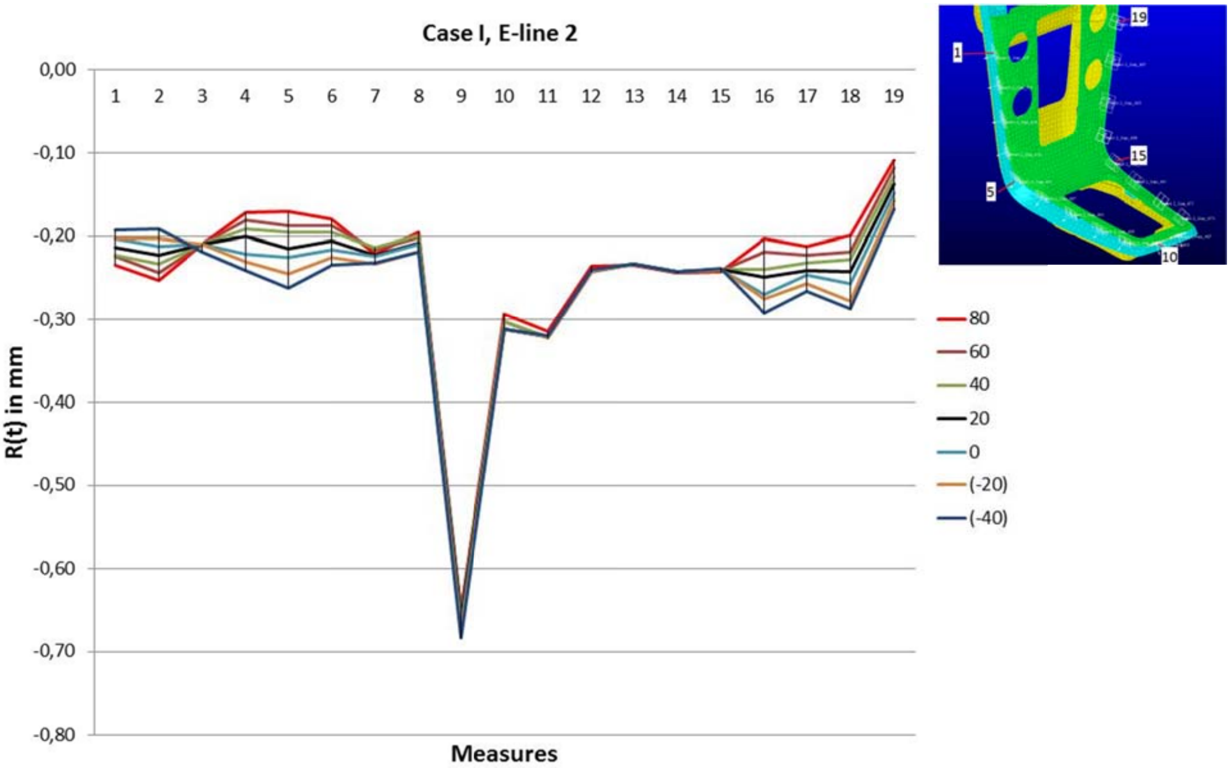
Graph 7: Dynamic displacement, Case I, E-line 2

6.1.3 Squeak and rattle analysis

The results were tabulated and effect of rattle was calculated as per equation (1). The graphs 8 and 9 indicate the values of *R(t)* for E-line 1 at different temperatures. Since the points having negative values of *R(t)* are sensitive to rattle and the points having positive values have no issues, it was observed that the measures 10, 11 and 12 which are present on the lower end of the Centre stack are prone to rattle for E-line 1. For these affected points the values of *R(t)* at 80°C is lower and values at -40°C is higher than the values at 20°C . *R(t)* indicates how prone points are to rattle, it could be that at low *R(t)* values there is squeaking instead of rattling though that is separately investigated. For E-line 2 all the values are below zero and measures 3 to 6 and measures 15 to 19 have lower values at 80°C in comparison to -40°C.

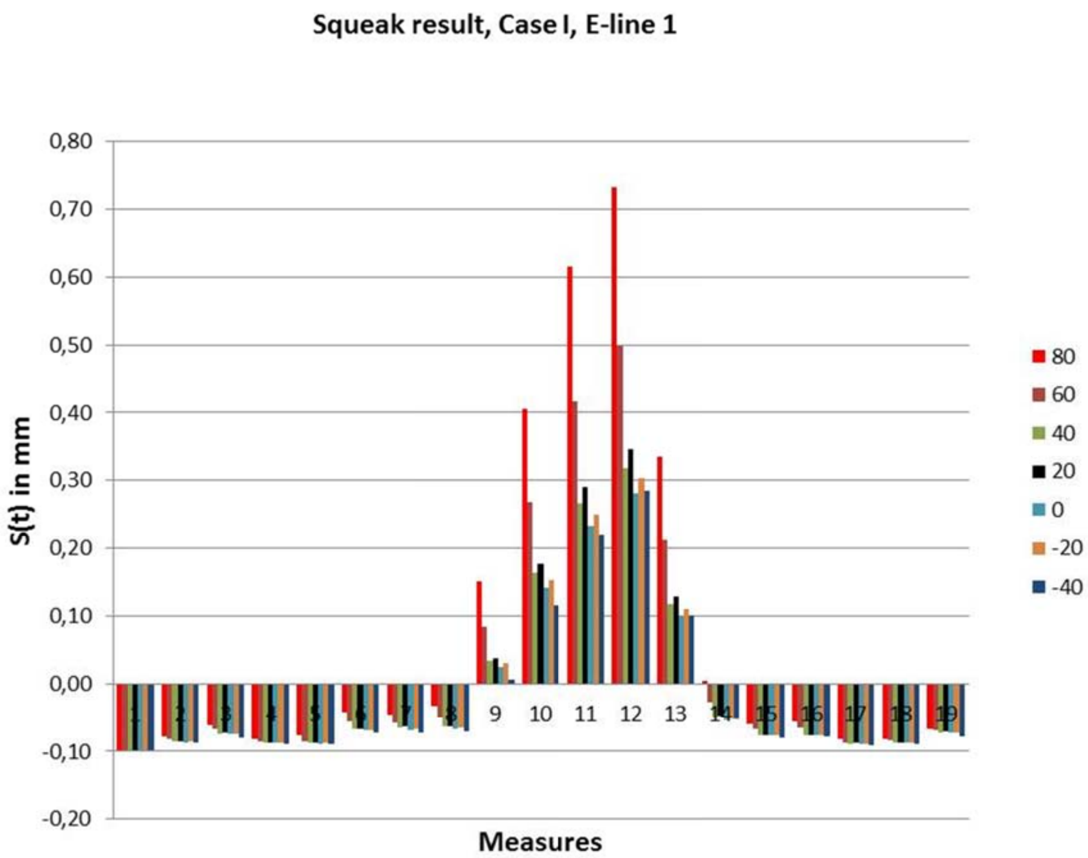


Graph 8: Rattle result , Case I, E-line 1



Graph 9: Rattle result, Case I, E-line 2

When the squeak condition was investigated according to equation (2) and equation (3), it was observed that there were five measures on E-line 1 from 9 to 13, which were in contact even without the dynamic displacement taken into account. The *S(t)* was calculated for these points where higher *S(t)* indicates more squeak. When the values were plotted in Graph 10, it was found that with increase in temperature *S(t)* increases. The change from 20°C to 80°C is significant depicted by taller bars. However with decrease in temperature, the values decrease gradually.



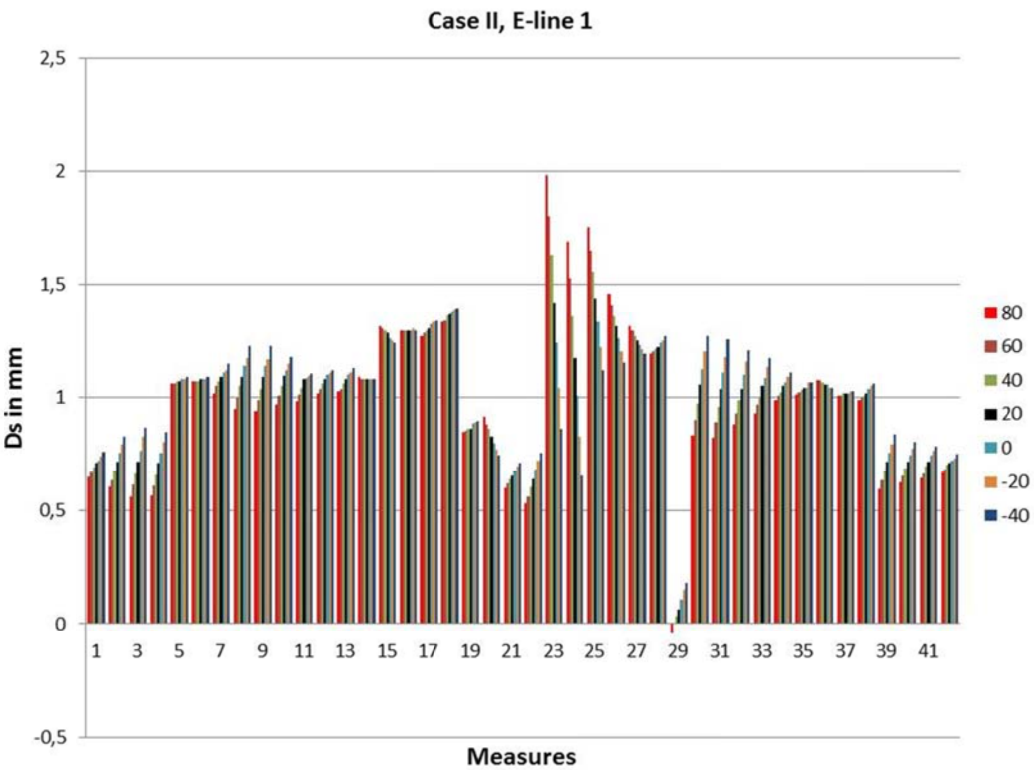
Graph 10: Squeak result, Case I, E-line 1

6.2 Case II

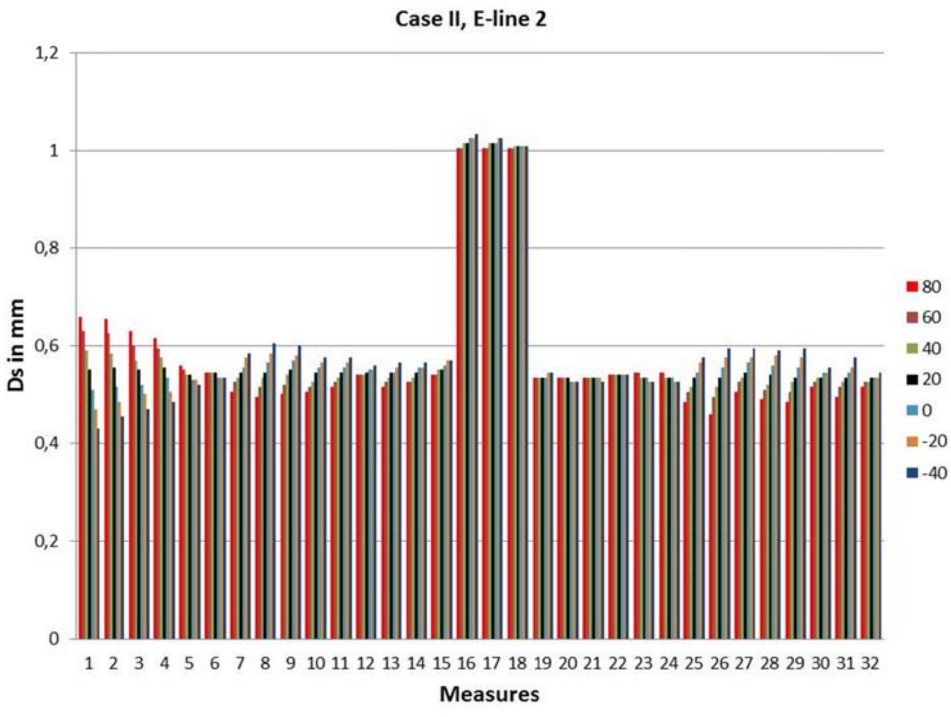
The result for Case II is with three E-lines, point masses on the radio and at different temperature.

6.2.1 Variation analysis

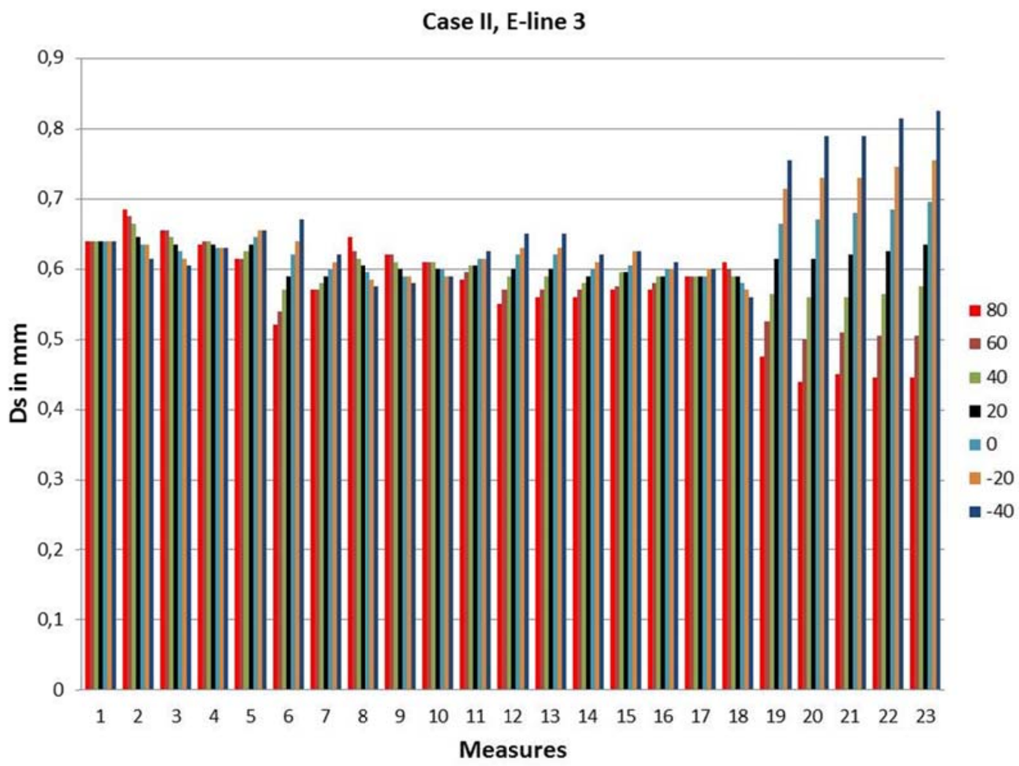
In this case, the static displacements for the measures on E-line 1, E-line 2 and E-line 3 are less than nominal gap at 20°C but increases with temperature for measures 23 to 28 on E-line 1 and 1 to 5 on E-line 2. But it was found out that the measures 18 to 23 on E-line 3 had greater *Ds* at -40°C and lower values at 80°C. This can be observed in the graphs 11, 12 and 13.



Graph 11: Static displacement, Case II, E-line 1



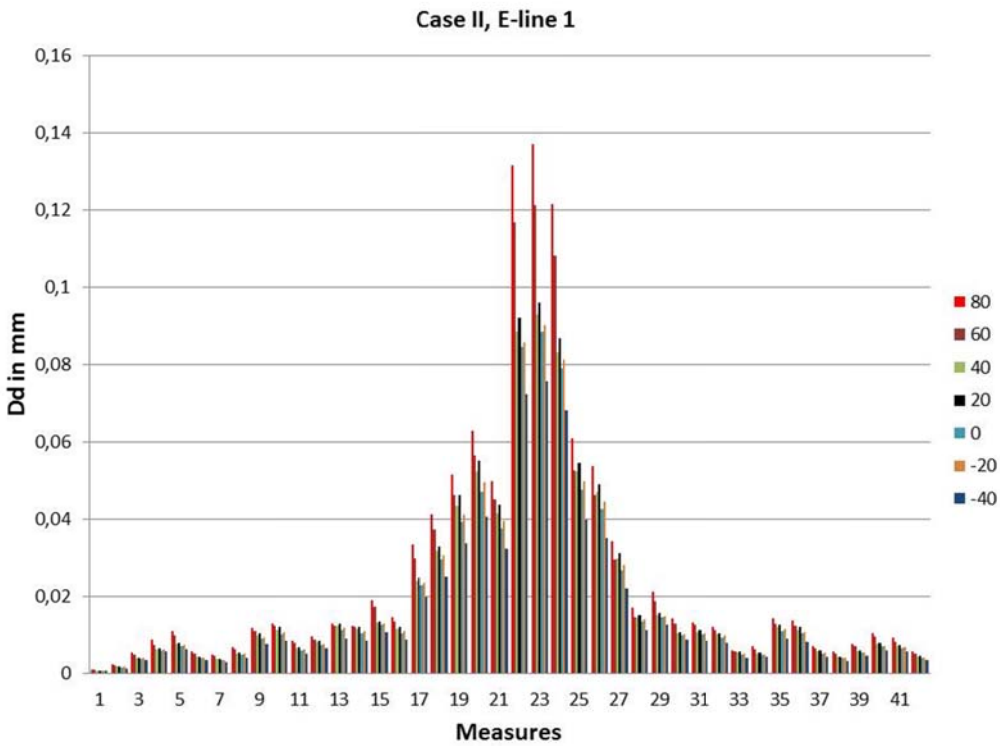
Graph 12: Static displacement, Case II, E-line 2



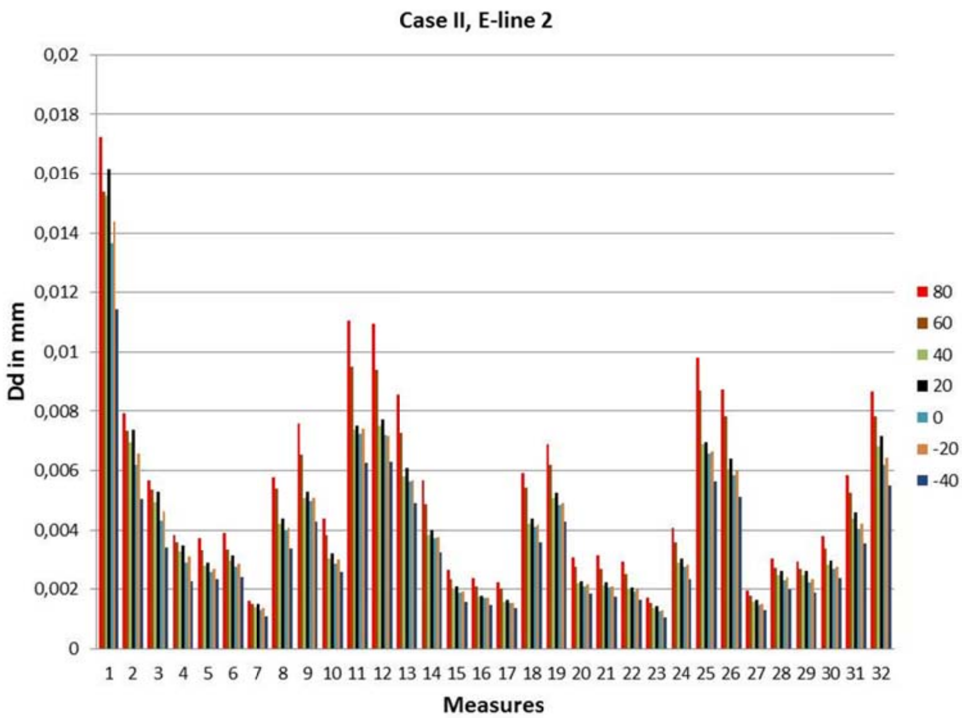
Graph 13: Static displacement, Case II, E-line 3

6.2.2 Modal analysis

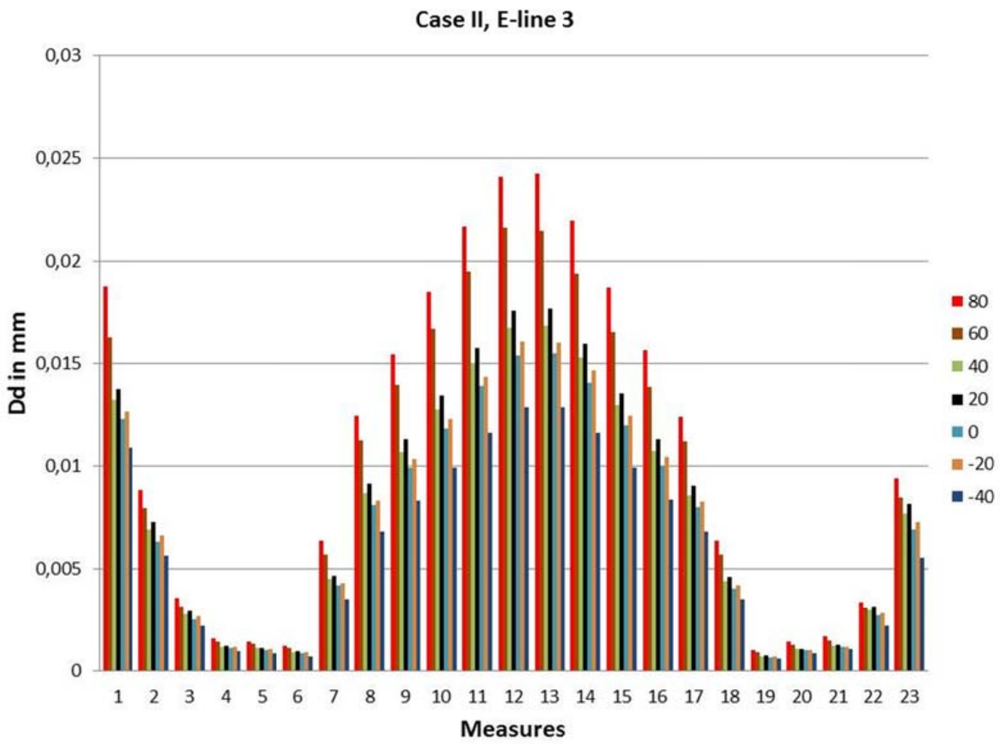
The dynamic displacements for the three E-lines have different values at different temperature and have been plotted in the graphs 14, 15 and 16. For all the three E-lines, the *Dd* at 80°C was higher than it was at other temperatures and the lowest values are observed at -40°C. Measures 21 to 25 on E-line 1, measures 1,11 to 13 on E-line 2 and measures 10 to 15 on E-line 3 were observed to have the highest difference between the *Dd* values at 80°C and -40°C).



Graph 14: Dynamic displacement, Case II, E-line 1



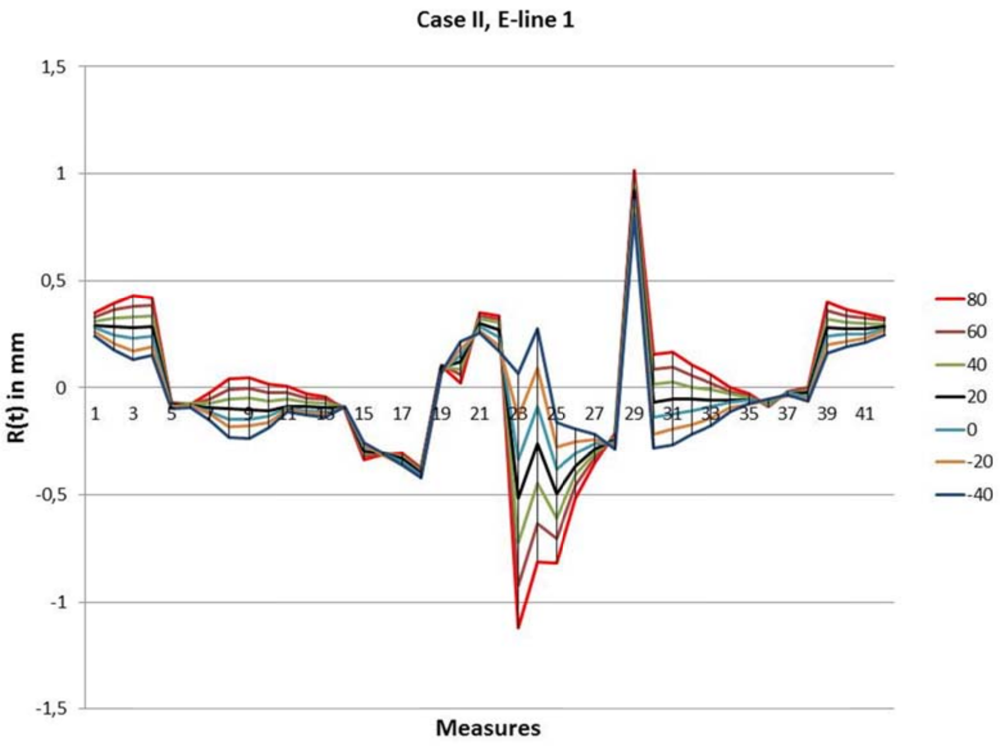
Graph 15: Dynamic displacement, Case II, E-line 2



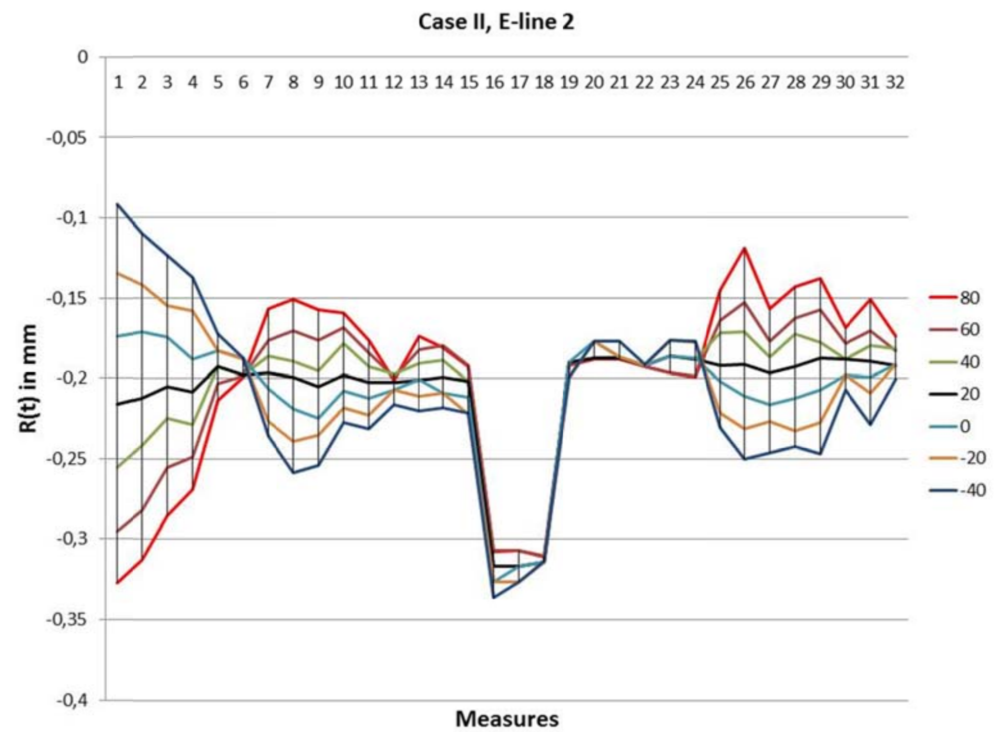
Graph 16: Dynamic displacement, Case II, E-line 3

6.2.3 Squeak and rattle analysis

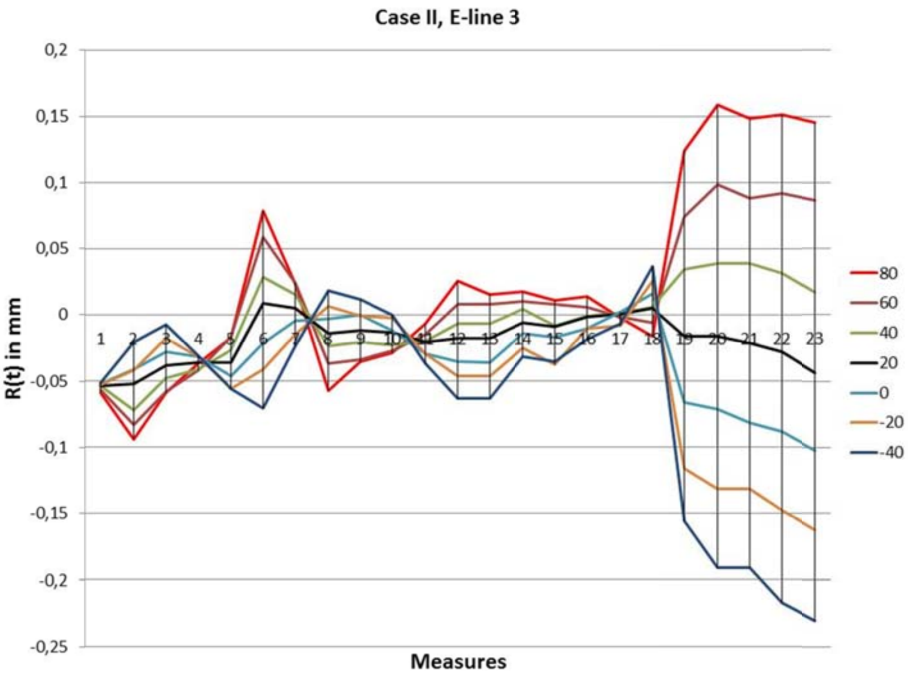
The values of *R(t)* were charted for the three different E-lines and the corresponding graphs have been plotted in Graphs 17, 18 and 19. It was observed that in E-line 1 the values of *R(t)* for different measures is close to zero at 20°C but value decreases for measures 21 to 25 at 80°C. In case of E-line 2 from measure 25 to 32 and in case of E-line 3 from measure 19 to 23 the value of *R(t)* decreases at -40°C and increases with increase in temperature.



Graph 17: Rattle result, Case II, E-line 1

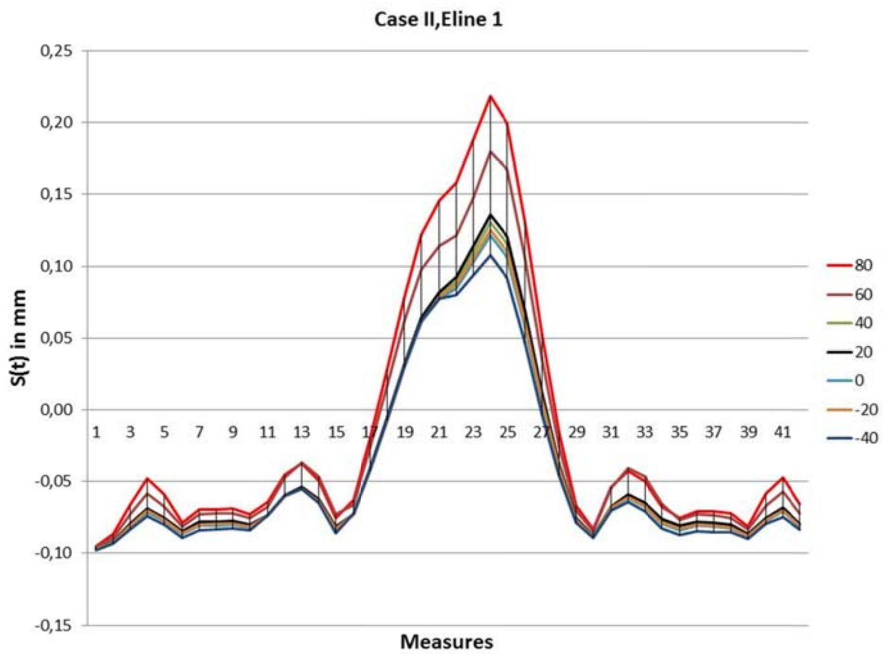


Graph 18: Rattle result, Case II, E-line 2



Graph 19: Rattle result, Case II, E-line 3

The values of *S(t)* was observed for the measures as per equation (3) which were in contact according to equation (2) . The values of *S(t)* for these measures increases with increase in temperature and is presented below in Graph 20.



Graph 20: Squeak result, Case II, E-line 1

6.2.4 Contribution analysis

The contribution sheet for one of the measure from E-line 1 at 20°C is shown in table 4. It was observed that the contribution of tolerance groups defined on the measures accounted for approximately 99 % of the total contribution together. It was almost the same for other measures on the E-line and can be found in the Ref document (29) at VCC.

Table 4: Contribution analysis, Case II, Seam 1

Contribution for the Measure: Seam 1_Gap_1078

Type: Point to Point distance.
Direction: Vector: 0.08, 0.02, 1.00
Description:
Points: CS_Inner\Node12408563
Ref. Points: CS_Ring\Node18602297
Alt. Asbl.:

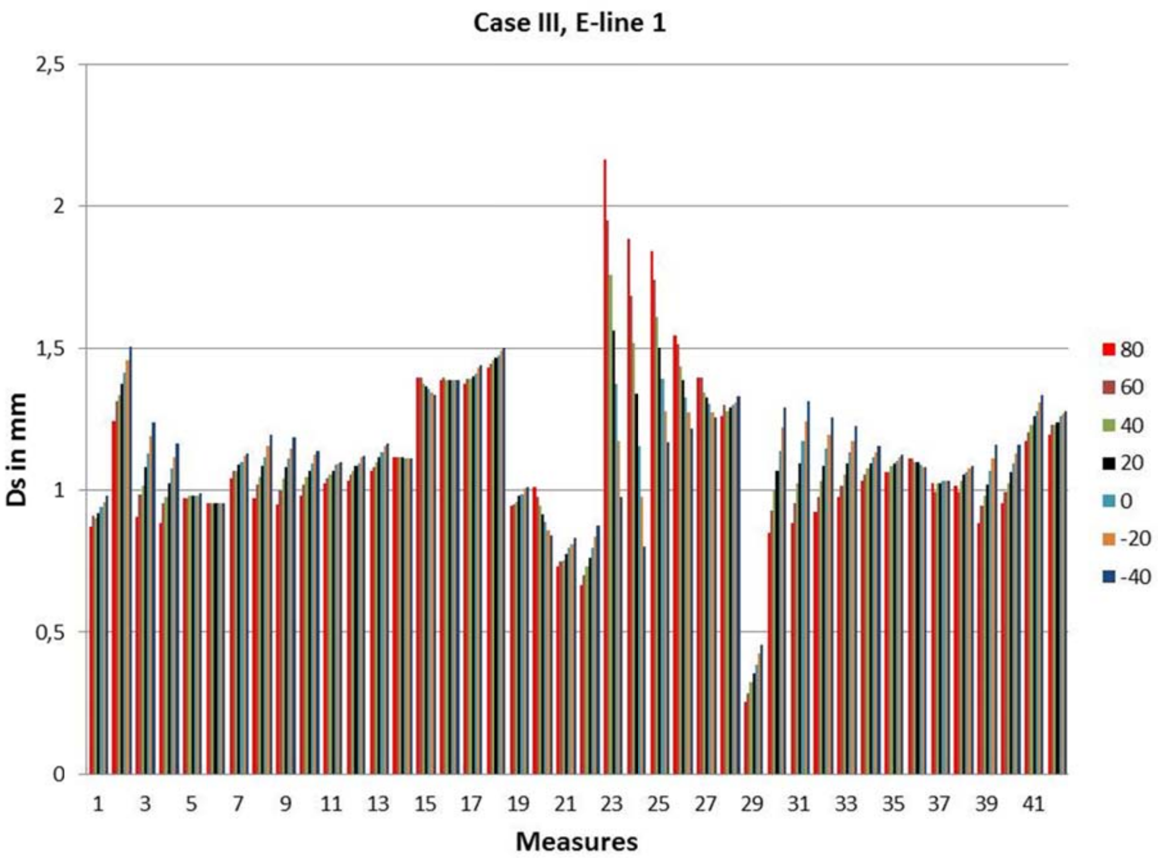
Part	Point/Arc	Tolerance	Range	Contr.	Tol. Dir.SubSystem
#Tolerance Group#	[1_I_T]	1_I_T_Tot	1.0	49.1%	0.1, 0.1, 1.0
#Tolerance Group#	[1_R_T]	1_R_T_Tot	1.0	49.1%	0.1,-0.1, 1.0
Fixture02	SubAssy01_Node12411403_2	Fixture02_SubAssy01_Node12411403_2_1	3.6	0.6%	1.0, 0.0, 0.0
Fixture02	SubAssy01_Node12412393	Fixture02_SubAssy01_Node12412393_1	3.5	0.5%	1.0, 0.0, 0.0
CS_Inner	Node12408563	1_I_T_Rel	0.1	0.2%	0.1, 0.0, 1.0
CS_Ring	Node18602297	1_R_T_Rel	0.1	0.2%	0.1, 0.0, 1.0
Fixture02	SubAssy01_Node12412559_2	Fixture02_SubAssy01_Node12412559_2_1	5.3	0.2%	0.0, 0.0, 1.0

6.3 Case III

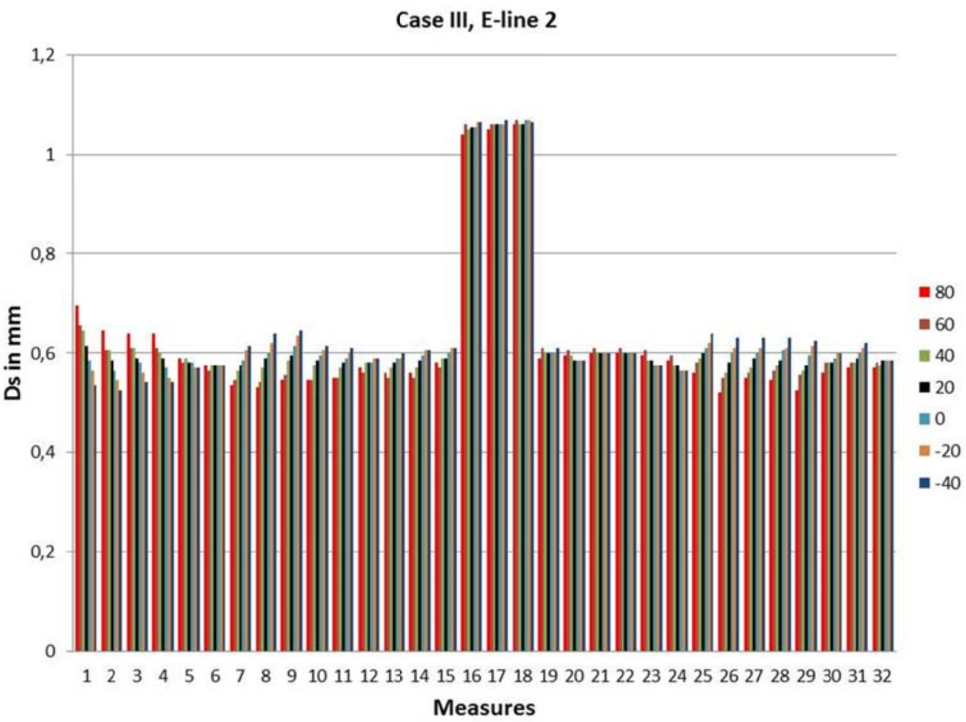
In this case the result is obtained for the three E-lines with tolerance on the screws and other parameters as in case 2 (point masses on the radio) and at different temperature.

6.3.1 Variation analysis

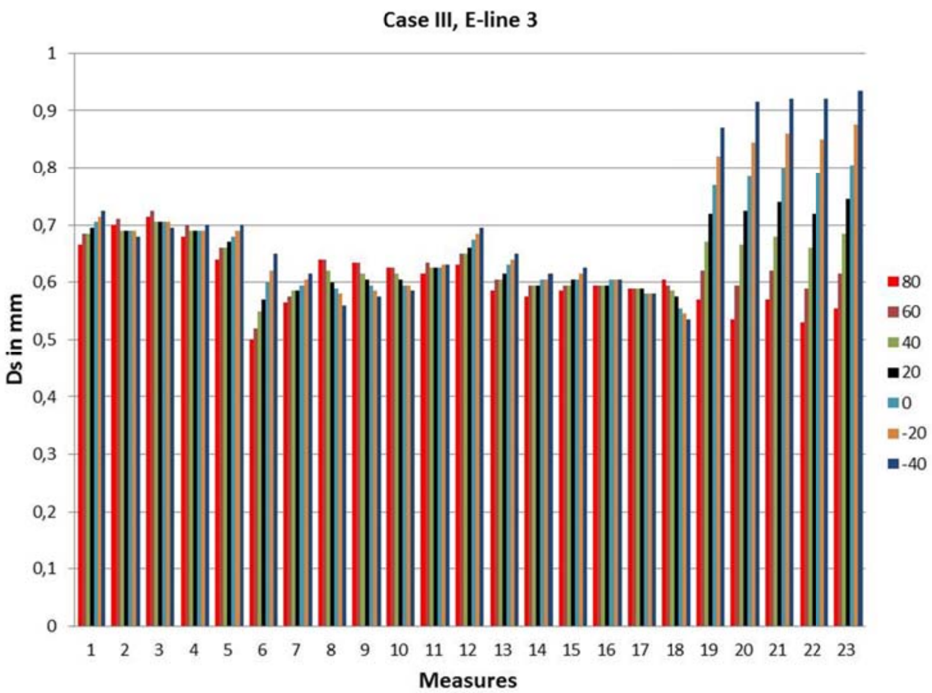
The values of Static displacement for different measures on E-line 1, E-line 2 and E-line 3 were observed to follow the same trend as in Case 2, but the overall values were slightly higher than previous case. The static displacements for the three E-lines have been plotted in Graphs 21, 22 and 23.



Graph 21: Static displacement, Case III, E-line 1



Graph 22: Static displacement, Case III, E-line 2



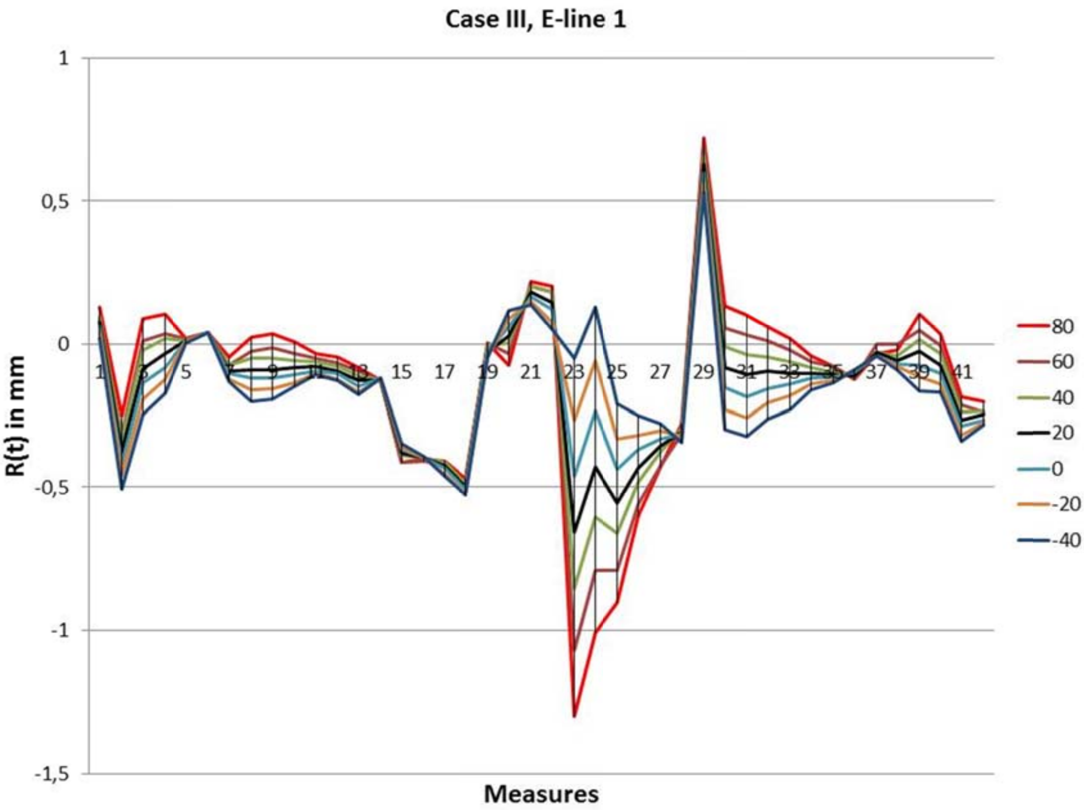
Graph 23: Static displacement, Case III, E-line 3

6.3.2 Modal analysis

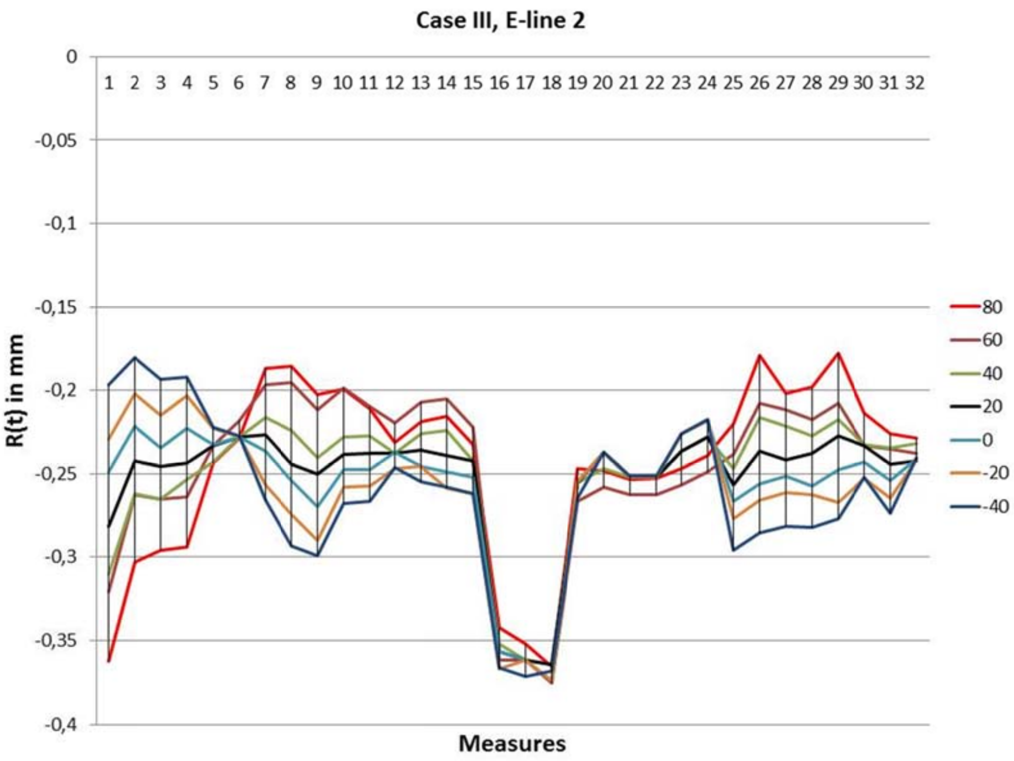
The dynamic displacements for the three E-lines are same as in case 2.

6.3.3 Squeak and rattle analysis

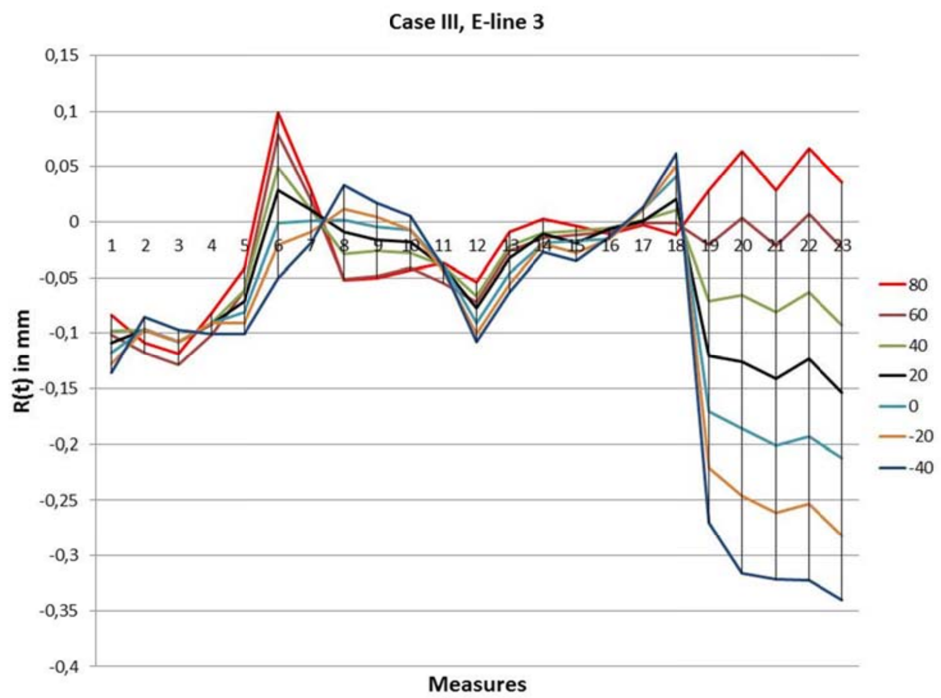
The *R(t)* values for the three E-lines in this case have the same trend as in case 2 but the values are slightly different. A number of measures have different values of *R(t)* at different temperatures in case of E-line 2. In case of E-line 3 the measures from 19 to 23 have wide range of values at different temperatures.



Graph 24: Rattle result, Case III, E-line 1

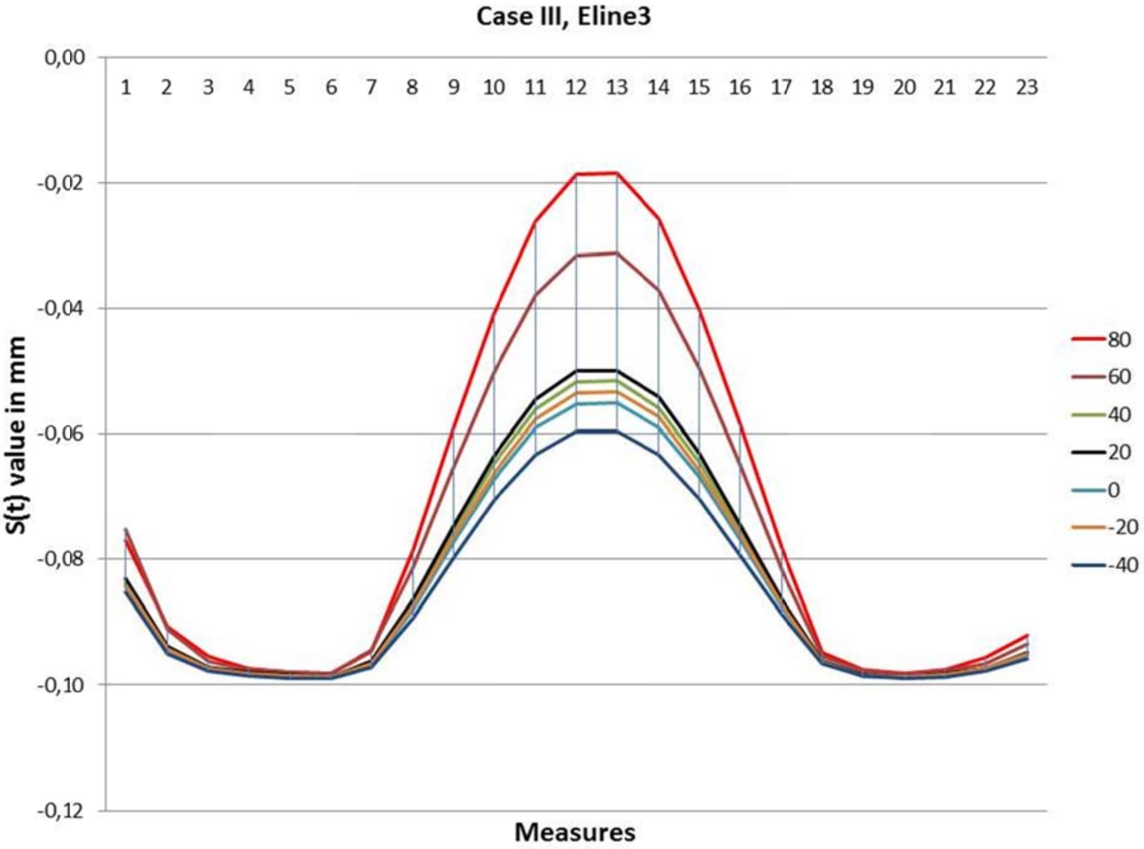


Graph 25: Rattle result, Case III, E-line 2



Graph 26: Rattle result, Case III, E-line 3

The *S(t)* values were observed for those measures which had no gap after static displacements. The *S(t)* values have been plotted in the graphs below.



Graph 27: Squeak result, Case III, E-line 2

6.3.4 Contribution analysis

The contribution sheet was observed for one the measures from E-line 1 at 20 deg. It was observed that the contribution of screw tolerance was significant in addition to the other tolerances on the measures and the locating schemes. These can be observed in Table 5 below:

Table 5: Contribution analysis, Case III, Seam 1

Contribution for the Measure: Seam 1_Gap_1166

Type: Point to Point distance.
Direction: Vector: 0.73, 0.59, 0.36
Description:
Points: CS_Inner\Node12408566
Ref. Points: CS_Ring\Node18593152
Alt. Asbl.:

Part	Point/Arc	Tolerance	Range	Contr.	Tol. Dir.SubSystem
#Tolerance Group#	[SubAssy01_Fastener12_ZdirL]	SubAssy01_Fastener12_ZdirL_Tot	0.4	32.9%	-0.0,-0.0, 1.0
#Tolerance Group#	[SubAssy01_Fastener11_ZdirL]	SubAssy01_Fastener11_ZdirL_Tot	0.4	23.2%	-0.0,-0.0, 1.0
Fixture02	SubAssy01_Node12412559_2	Fixture02_SubAssy01_Node12412559_2_1	5.3	10.6%	0.0, 0.0, 1.0
#Tolerance Group#	[1_R_B]	1_R_B_Tot	1.0	9.3%	0.4,-0.4, 0.8
#Tolerance Group#	[SubAssy01_Fastener09_ZdirL]	SubAssy01_Fastener09_ZdirL_Tot	0.4	8.3%	-0.0, 0.0, 1.0
#Tolerance Group#	[1_I_B]	1_I_B_Tot	0.8	6.0%	0.4,-0.4, 0.8
#Tolerance Group#	[SubAssy01_Fastener13_ZdirL]	SubAssy01_Fastener13_ZdirL_Tot	0.4	3.2%	-0.0,-0.0, 1.0
#Tolerance Group#	[SubAssy01_Fastener08_ZdirL]	SubAssy01_Fastener08_ZdirL_Tot	0.4	0.6%	-0.0, 0.0, 1.0
#Tolerance Group#	[SubAssy01_Fastener13_ZdirT]	SubAssy01_Fastener13_ZdirT_Tot	0.4	0.5%	-0.0,-0.0, 1.0
Fixture02	SubAssy01_Node12411878_2	Fixture02_SubAssy01_Node12411878_2_1	5.3	0.5%	0.0, 0.0, 1.0
#Tolerance Group#	[SubAssy01_Fastener16_ZdirL]	SubAssy01_Fastener16_ZdirL_Tot	0.4	0.3%	1.0, 0.0, 0.3
CS_Outer	Node24804202	SubAssy01_Fastener19_YdirT	0.4	0.3%	0.0, 1.0,-0.0
CS_Inner	Node12408231	SubAssy01_Fastener19_YdirL	0.4	0.3%	0.0, 1.0,-0.0
#Tolerance Group#	[SubAssy01_Fastener18_ZdirL]	SubAssy01_Fastener18_ZdirL_Tot	0.4	0.2%	-0.1,-0.0, 1.0
#Tolerance Group#	[SubAssy01_Fastener18_ZdirT]	SubAssy01_Fastener18_ZdirT_Tot	0.4	0.2%	-0.1,-0.0, 1.0
#Tolerance Group#	[SubAssy01_Fastener08_ZdirT]	SubAssy01_Fastener08_ZdirT_Tot	0.4	0.2%	-0.0, 0.0, 1.0
CS_Ring	Node18603647	SubAssy01_Fastener12_YdirL	0.4	0.2%	-0.0, 1.0, 0.0
CS_Outer	Node24804131	SubAssy01_Fastener12_YdirT	0.4	0.2%	-0.0, 1.0, 0.0
CS_Ring	Node18603437	SubAssy01_Fastener12_ZdirL_Rel	0.0	0.1%	-0.0,-0.0, 1.0
CS_Ring	Node18603238	SubAssy01_Fastener11_ZdirL_Rel	0.0	0.1%	-0.0,-0.0, 1.0
CS_Ring	Node18603658	SubAssy01_Fastener11_YdirL	0.4	0.1%	0.0, 1.0, 0.0
CS_Outer	Node24804332	SubAssy01_Fastener11_YdirT	0.4	0.1%	0.0, 1.0, 0.0

7 DISCUSSION AND CONCLUSION

Discussion, conclusions and deliverables are handled in this chapter.

7.1 DISCUSSION

In *case 1* it is clearly seen that the values for the static displacement are much higher than the dynamic displacement. It is clear that some areas of the parts, especially measures 11, 12 and 13 in E-line 1 are more prone to rattle than the other. These points are in the bottom end of the centre stack, far away from the closest fasteners see figure 41. It is obvious that these measures have high dynamic displacements also. Therefore the measures 11 to 13 are sensitive to rattle and it was desired to observe the changes between these measures by selecting more number of measures in *case 2* than in *case 1*. Since these measures have wide difference of both static and dynamic displacements, the variation of *R(t)* values is justified.

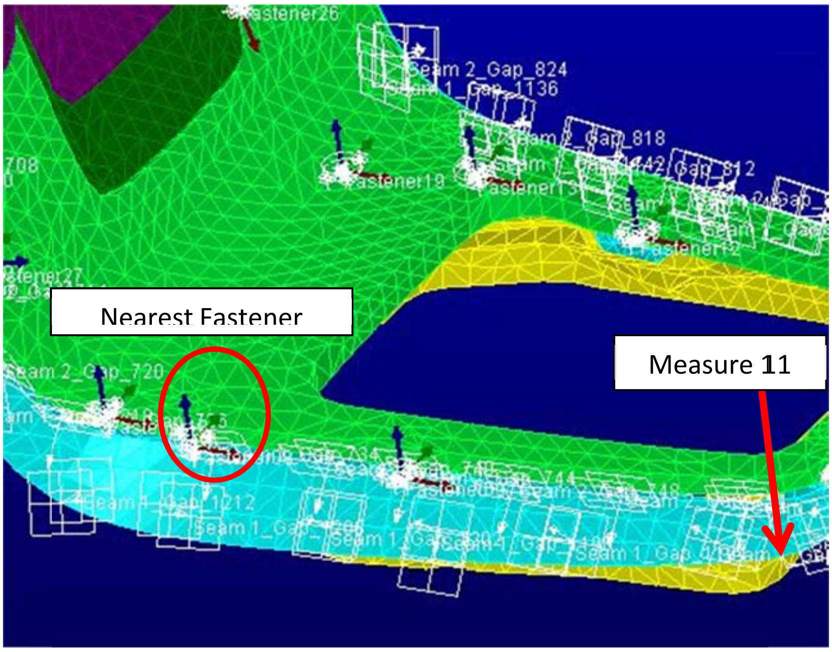


Figure 41: Long distance between measure 11 and nearest fastener

In E-line 2 there are a lot of screws between the parts which is why we have less dynamic displacement. The effect of temperature for some of the measures from 4 to 7 and 15 to 19 is observed, but they are not concerning. Moreover the parts are always in contact as they are flexible and have to be fit to shape. One could expect squeak in such case, but since there is a layer of chrome on ABS, no major squeak issues were found as observed in lower *S(t)* values.

In *case 2* the addition of masses affected the dynamic displacement. This is why the dynamic displacements for measures 21 to 27 were very high on E-line 1. As more measures were added for all the E-lines, the behaviour could be observed for these sensitive points which correspond to the sensitive measures in *case 1. The* addition of more parts made the model more realistic.

For E-line 2 in *case 2* the measure 16 lies in the corner and thus observed to have large negative values. The squeak was only investigated for E-line 1 since no points were observed to be in contact for E-line 2. It can be observed that the squeak increases with increased temperature. The Young's modulus being lower at higher temperatures decrease the stiffness and thus the relative displacement and subsequently the mpP2P is larger thus more squeak occurs.

For E-line 3 in *case 2* the measures 19 to 23 which lie near the upper right corner come closer to each other with decreasing temperature. Although it is understood that the parts shrink with decreasing temperature, but still the parts come closer to each other at lower temperatures in E-line 3. One of the reasons could be the position of the fasteners and also the shape of the parts along the split lines.

In order to make the model more realistic, tolerances were added on all the fasteners in *case 3*. The graphs have a similar trend as the other two cases, which validates that temperature does affect squeak and rattle. But higher values of static displacement are observed which is expected because of the tolerances of the fasteners. It is quite logical that with more tolerances on the attachments, the variation would be larger. This validates the correctness of the model.

Although it can be considered that the results are accurate there was lot of factors which could contribute error to the final result. In fact there were several uncertain factors which could have affected the result. One such factor is that the measures in RD&T were not exactly on the same positions as the spring elements in Ansa, both the geometry of the models and the way the measures/spring elements were created contributed to that uncertainty. One of the other factors is that the fasteners are created near the holes but are not in the exact centre. Additionally the tolerances which were given to the fasteners were acquired from drawings depicting later revisions of the parts actually used in this thesis. Thus many values had to be estimated.

A mesh size of 10 mm was considered for this thesis and it could be argued that a smaller mesh size could give more accurate results. The models considered in this thesis were meshed by experienced employees and have been used earlier in the NVH department at VCC. So the models with the particular mesh size were considered to be valid for this thesis work.

In this thesis, the developers of the RD&T software and the E-line were easily accessible and problems could be referred to them without any delay. This close association was understood to be an advantage as it decreased the lead time for software updates and obtaining assistance for performing simulations. The fact that many files in conjunction with Ansa and Nastran were in text format made it easy to modify and overview their content which was a crucial part in the work process.

7.2 CONCLUSION

Considering all the three cases, it can be concluded that temperature does affect squeak and rattle for case I, case II & case III. The dynamic displacement is larger at higher temperatures as the stiffness decreases for the parts. But the static displacements could either increase or decrease which depends on the position of the measures, the locating schemes and the shape of the part.

7.3 DELIVERABLES

- Along with this master thesis three manuals were created for VCC use only which in detail describe the steps needed in order to simulate squeak and rattle. These manuals can be found at VCC in Perceived Quality department.
- A number of modifications could be suggested in RD&T and the performance of features implemented parallel to the thesis work could be tried.

8 RECOMMENDATIONS

It is important that models in all programs represent reality as close as possible and also that model in one program corresponds to the model in the others. In this project, the measures in RD&T did not completely correspond to the spring elements in Ansa even though steps were taken in order to make it so, such as creating a great amount of measures and then deleting the superfluous ones. It would be desired to in the future be able to export the surface strip, which is planned, as well as all the nodes measures are connected to from RD&T to Ansa.

If measures could be exported from RD&T to Ansa it should be considered to revisit the verification of having expanded parts versus non-expanded ones in Ansa.

Many values for the squeak limit were taken from an already created database. It did not contain all values needed, especially not for temperatures other than 20°C. It should be considered to expand this database to include a more complete selection of materials at different temperatures and humidity. It should also be investigated how to simulate the contact force between two parts in contact. This could then be used in the stick slip experiment to get more valid results.

Due to time constraint only 500 runs were selected. With the new RD&T version with the optimizer, the other models could be simulated with higher number of runs to observe the changes in the result.

Due to the scope of the project, contact force used in the slip stick measurement was considered from expert advises. However in the future work it could be considered to deduce the correct contact forces when two parts are in contact with each other.

In order to observe if the dynamic displacement values obtained from simulations are accurate or not, they should be compared by conducting similar experiments. So, in the future the whole set up can be mounted on a shaker table and a climate chamber to obtain real time outputs. With the help of this set up the dynamic displacement values could be observed for various temperatures.

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Appendix A – Continuous improvements

In this appendix improvements that were implemented in RD&T are described.

- February 12th: New RD&T with thermal expansion also works for parabolic elements.
- February 19th: Contact modelling now works with solid elements.
- Mars 19th: The "Move Gap to Mesh" feature was implemented.
- Mars 21th: Using the composite feature for one material but several thicknesses was introduced.
- April 4th: To maintain the correct tolerance directions after using "Move Gap to Mesh" a "Copy Direction from Measures" was introduced which automatically accomplishes that.
- April 29th: A bug preventing a seam to be created if both compliant and rigid models were present was solved.
- May 19th: An optimisation routine for contact modelling was introduced effectively reducing the simulation time by 98%.

Appendix B – Result sheet

In this appendix the result sheet can be found from which the graphs in the result chapter were derived.

		20 DEGREES				80 DEGREES					60 DEGREES		
Measure	Nominal (	Mean	8 Sig	Ds(max)20	Dd(max) 2(	Mean	8 Sig	Ds(max)80	Dd(max)80	Mean	8 Sig	Ds(max)60	Dd(max) 6(
SEAM 1													
1001	1	3,68	1,84	0,92	0,00072	3,73	1,84	0,92	0,00099	3,69	1,84	0,92	0,00088
1002	1	3,43	2,75	1,375	0,00177	3,56	2,75	1,375	0,00232	3,49	2,75	1,375	0,00208
1003	1	3,45	2,16	1,08	0,0041	3,62	2,15	1,075	0,00548	3,54	2,15	1,075	0,00476
1004	1	3,62	2,05	1,025	0,00649	3,76	2,05	1,025	0,00872	3,69	2,05	1,025	0,00747
1005	1	4,03	1,96	0,98	0,00799	4,04	1,96	0,98	0,01088	4,04	1,96	0,98	0,0099
1006	1	4,02	1,91	0,955	0,00433	4,02	1,91	0,955	0,00573	4,02	1,91	0,955	0,00516
1007	1	4,08	2,18	1,09	0,00373	4,13	2,18	1,09	0,00493	4,1	2,18	1,09	0,00449
1008	1	4,05	2,17	1,085	0,00532	4,17	2,18	1,09	0,00687	4,12	2,18	1,09	0,00618
1009	1	3,85	2,16	1,08	0,01033	3,98	2,16	1,08	0,01181	3,93	2,16	1,08	0,01098
1010	1	3,95	2,14	1,07	0,0121	4,05	2,16	1,08	0,01277	4,01	2,16	1,08	0,01246
1011	1	3,95	2,14	1,07	0,00681	4,01	2,17	1,085	0,00848	3,99	2,16	1,08	0,00784
1012	1	4,01	2,17	1,085	0,00845	4,07	2,19	1,095	0,00967	4,05	2,19	1,095	0,00867
1013	1	4,16	2,23	1,115	0,01288	4,21	2,24	1,12	0,01276	4,2	2,24	1,12	0,01224
1014	1	3,14	2,23	1,115	0,01203	3,14	2,23	1,115	0,01245	3,14	2,23	1,115	0,01213
1015	1	3,1	2,73	1,365	0,01354	3,07	2,73	1,365	0,01909	3,07	2,73	1,365	0,01726
1016	1	3,1	2,77	1,385	0,01198	3,1	2,77	1,385	0,01458	3,09	2,77	1,385	0,01332
1017	1	3,08	2,8	1,4	0,02496	3,11	2,81	1,405	0,03337	3,09	2,8	1,4	0,02971
1018	1	3,11	2,93	1,465	0,03284	3,15	2,94	1,47	0,04126	3,13	2,93	1,465	0,03723
1019	1	3,1	1,96	0,98	0,0461	3,14	1,97	0,985	0,05152	3,13	1,96	0,98	0,04614
1020	1	3,59	1,83	0,915	0,05515	3,5	1,84	0,92	0,06279	3,53	1,83	0,915	0,0566
1021	1	3,6	1,55	0,775	0,0437	3,65	1,56	0,78	0,04971	3,63	1,56	0,78	0,04504
1022	1	3,64	1,52	0,76	0,09217	3,74	1,53	0,765	0,13157	3,7	1,52	0,76	0,11667
1023	1	3,23	3,12	1,56	0,09583	2,62	3,11	1,555	0,13692	2,84	3,12	1,56	0,12125
1024	1	2,38	2,68	1,34	0,08689	1,83	2,67	1,335	0,12142	2,03	2,67	1,335	0,10809
1025	1	3,67	3	1,5	0,05442	3,33	3	1,5	0,06107	3,43	3	1,5	0,05254
1026	1	4,63	2,77	1,385	0,04911	4,47	2,77	1,385	0,05364	4,5	2,77	1,385	0,04633
1027	1	4,21	2,65	1,325	0,03123	4,14	2,65	1,325	0,03425	4,14	2,65	1,325	0,02954
1028	1	4,1	2,58	1,29	0,01523	4,13	2,58	1,29	0,01702	4,09	2,58	1,29	0,01455
1029	1	4,13	0,71	0,355	0,01566	4,23	0,711	0,3555	0,02125	4,2	0,711	0,3555	0,0188
1030	1	4,2	2,14	1,07	0,01067	4,42	2,14	1,07	0,0144	4,34	2,14	1,07	0,01295
1031	1	3,94	2,19	1,095	0,0112	4,15	2,19	1,095	0,01308	4,08	2,19	1,095	0,01248
1032	1	3,93	2,17	1,085	0,01052	4,09	2,17	1,085	0,01211	4,04	2,17	1,085	0,01135
1033	1	3,93	2,19	1,095	0,00557	4,05	2,19	1,095	0,00606	4,01	2,19	1,095	0,00567
1034	1	3,94	2,19	1,095	0,0053	4	2,19	1,095	0,00696	3,98	2,19	1,095	0,00622
1035	1	4,06	2,19	1,095	0,01268	4,09	2,19	1,095	0,01433	4,09	2,19	1,095	0,0129
1036	1	4,09	2,2	1,1	0,01195	4,08	2,2	1,1	0,01361	4,08	2,2	1,1	0,01233
1037	1	4,1	2,05	1,025	0,00584	4,1	2,05	1,025	0,00715	4,13	2,05	1,025	0,0064
1038	1	4,29	2,11	1,055	0,00431	4,33	2,11	1,055	0,00572	4,35	2,11	1,055	0,00508
1039	1	3,53	2,04	1,02	0,00591	3,66	2,03	1,015	0,00774	3,6	2,03	1,015	0,00711
1040	1	3,44	2,13	1,065	0,00787	3,55	2,13	1,065	0,01046	3,51	2,13	1,065	0,00947
1041	1	3,68	2,52	1,26	0,0073	3,76	2,51	1,255	0,00924	3,73	2,51	1,255	0,00829
1042	1	3,46	2,48	1,24	0,00446	3,5	2,47	1,235	0,00573	3,47	2,48	1,24	0,00505

Figure 42: Result sheet with nominal gap, static displacement and dynamic displacement at 20°C,80°C and 60°CFor E-line 1.

		40 DEGREES				0 DEGREES				~20 DEGREES				~40 DEGREES		
Measure	**Mean**	**8 Sig**	**Ds(max) 40**	**Dd(max) 40**	**Mean**	**8 Sig**	**Ds(max)0**	**Dd(max) 0**	**Mean**	**8 Sig**	**Ds(max) -20**	**Dd(max) -2**	**Mean**	**8 Sig**	**Ds(max)-40**	**Dd(max)-40**
SEAM 1																
1001	3,7	1,84	0,92	0,00071	3,66	1,84	0,92	0,00064	3,64	1,84	0,92	0,00064	3,62	1,84	0,92	0,00056
1002	3,47	2,75	1,375	0,0017	3,39	2,75	1,375	0,00157	3,35	2,75	1,375	0,00164	3,3	2,75	1,375	0,00136
1003	3,51	2,15	1,075	0,00402	3,4	2,16	1,08	0,00383	3,34	2,16	1,08	0,00393	3,29	2,16	1,08	0,00348
1004	3,67	2,05	1,025	0,00632	3,57	2,05	1,025	0,00604	3,53	2,05	1,025	0,00615	3,48	2,05	1,025	0,00554
1005	4,03	1,96	0,98	0,00764	4,03	1,96	0,98	0,00694	4,03	1,96	0,98	0,00729	4,02	1,96	0,98	0,00615
1006	4,02	1,91	0,955	0,00414	4,02	1,91	0,955	0,00391	4,02	1,91	0,955	0,00401	4,02	1,91	0,955	0,00335
1007	4,1	2,18	1,09	0,00361	4,07	2,18	1,09	0,00336	4,05	2,18	1,09	0,00347	4,04	2,18	1,09	0,00281
1008	4,09	2,17	1,085	0,00515	4,02	2,17	1,085	0,00474	3,98	2,17	1,085	0,00498	3,94	2,17	1,085	0,00401
1009	3,89	2,16	1,08	0,00982	3,82	2,16	1,08	0,00892	3,78	2,15	1,075	0,00932	3,74	2,15	1,075	0,00754
1010	3,98	2,15	1,075	0,01133	3,92	2,13	1,065	0,0101	3,89	2,13	1,065	0,0106	3,87	2,12	1,06	0,00831
1011	3,97	2,15	1,075	0,00655	3,93	2,14	1,07	0,00595	3,92	2,13	1,065	0,0062	3,91	2,12	1,06	0,00504
1012	4,03	2,18	1,09	0,00807	4	2,17	1,085	0,00742	3,98	2,17	1,085	0,00768	3,97	2,16	1,08	0,00639
1013	4,18	2,24	1,12	0,01227	4,14	2,23	1,115	0,0111	4,12	2,23	1,115	0,01166	4,11	2,23	1,115	0,00891
1014	3,14	2,23	1,115	0,01153	3,14	2,22	1,11	0,01052	3,14	2,22	1,11	0,01099	3,14	2,22	1,11	0,00837
1015	3,09	2,73	1,365	0,01313	3,11	2,73	1,365	0,01252	3,12	2,73	1,365	0,01281	3,13	2,73	1,365	0,0108
1016	3,1	2,77	1,385	0,01141	3,1	2,77	1,385	0,01049	3,1	2,77	1,385	0,01094	3,1	2,77	1,385	0,0088
1017	3,09	2,8	1,4	0,02405	3,07	2,8	1,4	0,02297	3,05	2,8	1,4	0,02345	3,04	2,8	1,4	0,01982
1018	3,12	2,93	1,465	0,0319	3,1	2,93	1,465	0,02959	3,08	2,92	1,46	0,03077	3,07	2,92	1,46	0,02514
1019	3,12	1,96	0,98	0,04351	3,09	1,95	0,975	0,03915	3,07	1,95	0,975	0,0411	3,06	1,94	0,97	0,03365
1020	3,56	1,83	0,915	0,05222	3,61	1,82	0,91	0,0471	3,64	1,82	0,91	0,04944	3,66	1,82	0,91	0,04061
1021	3,62	1,55	0,775	0,04158	3,58	1,55	0,775	0,03768	3,56	1,54	0,77	0,03952	3,54	1,54	0,77	0,03246
1022	3,67	1,52	0,76	0,08848	3,6	1,51	0,755	0,08447	3,56	1,51	0,755	0,08577	3,52	1,51	0,755	0,07221
1023	3,03	3,12	1,56	0,0928	3,42	3,13	1,565	0,08841	3,62	3,13	1,565	0,09004	3,82	3,13	1,565	0,07561
1024	2,2	2,68	1,34	0,08321	2,57	2,69	1,345	0,07909	2,75	2,69	1,345	0,08126	2,93	2,7	1,35	0,06807
1025	3,56	3	1,5	0,05229	3,78	3	1,5	0,04762	3,89	3	1,5	0,0498	4	3	1,5	0,03979
1026	4,58	2,77	1,385	0,04694	4,69	2,77	1,385	0,0425	4,74	2,77	1,385	0,04467	4,8	2,77	1,385	0,03517
1027	4,19	2,65	1,325	0,02985	4,23	2,65	1,325	0,02682	4,26	2,65	1,325	0,02823	4,28	2,65	1,325	0,02214
1028	4,11	2,58	1,29	0,01465	4,09	2,58	1,29	0,01332	4,08	2,58	1,29	0,01394	4,06	2,58	1,29	0,01113
1029	4,16	0,71	0,355	0,01512	4,1	0,711	0,3555	0,01451	4,06	0,711	0,3555	0,01475	4,03	0,711	0,3555	0,0125
1030	4,27	2,14	1,07	0,01036	4,13	2,14	1,07	0,00997	4,05	2,14	1,07	0,01001	3,98	2,14	1,07	0,00861
1031	4,01	2,19	1,095	0,01079	3,86	2,19	1,095	0,01003	3,79	2,19	1,095	0,01042	3,72	2,19	1,095	0,00837
1032	3,98	2,17	1,085	0,01007	3,87	2,17	1,085	0,0093	3,82	2,17	1,085	0,00972	3,76	2,17	1,085	0,0078
1033	3,97	2,19	1,095	0,00536	3,89	2,19	1,095	0,00492	3,85	2,19	1,095	0,00512	3,8	2,19	1,095	0,00409
1034	3,96	2,19	1,095	0,00507	3,92	2,19	1,095	0,00477	3,9	2,19	1,095	0,00486	3,88	2,19	1,095	0,00419
1035	4,07	2,19	1,095	0,012	4,05	2,19	1,095	0,01091	4,04	2,19	1,095	0,0115	4,03	2,19	1,095	0,0091
1036	4,09	2,2	1,1	0,01128	4,1	2,2	1,1	0,01025	4,11	2,2	1,1	0,01073	4,11	2,2	1,1	0,0083
1037	4,1	2,05	1,025	0,00563	4,09	2,05	1,025	0,00512	4,09	2,05	1,025	0,00538	4,09	2,05	1,025	0,00428
1038	4,31	2,11	1,055	0,00418	4,28	2,11	1,055	0,00392	4,27	2,11	1,055	0,00404	4,26	2,11	1,055	0,0033
1039	3,57	2,04	1,02	0,0057	3,48	2,04	1,02	0,00533	3,44	2,04	1,02	0,0055	3,39	2,04	1,02	0,00453
1040	3,48	2,13	1,065	0,00754	3,41	2,13	1,065	0,00693	3,38	2,14	1,07	0,00716	3,35	2,14	1,07	0,00594
1041	3,71	2,52	1,26	0,00702	3,66	2,52	1,26	0,00658	3,63	2,52	1,26	0,00678	3,61	2,53	1,265	0,00575
1042	3,47	2,48	1,24	0,00428	3,44	2,48	1,24	0,004	3,43	2,48	1,24	0,00413	3,42	2,48	1,24	0,00351

Figure 43: Result sheet with nominal gap, static displacement and dynamic displacement at 40°C,0°C, -20°C and -40°C for E-line 1.

	RATTLE AT							MEAN SHIFT					
Measure	**80**	**60**	**40**	**20**	**0**	**(-20)**	**(-40)**	**80**	**60**	**40**	**0**	**-20**	**-40**
SEAM 1													
1001	0,12901	0,08912	0,09929	0,07928	0,05936	0,03936	0,0194	0,05	0,01	0,02	-0,02	-0,04	-0,06
1002	-0,24732	-0,31708	-0,3367	-0,37677	-0,41657	-0,45664	-0,5064	0,13	0,06	0,04	-0,04	-0,08	-0,13
1003	0,08952	0,01024	-0,01902	-0,0841	-0,13383	-0,19393	-0,2435	0,17	0,09	0,06	-0,05	-0,11	-0,16
1004	0,10628	0,03753	0,01868	-0,03149	-0,08104	-0,12115	-0,1705	0,14	0,07	0,05	-0,05	-0,09	-0,14
1005	0,01912	0,0201	0,01236	0,01201	0,01306	0,01271	0,0038	0,01	0,01	0	0	0	-0,01
1006	0,03927	0,03984	0,04086	0,04067	0,04109	0,04099	0,0417	0	0	0	0	0	0
1007	-0,04493	-0,07449	-0,07361	-0,09373	-0,10336	-0,12347	-0,1328	0,05	0,02	0,02	-0,01	-0,03	-0,04
1008	0,02313	-0,02618	-0,05015	-0,09032	-0,11974	-0,15998	-0,1990	0,12	0,07	0,04	-0,03	-0,07	-0,11
1009	0,03819	-0,01098	-0,04982	-0,09033	-0,11892	-0,15432	-0,1925	0,13	0,08	0,04	-0,03	-0,07	-0,11
1010	0,00723	-0,03246	-0,05633	-0,0821	-0,1051	-0,1356	-0,1483	0,1	0,06	0,03	-0,03	-0,06	-0,08
1011	-0,03348	-0,04784	-0,06155	-0,07681	-0,09595	-0,1012	-0,1050	0,06	0,04	0,02	-0,02	-0,03	-0,04
1012	-0,04467	-0,06367	-0,07807	-0,09345	-0,10242	-0,12268	-0,1264	0,06	0,04	0,02	-0,01	-0,03	-0,04
1013	-0,08276	-0,09224	-0,11227	-0,12788	-0,1461	-0,16666	-0,1739	0,05	0,04	0,02	-0,02	-0,04	-0,05
1014	-0,12745	-0,12713	-0,12653	-0,12703	-0,12052	-0,12099	-0,1184	0	0	0	0	0	0
1015	-0,41409	-0,41226	-0,38813	-0,37854	-0,36752	-0,35781	-0,3458	-0,03	-0,03	-0,01	0,01	0,02	0,03
1016	-0,39958	-0,40832	-0,39641	-0,39698	-0,39549	-0,39594	-0,3938	0	-0,01	0	0	0	0
1017	-0,40837	-0,41971	-0,41405	-0,42496	-0,43297	-0,45345	-0,4598	0,03	0,01	0,01	-0,01	-0,03	-0,04
1018	-0,47126	-0,48223	-0,4869	-0,49784	-0,50459	-0,52077	-0,5251	0,04	0,02	0,01	-0,01	-0,03	-0,04
1019	0,00348	0,00386	-0,00351	-0,0261	-0,02415	-0,0461	-0,0437	0,04	0,03	0,02	-0,01	-0,03	-0,04
1020	-0,07279	-0,0316	0,00278	0,02985	0,0629	0,09056	0,1194	-0,09	-0,06	-0,03	0,02	0,05	0,07
1021	0,22029	0,20496	0,20342	0,1813	0,16732	0,15048	0,1375	0,05	0,03	0,02	-0,02	-0,04	-0,06
1022	0,20343	0,18333	0,18152	0,14783	0,12053	0,07923	0,0528	0,1	0,06	0,03	-0,04	-0,08	-0,12
1023	-1,30192	-1,07125	-0,8528	-0,65583	-0,46341	-0,26504	-0,0506	-0,61	-0,39	-0,2	0,19	0,39	0,59
1024	-1,00642	-0,79309	-0,60321	-0,42689	-0,23409	-0,05626	0,1319	-0,55	-0,35	-0,18	0,19	0,37	0,55
1025	-0,90107	-0,79254	-0,66229	-0,55442	-0,43762	-0,3298	-0,2098	-0,34	-0,24	-0,11	0,11	0,22	0,33
1026	-0,59864	-0,56133	-0,48194	-0,43411	-0,3675	-0,31967	-0,2502	-0,16	-0,13	-0,05	0,06	0,11	0,17
1027	-0,42925	-0,42454	-0,37485	-0,35623	-0,33182	-0,30323	-0,2771	-0,07	-0,07	-0,02	0,02	0,05	0,07
1028	-0,27702	-0,31455	-0,29465	-0,30523	-0,31332	-0,32394	-0,3411	0,03	-0,01	0,01	-0,01	-0,02	-0,04
1029	0,72325	0,6957	0,65988	0,62934	0,59999	0,55975	0,5320	0,1	0,07	0,03	-0,03	-0,07	-0,1
1030	0,1356	0,05705	-0,01036	-0,08067	-0,14997	-0,23001	-0,2986	0,22	0,14	0,07	-0,07	-0,15	-0,22
1031	0,10192	0,03252	-0,03579	-0,1062	-0,18503	-0,25542	-0,3234	0,21	0,14	0,07	-0,08	-0,15	-0,22
1032	0,06289	0,01365	-0,04507	-0,09552	-0,1543	-0,20472	-0,2628	0,16	0,11	0,05	-0,06	-0,11	-0,17
1033	0,01894	-0,02067	-0,06036	-0,10057	-0,13992	-0,18012	-0,2291	0,12	0,08	0,04	-0,04	-0,08	-0,13
1034	-0,04196	-0,06122	-0,08007	-0,1003	-0,11977	-0,13986	-0,1592	0,06	0,04	0,02	-0,02	-0,04	-0,06
1035	-0,07933	-0,0779	-0,097	-0,10768	-0,11591	-0,1265	-0,1341	0,03	0,03	0,01	-0,01	-0,02	-0,03
1036	-0,12361	-0,12233	-0,11128	-0,11195	-0,10025	-0,09073	-0,0883	-0,01	-0,01	0	0,01	0,02	0,02
1037	-0,03215	-0,0014	-0,03063	-0,03084	-0,04012	-0,04038	-0,0393	0	0,03	0	-0,01	-0,01	-0,01
1038	-0,02072	-8E-05	-0,03918	-0,05931	-0,06892	-0,07904	-0,0883	0,04	0,06	0,02	-0,01	-0,02	-0,03
1039	0,10726	0,04789	0,0143	-0,02591	-0,07533	-0,1155	-0,1645	0,13	0,07	0,04	-0,05	-0,09	-0,14
1040	0,03454	-0,00447	-0,03254	-0,07287	-0,10193	-0,13716	-0,1659	0,11	0,07	0,04	-0,03	-0,06	-0,09
1041	-0,18424	-0,21329	-0,23702	-0,2673	-0,28658	-0,31678	-0,3408	0,08	0,05	0,03	-0,02	-0,05	-0,07
1042	-0,20073	-0,23505	-0,23428	-0,24446	-0,264	-0,27413	-0,2835	0,04	0,01	0,01	-0,02	-0,03	-0,04

Figure 44: Result sheet with rattle condition according to formula 1 and mean shift from static displacement simulations for E-line 1.

	STATIC DISPLACEMENT						
Measure	**80**	**60**	**40**	**20**	**0**	**-20**	**-40**
SEAM 1							
1001	0,87	0,91	0,9	0,92	0,94	0,96	0,98
1002	1,245	1,315	1,335	1,375	1,415	1,455	1,505
1003	0,905	0,985	1,015	1,08	1,13	1,19	1,24
1004	0,885	0,955	0,975	1,025	1,075	1,115	1,165
1005	0,97	0,97	0,98	0,98	0,98	0,98	0,99
1006	0,955	0,955	0,955	0,955	0,955	0,955	0,955
1007	1,04	1,07	1,07	1,09	1,1	1,12	1,13
1008	0,97	1,02	1,045	1,085	1,115	1,155	1,195
1009	0,95	1	1,04	1,08	1,11	1,145	1,185
1010	0,98	1,02	1,045	1,07	1,095	1,125	1,14
1011	1,025	1,04	1,055	1,07	1,09	1,095	1,1
1012	1,035	1,055	1,07	1,085	1,095	1,115	1,12
1013	1,07	1,08	1,1	1,115	1,135	1,155	1,165
1014	1,115	1,115	1,115	1,115	1,11	1,11	1,11
1015	1,395	1,395	1,375	1,365	1,355	1,345	1,335
1016	1,385	1,395	1,385	1,385	1,385	1,385	1,385
1017	1,375	1,39	1,39	1,4	1,41	1,43	1,44
1018	1,43	1,445	1,455	1,465	1,475	1,49	1,5
1019	0,945	0,95	0,96	0,98	0,985	1,005	1,01
1020	1,01	0,975	0,945	0,915	0,89	0,86	0,84
1021	0,73	0,75	0,755	0,775	0,795	0,81	0,83
1022	0,665	0,7	0,73	0,76	0,795	0,835	0,875
1023	2,165	1,95	1,76	1,56	1,375	1,175	0,975
1024	1,885	1,685	1,52	1,34	1,155	0,975	0,8
1025	1,84	1,74	1,61	1,5	1,39	1,28	1,17
1026	1,545	1,515	1,435	1,385	1,325	1,275	1,215
1027	1,395	1,395	1,345	1,325	1,305	1,275	1,255
1028	1,26	1,3	1,28	1,29	1,3	1,31	1,33
1029	0,2555	0,2855	0,325	0,355	0,3855	0,4255	0,4555
1030	0,85	0,93	1	1,07	1,14	1,22	1,29
1031	0,885	0,955	1,025	1,095	1,175	1,245	1,315
1032	0,925	0,975	1,035	1,085	1,145	1,195	1,255
1033	0,975	1,015	1,055	1,095	1,135	1,175	1,225
1034	1,035	1,055	1,075	1,095	1,115	1,135	1,155
1035	1,065	1,065	1,085	1,095	1,105	1,115	1,125
1036	1,11	1,11	1,1	1,1	1,09	1,08	1,08
1037	1,025	0,995	1,025	1,025	1,035	1,035	1,035
1038	1,015	0,995	1,035	1,055	1,065	1,075	1,085
1039	0,885	0,945	0,98	1,02	1,07	1,11	1,16
1040	0,955	0,995	1,025	1,065	1,095	1,13	1,16
1041	1,175	1,205	1,23	1,26	1,28	1,31	1,335
1042	1,195	1,23	1,23	1,24	1,26	1,27	1,28

Figure 45: Results from static displacement simulations for E-line 1.

		20 DEGREES				80 DEGREES					60 DEGREES		
Measure	Nominal Gap	Mean	8 Sig	Ds(max)20	Dd(max) 20	Mean	8 Sig	Ds(max)80	Dd(max)80	Mean	8 Sig	Ds(max)60	Dd(max) 6
SEAM 2													
3001	0,35	2,18	1,23	0,615	0,01616	2,1	1,23	0,615	0,01723	2,14	1,23	0,615	0,01539
3002	0,35	2,08	1,17	0,585	0,00738	2,02	1,17	0,585	0,00794	2,06	1,17	0,585	0,00735
3003	0,35	2,07	1,18	0,59	0,00528	2,02	1,18	0,59	0,00568	2,05	1,18	0,59	0,00536
3004	0,35	2,06	1,18	0,59	0,0035	2,01	1,18	0,59	0,00384	2,04	1,18	0,59	0,0036
3005	0,35	2,05	1,16	0,58	0,0029	2,04	1,16	0,58	0,00374	2,05	1,16	0,58	0,00332
3006	0,35	2,04	1,15	0,575	0,00312	2,04	1,15	0,575	0,0039	2,05	1,15	0,575	0,00336
3007	0,35	2,03	1,15	0,575	0,00151	2,07	1,15	0,575	0,00162	2,06	1,15	0,575	0,0015
3008	0,35	2,12	1,18	0,59	0,00439	2,18	1,18	0,59	0,00577	2,17	1,18	0,59	0,00538
3009	0,35	2,31	1,19	0,595	0,00528	2,36	1,19	0,595	0,00757	2,35	1,19	0,595	0,00655
3010	0,35	2,1	1,17	0,585	0,0032	2,14	1,17	0,585	0,00439	2,14	1,17	0,585	0,00384
3011	0,35	2,12	1,16	0,58	0,00752	2,15	1,16	0,58	0,01106	2,15	1,16	0,58	0,0095
3012	0,35	2,11	1,16	0,58	0,00771	2,12	1,16	0,58	0,01094	2,13	1,16	0,58	0,00939
3013	0,35	2,13	1,16	0,58	0,00609	2,15	1,16	0,58	0,00854	2,16	1,16	0,58	0,00728
3014	0,35	2,13	1,17	0,585	0,00399	2,15	1,16	0,58	0,00566	2,16	1,16	0,58	0,00487
3015	0,35	2,16	1,18	0,59	0,00208	2,17	1,18	0,59	0,00264	2,18	1,18	0,59	0,00235
3016	0,70	1,96	2,11	1,055	0,00179	1,98	2,12	1,06	0,00237	1,96	2,12	1,06	0,00211
3017	0,70	2,03	2,12	1,06	0,00164	2,04	2,12	1,06	0,00224	2,03	2,12	1,06	0,00202
3018	0,70	2,06	2,12	1,06	0,00439	2,06	2,12	1,06	0,00592	2,05	2,12	1,06	0,00544
3019	0,35	2,14	1,2	0,6	0,00525	2,15	1,2	0,6	0,0069	2,13	1,2	0,6	0,0062
3020	0,35	2,16	1,17	0,585	0,00227	2,15	1,17	0,585	0,00308	2,14	1,17	0,585	0,00276
3021	0,35	2,14	1,2	0,6	0,00222	2,14	1,2	0,6	0,00314	2,13	1,2	0,6	0,00267
3022	0,35	2,14	1,2	0,6	0,00207	2,14	1,2	0,6	0,00294	2,13	1,2	0,6	0,00251
3023	0,35	2,1	1,17	0,585	0,00142	2,09	1,17	0,585	0,00171	2,08	1,17	0,585	0,00154
3024	0,35	2,1	1,15	0,575	0,00304	2,09	1,15	0,575	0,00407	2,08	1,15	0,575	0,00359
3025	0,35	2,14	1,2	0,6	0,00695	2,18	1,2	0,6	0,00979	2,16	1,2	0,6	0,0087
3026	0,35	2,03	1,16	0,58	0,00639	2,09	1,16	0,58	0,00872	2,06	1,16	0,58	0,00781
3027	0,35	2,03	1,18	0,59	0,00165	2,07	1,18	0,59	0,00197	2,06	1,18	0,59	0,00178
3028	0,35	2,05	1,17	0,585	0,00261	2,09	1,17	0,585	0,00302	2,07	1,17	0,585	0,00272
3029	0,35	2,06	1,15	0,575	0,00261	2,11	1,15	0,575	0,00293	2,08	1,15	0,575	0,0027
3030	0,35	2,07	1,16	0,58	0,00295	2,09	1,16	0,58	0,0038	2,07	1,16	0,58	0,00338
3031	0,35	2,08	1,18	0,59	0,00459	2,1	1,18	0,59	0,00586	2,09	1,18	0,59	0,00525
3032	0,35	2,08	1,17	0,585	0,00718	2,09	1,16	0,58	0,00865	2,08	1,16	0,58	0,00781
SEAM 3													
5001	0,6	2,41	1,39	0,695	0,01379	2,44	1,39	0,695	0,01878	2,42	1,39	0,695	0,01625
5002	0,6	2,42	1,38	0,69	0,00728	2,41	1,38	0,69	0,0088	2,4	1,38	0,69	0,00794
5003	0,6	2,42	1,41	0,705	0,00296	2,41	1,41	0,705	0,00356	2,4	1,41	0,705	0,00317
5004	0,6	2,43	1,38	0,69	0,0012	2,44	1,38	0,69	0,00158	2,42	1,38	0,69	0,00141
5005	0,6	2,45	1,34	0,67	0,00113	2,48	1,34	0,67	0,00145	2,46	1,34	0,67	0,00134
5006	0,6	2,45	1,14	0,57	0,00097	2,52	1,14	0,57	0,00121	2,5	1,14	0,57	0,00114
5007	0,6	2,52	1,17	0,585	0,00466	2,54	1,17	0,585	0,0064	2,53	1,17	0,585	0,00571
5008	0,6	2,52	1,2	0,6	0,00912	2,48	1,2	0,6	0,01247	2,48	1,2	0,6	0,01125
5009	0,6	2,53	1,21	0,605	0,01131	2,5	1,21	0,605	0,01543	2,5	1,21	0,605	0,01396
5010	0,6	2,53	1,21	0,605	0,01346	2,51	1,21	0,605	0,01853	2,51	1,21	0,605	0,01671
5011	0,6	2,53	1,25	0,625	0,01577	2,54	1,25	0,625	0,02169	2,52	1,25	0,625	0,01952
5012	0,6	2,53	1,32	0,66	0,01755	2,56	1,32	0,66	0,02406	2,54	1,32	0,66	0,02164
5013	0,6	2,53	1,23	0,615	0,01767	2,56	1,23	0,615	0,02424	2,54	1,23	0,615	0,02149
5014	0,6	2,53	1,19	0,595	0,01594	2,55	1,19	0,595	0,02194	2,53	1,19	0,595	0,01939
5015	0,6	2,52	1,21	0,605	0,01356	2,54	1,21	0,605	0,01874	2,53	1,21	0,605	0,01654
5016	0,6	2,52	1,19	0,595	0,01131	2,52	1,19	0,595	0,01567	2,52	1,19	0,595	0,01387
5017	0,6	2,51	1,18	0,59	0,00901	2,51	1,18	0,59	0,01244	2,51	1,18	0,59	0,01121
5018	0,6	2,54	1,15	0,575	0,00458	2,51	1,15	0,575	0,0064	2,52	1,15	0,575	0,0057
5019	0,6	2,33	1,44	0,72	0,00074	2,48	1,44	0,72	0,00102	2,43	1,44	0,72	0,00089
5020	0,6	2,42	1,45	0,725	0,00107	2,61	1,45	0,725	0,00144	2,55	1,45	0,725	0,00126
5021	0,6	2,41	1,48	0,74	0,00125	2,58	1,48	0,74	0,00168	2,53	1,48	0,74	0,00149
5022	0,6	2,42	1,44	0,72	0,00315	2,61	1,44	0,72	0,00335	2,55	1,44	0,72	0,00311
5023	0,6	2,41	1,49	0,745	0,00817	2,6	1,49	0,745	0,00939	2,54	1,49	0,745	0,00845

Figure 46: Result sheet with nominal gap, static displacement and dynamic displacement at 20°C,80°C and 60°CFor E-line 2 and 3.

		40 DEGREES				0 DEGREES				~20 DEGREES				~40 DEGREES		
Measure	Mean	8 Sig	Ds(max) 40	Dd(max) 40	Mean	8 Sig	Ds(max)0	Dd(max) 0	Mean	8 Sig	Ds(max) -20	Dd(max) -20	Mean	8 Sig	Ds(max)-40	Dd(max)-40
SEAM 2																
3001	2,15	1,23	0,615	0,01525	2,21	1,23	0,615	0,01365	2,23	1,23	0,615	0,01439	2,26	1,23	0,615	0,01143
3002	2,06	1,17	0,585	0,00694	2,1	1,17	0,585	0,00619	2,12	1,17	0,585	0,00659	2,14	1,17	0,585	0,00506
3003	2,05	1,18	0,59	0,00495	2,08	1,18	0,59	0,00432	2,1	1,18	0,59	0,00463	2,12	1,18	0,59	0,00342
3004	2,05	1,18	0,59	0,00329	2,08	1,18	0,59	0,00289	2,1	1,18	0,59	0,00309	2,11	1,18	0,59	0,00228
3005	2,04	1,16	0,58	0,00279	2,05	1,16	0,58	0,00259	2,06	1,16	0,58	0,0027	2,06	1,16	0,58	0,00233
3006	2,04	1,15	0,575	0,00298	2,04	1,15	0,575	0,00277	2,04	1,15	0,575	0,00286	2,04	1,15	0,575	0,00242
3007	2,04	1,15	0,575	0,00141	2,02	1,15	0,575	0,00128	2	1,15	0,575	0,00136	1,99	1,15	0,575	0,00108
3008	2,14	1,18	0,59	0,00423	2,11	1,18	0,59	0,004	2,09	1,18	0,59	0,00409	2,07	1,18	0,59	0,00338
3009	2,32	1,19	0,595	0,00508	2,29	1,19	0,595	0,00496	2,27	1,19	0,595	0,00507	2,26	1,19	0,595	0,00429
3010	2,11	1,17	0,585	0,00302	2,09	1,17	0,585	0,00285	2,08	1,17	0,585	0,00299	2,07	1,17	0,585	0,00259
3011	2,13	1,16	0,58	0,00737	2,11	1,16	0,58	0,00722	2,1	1,16	0,58	0,0074	2,09	1,16	0,58	0,00626
3012	2,11	1,16	0,58	0,00752	2,11	1,16	0,58	0,00719	2,1	1,16	0,58	0,00717	2,1	1,16	0,58	0,00628
3013	2,14	1,16	0,58	0,0058	2,12	1,16	0,58	0,00565	2,12	1,16	0,58	0,00568	2,11	1,16	0,58	0,0049
3014	2,14	1,16	0,58	0,00383	2,12	1,17	0,585	0,00372	2,11	1,17	0,585	0,00376	2,11	1,17	0,585	0,00324
3015	2,16	1,18	0,59	0,00201	2,15	1,18	0,59	0,00187	2,14	1,18	0,59	0,00193	2,14	1,18	0,59	0,00158
3016	1,97	2,12	1,06	0,00175	1,96	2,11	1,055	0,0017	1,95	2,11	1,055	0,00171	1,95	2,11	1,055	0,00146
3017	2,03	2,12	1,06	0,00159	2,03	2,12	1,06	0,00154	2,03	2,12	1,06	0,00154	2,02	2,12	1,06	0,00136
3018	2,06	2,12	1,06	0,00423	2,05	2,12	1,06	0,0041	2,05	2,12	1,06	0,00419	2,05	2,11	1,055	0,0036
3019	2,14	1,2	0,6	0,00507	2,14	1,2	0,6	0,00485	2,14	1,2	0,6	0,00492	2,13	1,2	0,6	0,00428
3020	2,15	1,17	0,585	0,0022	2,16	1,17	0,585	0,0021	2,16	1,17	0,585	0,00216	2,16	1,17	0,585	0,00186
3021	2,14	1,2	0,6	0,00213	2,14	1,2	0,6	0,00206	2,14	1,2	0,6	0,00211	2,14	1,2	0,6	0,00175
3022	2,14	1,2	0,6	0,00203	2,14	1,2	0,6	0,00191	2,14	1,2	0,6	0,00199	2,14	1,2	0,6	0,00165
3023	2,1	1,17	0,585	0,00136	2,11	1,17	0,585	0,00126	2,11	1,17	0,585	0,0013	2,11	1,17	0,585	0,00106
3024	2,1	1,15	0,575	0,00289	2,11	1,15	0,575	0,00277	2,11	1,15	0,575	0,00284	2,11	1,15	0,575	0,00233
3025	2,15	1,2	0,6	0,00687	2,13	1,2	0,6	0,00657	2,12	1,2	0,6	0,00666	2,1	1,2	0,6	0,00564
3026	2,05	1,16	0,58	0,00607	2,01	1,16	0,58	0,00583	2	1,16	0,58	0,00599	1,98	1,16	0,58	0,00511
3027	2,05	1,18	0,59	0,00156	2,02	1,18	0,59	0,00148	2,01	1,18	0,59	0,00149	1,99	1,18	0,59	0,00128
3028	2,06	1,17	0,585	0,00249	2,03	1,17	0,585	0,00229	2,02	1,16	0,58	0,0024	2	1,16	0,58	0,002
3029	2,07	1,15	0,575	0,00247	2,04	1,15	0,575	0,00225	2,02	1,15	0,575	0,00234	2,01	1,15	0,575	0,00188
3030	2,07	1,16	0,58	0,00283	2,06	1,16	0,58	0,00267	2,05	1,16	0,58	0,00274	2,05	1,16	0,58	0,00236
3031	2,09	1,18	0,59	0,00437	2,07	1,18	0,59	0,00403	2,06	1,18	0,59	0,0042	2,05	1,18	0,59	0,00357
3032	2,09	1,17	0,585	0,00681	2,08	1,17	0,585	0,0062	2,08	1,17	0,585	0,00644	2,08	1,17	0,585	0,0055
SEAM 3																
5001	2,42	1,39	0,695	0,01324	2,4	1,39	0,695	0,01231	2,39	1,39	0,695	0,01269	2,38	1,39	0,695	0,01093
5002	2,42	1,38	0,69	0,00692	2,42	1,38	0,69	0,00632	2,42	1,38	0,69	0,00661	2,43	1,38	0,69	0,00562
5003	2,42	1,41	0,705	0,0028	2,42	1,41	0,705	0,00254	2,42	1,41	0,705	0,00267	2,43	1,41	0,705	0,00223
5004	2,43	1,38	0,69	0,00116	2,43	1,38	0,69	0,00111	2,43	1,38	0,69	0,00115	2,42	1,38	0,69	0,00097
5005	2,46	1,34	0,67	0,00109	2,44	1,34	0,67	0,00101	2,43	1,34	0,67	0,00106	2,42	1,34	0,67	0,00085
5006	2,47	1,14	0,57	0,00092	2,42	1,14	0,57	0,00084	2,4	1,14	0,57	0,00089	2,37	1,14	0,57	0,00068
5007	2,52	1,17	0,585	0,00449	2,51	1,17	0,585	0,00418	2,5	1,17	0,585	0,00431	2,49	1,17	0,585	0,00353
5008	2,5	1,2	0,6	0,00869	2,53	1,2	0,6	0,00808	2,54	1,2	0,6	0,0083	2,56	1,2	0,6	0,00681
5009	2,52	1,21	0,605	0,01072	2,54	1,21	0,605	0,00994	2,55	1,21	0,605	0,01032	2,56	1,21	0,605	0,00831
5010	2,52	1,21	0,605	0,0128	2,54	1,21	0,605	0,01186	2,54	1,21	0,605	0,0123	2,55	1,21	0,605	0,00993
5011	2,53	1,25	0,625	0,01501	2,53	1,25	0,625	0,01391	2,53	1,26	0,63	0,01435	2,53	1,26	0,63	0,01161
5012	2,54	1,32	0,66	0,01672	2,52	1,33	0,665	0,01541	2,51	1,33	0,665	0,01606	2,5	1,33	0,665	0,01288
5013	2,54	1,23	0,615	0,01682	2,52	1,24	0,62	0,01551	2,51	1,24	0,62	0,01601	2,5	1,24	0,62	0,01286
5014	2,53	1,19	0,595	0,0153	2,52	1,19	0,595	0,01409	2,52	1,19	0,595	0,01464	2,51	1,19	0,595	0,01166
5015	2,53	1,21	0,605	0,013	2,52	1,21	0,605	0,012	2,51	1,21	0,605	0,01247	2,5	1,21	0,605	0,00994
5016	2,52	1,19	0,595	0,01077	2,51	1,19	0,595	0,00999	2,51	1,19	0,595	0,01042	2,51	1,19	0,595	0,00837
5017	2,51	1,18	0,59	0,00857	2,52	1,18	0,59	0,00798	2,52	1,18	0,59	0,00823	2,52	1,18	0,59	0,00677
5018	2,53	1,15	0,575	0,00437	2,56	1,15	0,575	0,00403	2,57	1,15	0,575	0,00417	2,58	1,15	0,575	0,0035
5019	2,38	1,44	0,72	0,00071	2,28	1,44	0,72	0,00067	2,23	1,44	0,72	0,0007	2,18	1,44	0,72	0,00058
5020	2,48	1,45	0,725	0,00104	2,36	1,45	0,725	0,001	2,3	1,45	0,725	0,001	2,23	1,45	0,725	0,00088
5021	2,47	1,48	0,74	0,00121	2,35	1,48	0,74	0,00115	2,29	1,48	0,74	0,00119	2,23	1,48	0,74	0,00106
5022	2,48	1,44	0,72	0,00298	2,35	1,44	0,72	0,00273	2,29	1,44	0,72	0,00285	2,22	1,44	0,72	0,00222
5023	2,47	1,49	0,745	0,0077	2,35	1,49	0,745	0,00689	2,28	1,49	0,745	0,00726	2,22	1,49	0,745	0,00554

Figure 47: Result sheet with nominal gap, static displacement and dynamic displacement at 40°C,0°C, -20°C and -40°C for E-line 2 and 3.

	RATTLE AT							MEAN SHIFT					
Measure	**80**	**60**	**40**	**20**	**0**	**(-20)**	**(-40)**	**80**	**60**	**40**	**0**	**-20**	**-40**
SEAM 2													
3001	-0,36223	-0,32039	-0,31025	-0,28116	-0,24865	-0,22939	-0,1964	-0,08	-0,04	-0,03	0,03	0,05	0,08
3002	-0,30294	-0,26235	-0,26194	-0,24238	-0,22119	-0,20159	-0,1801	-0,06	-0,02	-0,02	0,02	0,04	0,06
3003	-0,29568	-0,26536	-0,26495	-0,24528	-0,23432	-0,21463	-0,1934	-0,05	-0,02	-0,02	0,01	0,03	0,05
3004	-0,29384	-0,2636	-0,25329	-0,2435	-0,22289	-0,20309	-0,1923	-0,05	-0,02	-0,01	0,02	0,04	0,05
3005	-0,24374	-0,23332	-0,24279	-0,2329	-0,23259	-0,2227	-0,2223	-0,01	0	-0,01	0	0,01	0,01
3006	-0,2289	-0,21836	-0,22798	-0,22812	-0,22777	-0,22786	-0,2274	0	0,01	0	0	0	0
3007	-0,18662	-0,1965	-0,21641	-0,22651	-0,23628	-0,25636	-0,2661	0,04	0,03	0,01	-0,01	-0,03	-0,04
3008	-0,18577	-0,19538	-0,22423	-0,24439	-0,254	-0,27409	-0,2934	0,06	0,05	0,02	-0,01	-0,03	-0,05
3009	-0,20257	-0,21155	-0,24008	-0,25028	-0,26996	-0,29007	-0,2993	0,05	0,04	0,01	-0,02	-0,04	-0,05
3010	-0,19939	-0,19884	-0,22802	-0,2382	-0,24785	-0,25799	-0,2676	0,04	0,04	0,01	-0,01	-0,02	-0,03
3011	-0,21106	-0,2095	-0,22737	-0,23752	-0,24722	-0,2574	-0,2663	0,03	0,03	0,01	-0,01	-0,02	-0,03
3012	-0,23094	-0,21939	-0,23752	-0,23771	-0,23719	-0,24717	-0,2463	0,01	0,02	0	0	-0,01	-0,01
3013	-0,21854	-0,20728	-0,2258	-0,23609	-0,24565	-0,24568	-0,2549	0,02	0,03	0,01	-0,01	-0,01	-0,02
3014	-0,21566	-0,20487	-0,22383	-0,23899	-0,24872	-0,25876	-0,2582	0,02	0,03	0,01	-0,01	-0,02	-0,02
3015	-0,23264	-0,22235	-0,24201	-0,24208	-0,25187	-0,26193	-0,2616	0,01	0,02	0	-0,01	-0,02	-0,02
3016	-0,34237	-0,36211	-0,35175	-0,35679	-0,3567	-0,36671	-0,3665	0,02	0	0,01	0	-0,01	-0,01
3017	-0,35224	-0,36202	-0,36159	-0,36164	-0,36154	-0,36154	-0,3714	0,01	0	0	0	0	-0,01
3018	-0,36592	-0,37544	-0,36423	-0,36439	-0,3741	-0,37419	-0,3686	0	-0,01	0	-0,01	-0,01	-0,01
3019	-0,2469	-0,2662	-0,25507	-0,25525	-0,25485	-0,25492	-0,2643	0,01	-0,01	0	0	0	-0,01
3020	-0,24808	-0,25776	-0,2472	-0,23727	-0,2371	-0,23716	-0,2369	-0,01	-0,02	-0,01	0	0	0
3021	-0,25314	-0,26267	-0,25213	-0,25222	-0,25206	-0,25211	-0,2518	0	-0,01	0	0	0	0
3022	-0,25294	-0,26251	-0,25203	-0,25207	-0,25191	-0,25199	-0,2517	0	-0,01	0	0	0	0
3023	-0,24671	-0,25654	-0,23636	-0,23642	-0,22626	-0,2263	-0,2261	-0,01	-0,02	0	0,01	0,01	0,01
3024	-0,23907	-0,24859	-0,22789	-0,22804	-0,21777	-0,21784	-0,2173	-0,01	-0,02	0	0,01	0,01	0,01
3025	-0,21979	-0,2387	-0,24687	-0,25695	-0,26657	-0,27666	-0,2956	0,04	0,02	0,01	-0,01	-0,02	-0,04
3026	-0,17872	-0,20781	-0,21607	-0,23639	-0,25583	-0,26599	-0,2851	0,06	0,03	0,02	-0,02	-0,03	-0,05
3027	-0,20197	-0,21178	-0,22156	-0,24165	-0,25148	-0,26149	-0,2813	0,04	0,03	0,02	-0,01	-0,02	-0,04
3028	-0,19802	-0,21772	-0,22749	-0,23761	-0,25729	-0,2624	-0,2820	0,04	0,02	0,01	-0,02	-0,03	-0,05
3029	-0,17793	-0,2077	-0,21747	-0,22761	-0,24725	-0,26734	-0,2769	0,05	0,02	0,01	-0,02	-0,04	-0,05
3030	-0,2138	-0,23338	-0,23283	-0,23295	-0,24267	-0,25274	-0,2524	0,02	0	0	-0,01	-0,02	-0,02
3031	-0,22586	-0,23525	-0,23437	-0,24459	-0,25403	-0,2642	-0,2736	0,02	0,01	0,01	-0,01	-0,02	-0,03
3032	-0,22865	-0,23781	-0,23181	-0,24218	-0,2412	-0,24144	-0,2405	0,01	0	0,01	0	0	0
SEAM 3													
5001	-0,08378	-0,10125	-0,09824	-0,10879	-0,11731	-0,12769	-0,1359	0,03	0,01	0,01	-0,01	-0,02	-0,03
5002	-0,1088	-0,11794	-0,09692	-0,09728	-0,09632	-0,09661	-0,0856	-0,01	-0,02	0	0	0	0,01
5003	-0,11856	-0,12817	-0,1078	-0,10796	-0,10754	-0,10767	-0,0972	-0,01	-0,02	0	0	0	0,01
5004	-0,08158	-0,10141	-0,09116	-0,0912	-0,09111	-0,09115	-0,1010	0,01	-0,01	0	0	0	-0,01
5005	-0,04145	-0,06134	-0,06109	-0,07113	-0,08101	-0,09106	-0,1009	0,03	0,01	0,01	-0,01	-0,02	-0,03
5006	0,09879	0,07886	0,04908	0,02903	-0,00084	-0,02089	-0,0507	0,07	0,05	0,02	-0,03	-0,05	-0,08
5007	0,0286	0,01929	0,01051	0,01034	0,00082	-0,00931	-0,0185	0,02	0,01	0	-0,01	-0,02	-0,03
5008	-0,05247	-0,05125	-0,02869	-0,00912	0,00192	0,0117	0,0332	-0,04	-0,04	-0,02	0,01	0,02	0,04
5009	-0,05043	-0,04896	-0,02572	-0,01631	-0,00494	0,00468	0,0167	-0,03	-0,03	-0,01	0,01	0,02	0,03
5010	-0,04353	-0,04171	-0,0278	-0,01846	-0,00686	-0,0073	0,0051	-0,02	-0,02	-0,01	0,01	0,01	0,02
5011	-0,03669	-0,05452	-0,04001	-0,04077	-0,03891	-0,04435	-0,0416	0,01	-0,01	0	0	0	0
5012	-0,05406	-0,07164	-0,06672	-0,07755	-0,09041	-0,10106	-0,1079	0,03	0,01	0,01	-0,01	-0,02	-0,03
5013	-0,00924	-0,02649	-0,02182	-0,03267	-0,04551	-0,05601	-0,0629	0,03	0,01	0,01	-0,01	-0,02	-0,03
5014	0,00306	-0,01439	-0,0103	-0,01094	-0,01909	-0,01964	-0,0267	0,02	0	0	-0,01	-0,01	-0,02
5015	-0,00374	-0,01154	-0,008	-0,01856	-0,017	-0,02747	-0,0349	0,02	0,01	0,01	0	-0,01	-0,02
5016	-0,01067	-0,00887	-0,00577	-0,00631	-0,01499	-0,01542	-0,0134	0	0	0	-0,01	-0,01	-0,01
5017	-0,00244	-0,00121	0,00143	0,00099	0,01202	0,01177	0,0132	0	0	0	0,01	0,01	0,01
5018	-0,0114	-0,0007	0,01063	0,02042	0,04097	0,05083	0,0615	-0,03	-0,02	-0,01	0,02	0,03	0,04
5019	0,02898	-0,02089	-0,07071	-0,12074	-0,17067	-0,2207	-0,2706	0,15	0,1	0,05	-0,05	-0,1	-0,15
5020	0,06356	0,00374	-0,06604	-0,12607	-0,186	-0,246	-0,3159	0,19	0,13	0,06	-0,06	-0,12	-0,19
5021	0,02832	-0,02149	-0,08121	-0,14125	-0,20115	-0,26119	-0,3211	0,17	0,12	0,06	-0,06	-0,12	-0,18
5022	0,06665	0,00689	-0,06298	-0,12315	-0,19273	-0,25285	-0,3222	0,19	0,13	0,06	-0,07	-0,13	-0,2
5023	0,03561	-0,02345	-0,0927	-0,15317	-0,21189	-0,28226	-0,3405	0,19	0,13	0,06	-0,06	-0,13	-0,19

Figure 48: Result sheet with rattle condition according to formula 1 and mean shift from static displacement simulations for E-line 2 and 3.

	STATIC DISPLACEMENT						
Measure	**80**	**60**	**40**	**20**	**0**	**-20**	**-40**
SEAM 2							
3001	0,695	0,655	0,645	0,615	0,585	0,565	0,535
3002	0,645	0,605	0,605	0,585	0,565	0,545	0,525
3003	0,64	0,61	0,61	0,59	0,58	0,56	0,54
3004	0,64	0,61	0,6	0,59	0,57	0,55	0,54
3005	0,59	0,58	0,59	0,58	0,58	0,57	0,57
3006	0,575	0,565	0,575	0,575	0,575	0,575	0,575
3007	0,535	0,545	0,565	0,575	0,585	0,605	0,615
3008	0,53	0,54	0,57	0,59	0,6	0,62	0,64
3009	0,545	0,555	0,585	0,595	0,615	0,635	0,645
3010	0,545	0,545	0,575	0,585	0,595	0,605	0,615
3011	0,55	0,55	0,57	0,58	0,59	0,6	0,61
3012	0,57	0,56	0,58	0,58	0,58	0,59	0,59
3013	0,56	0,55	0,57	0,58	0,59	0,59	0,6
3014	0,56	0,55	0,57	0,585	0,595	0,605	0,605
3015	0,58	0,57	0,59	0,59	0,6	0,61	0,61
3016	1,04	1,06	1,05	1,055	1,055	1,065	1,065
3017	1,05	1,06	1,06	1,06	1,06	1,06	1,07
3018	1,06	1,07	1,06	1,06	1,07	1,07	1,065
3019	0,59	0,61	0,6	0,6	0,6	0,6	0,61
3020	0,595	0,605	0,595	0,585	0,585	0,585	0,585
3021	0,6	0,61	0,6	0,6	0,6	0,6	0,6
3022	0,6	0,61	0,6	0,6	0,6	0,6	0,6
3023	0,595	0,605	0,585	0,585	0,575	0,575	0,575
3024	0,585	0,595	0,575	0,575	0,565	0,565	0,565
3025	0,56	0,58	0,59	0,6	0,61	0,62	0,64
3026	0,52	0,55	0,56	0,58	0,6	0,61	0,63
3027	0,55	0,56	0,57	0,59	0,6	0,61	0,63
3028	0,545	0,565	0,575	0,585	0,605	0,61	0,63
3029	0,525	0,555	0,565	0,575	0,595	0,615	0,625
3030	0,56	0,58	0,58	0,58	0,59	0,6	0,6
3031	0,57	0,58	0,58	0,59	0,6	0,61	0,62
3032	0,57	0,58	0,575	0,585	0,585	0,585	0,585
SEAM 3							
5001	0,665	0,685	0,685	0,695	0,705	0,715	0,725
5002	0,7	0,71	0,69	0,69	0,69	0,69	0,68
5003	0,715	0,725	0,705	0,705	0,705	0,705	0,695
5004	0,68	0,7	0,69	0,69	0,69	0,69	0,7
5005	0,64	0,66	0,66	0,67	0,68	0,69	0,7
5006	0,5	0,52	0,55	0,57	0,6	0,62	0,65
5007	0,565	0,575	0,585	0,585	0,595	0,605	0,615
5008	0,64	0,64	0,62	0,6	0,59	0,58	0,56
5009	0,635	0,635	0,615	0,605	0,595	0,585	0,575
5010	0,625	0,625	0,615	0,605	0,595	0,595	0,585
5011	0,615	0,635	0,625	0,625	0,625	0,63	0,63
5012	0,63	0,65	0,65	0,66	0,675	0,685	0,695
5013	0,585	0,605	0,605	0,615	0,63	0,64	0,65
5014	0,575	0,595	0,595	0,595	0,605	0,605	0,615
5015	0,585	0,595	0,595	0,605	0,605	0,615	0,625
5016	0,595	0,595	0,595	0,595	0,605	0,605	0,605
5017	0,59	0,59	0,59	0,59	0,58	0,58	0,58
5018	0,605	0,595	0,585	0,575	0,555	0,545	0,535
5019	0,57	0,62	0,67	0,72	0,77	0,82	0,87
5020	0,535	0,595	0,665	0,725	0,785	0,845	0,915
5021	0,57	0,62	0,68	0,74	0,8	0,86	0,92
5022	0,53	0,59	0,66	0,72	0,79	0,85	0,92
5023	0,555	0,615	0,685	0,745	0,805	0,875	0,935

Figure 49: Results from static displacement simulations for E-line 2 and 3.

	20 DEGREES		80 DEGREES		60 DEGREES		40 DEGREES		0 DEGREES		~20 DEGREES		~40 DEGREES	
Measure	mP2P	SQ max 20	mP2P	SQ max 80	mP2P	SQ max 60	mP2P	SQ max 40	mP2P	SQ max 0	mP2P	SQ max -20	mP2P	SQ max -40
SEAM 1														
1001	0,00304	0,10	0,00504	0,10	0,00399	0,10	0,00293	0,10	0,00278	0,10	0,00286	0,10	0,0025	0,10
1002	0,00818	0,10	0,01338	0,10	0,01074	0,10	0,00804	0,10	0,00755	0,10	0,0078	0,10	0,00683	0,10
1003	0,02029	0,10	0,03381	0,10	0,02701	0,10	0,01985	0,10	0,01862	0,10	0,01929	0,10	0,01673	0,10
1004	0,03118	0,10	0,05213	0,10	0,04181	0,10	0,03033	0,10	0,02855	0,10	0,02955	0,10	0,02559	0,10
1005	0,02458	0,10	0,04107	0,10	0,0324	0,10	0,0238	0,10	0,02234	0,10	0,02325	0,10	0,02009	0,10
1006	0,01522	0,10	0,02103	0,10	0,01874	0,10	0,01466	0,10	0,0135	0,10	0,01412	0,10	0,01096	0,10
1007	0,02197	0,10	0,03015	0,10	0,02719	0,10	0,02101	0,10	0,01916	0,10	0,0201	0,10	0,01574	0,10
1008	0,02211	0,10	0,03072	0,10	0,02771	0,10	0,02124	0,10	0,01957	0,10	0,0204	0,10	0,01674	0,10
1009	0,0224	0,10	0,03111	0,10	0,02795	0,10	0,02158	0,10	0,02	0,10	0,02078	0,10	0,01719	0,10
1010	0,01989	0,10	0,02732	0,10	0,02427	0,10	0,0192	0,10	0,01799	0,10	0,01859	0,10	0,01583	0,10
1011	0,0267	0,10	0,03597	0,10	0,03255	0,10	0,0264	0,10	0,0262	0,10	0,02623	0,10	0,02624	0,10
1012	0,0405	0,10	0,05499	0,10	0,05284	0,10	0,04017	0,10	0,03979	0,10	0,03994	0,10	0,04025	0,10
1013	0,04632	0,10	0,06256	0,10	0,0631	0,10	0,04555	0,10	0,04473	0,10	0,04499	0,10	0,04485	0,10
1014	0,03782	0,10	0,05097	0,10	0,05314	0,10	0,03688	0,10	0,03563	0,10	0,03613	0,10	0,03512	0,10
1015	0,01895	0,10	0,02481	0,10	0,02706	0,10	0,01803	0,10	0,01642	0,10	0,01718	0,10	0,01376	0,10
1016	0,02715	0,10	0,03728	0,10	0,03346	0,10	0,027	0,10	0,0272	0,10	0,02705	0,10	0,0277	0,10
1017	0,0592	0,10	0,08015	0,10	0,07394	0,10	0,05869	0,10	0,05821	0,10	0,05832	0,10	0,05851	0,10
1018	0,09459	0,10	0,12817	0,10	0,11713	0,10	0,09367	0,10	0,09297	0,10	0,09303	0,10	0,09338	0,10
1019	0,1316	0,10	0,17829	0,10	0,16145	0,10	0,13018	0,10	0,1293	0,10	0,12934	0,10	0,13012	0,10
1020	0,16401	0,10	0,22218	0,10	0,19794	0,10	0,16251	0,10	0,16098	0,10	0,16144	0,10	0,16207	0,10
1021	0,18229	0,10	0,24584	0,10	0,21443	0,10	0,18057	0,10	0,1776	0,10	0,1789	0,10	0,17744	0,10
1022	0,1925	0,10	0,25816	0,10	0,22108	0,10	0,18946	0,10	0,18481	0,10	0,18719	0,10	0,18003	0,10
1023	0,21422	0,10	0,28799	0,10	0,24759	0,10	0,20985	0,10	0,2029	0,10	0,20565	0,10	0,19387	0,10
1024	0,2358	0,10	0,31839	0,10	0,27994	0,10	0,23052	0,10	0,22132	0,10	0,2255	0,10	0,20788	0,10
1025	0,22057	0,10	0,29972	0,10	0,26722	0,10	0,21533	0,10	0,20617	0,10	0,21008	0,10	0,19203	0,10
1026	0,16889	0,10	0,23041	0,10	0,20585	0,10	0,16494	0,10	0,1578	0,10	0,16095	0,10	0,14642	0,10
1027	0,11169	0,10	0,15245	0,10	0,13509	0,10	0,10904	0,10	0,10424	0,10	0,10642	0,10	0,09677	0,10
1028	0,06171	0,10	0,08428	0,10	0,07408	0,10	0,06044	0,10	0,05776	0,10	0,05901	0,10	0,05394	0,10
1029	0,02427	0,10	0,03336	0,10	0,03001	0,10	0,02376	0,10	0,02279	0,10	0,02321	0,10	0,02126	0,10
1030	0,01189	0,10	0,01669	0,10	0,01553	0,10	0,01163	0,10	0,01127	0,10	0,01142	0,10	0,01058	0,10
1031	0,03267	0,10	0,0459	0,10	0,04528	0,10	0,03202	0,10	0,0311	0,10	0,0315	0,10	0,0296	0,10
1032	0,04062	0,10	0,05751	0,10	0,05912	0,10	0,03959	0,10	0,03805	0,10	0,03876	0,10	0,03587	0,10
1033	0,03518	0,10	0,04994	0,10	0,05316	0,10	0,03402	0,10	0,03217	0,10	0,03306	0,10	0,02945	0,10
1034	0,02371	0,10	0,03212	0,10	0,03461	0,10	0,02259	0,10	0,02047	0,10	0,02149	0,10	0,0172	0,10
1035	0,01921	0,10	0,02461	0,10	0,02321	0,10	0,01827	0,10	0,01625	0,10	0,01724	0,10	0,01244	0,10
1036	0,02218	0,10	0,02934	0,10	0,02708	0,10	0,02111	0,10	0,01899	0,10	0,02005	0,10	0,01506	0,10
1037	0,02123	0,10	0,02928	0,10	0,02622	0,10	0,02029	0,10	0,01836	0,10	0,01932	0,10	0,01469	0,10
1038	0,01962	0,10	0,02779	0,10	0,02445	0,10	0,01882	0,10	0,01728	0,10	0,01801	0,10	0,01466	0,10
1039	0,01319	0,10	0,01856	0,10	0,01636	0,10	0,01272	0,10	0,01182	0,10	0,01226	0,10	0,01026	0,10
1040	0,02483	0,10	0,04128	0,10	0,0329	0,10	0,02402	0,10	0,02263	0,10	0,02329	0,10	0,02032	0,10
1041	0,03172	0,10	0,05245	0,10	0,0429	0,10	0,03076	0,10	0,02897	0,10	0,02998	0,10	0,02547	0,10
1042	0,02073	0,10	0,0341	0,10	0,02812	0,10	0,02014	0,10	0,01888	0,10	0,01952	0,10	0,01647	0,10

Figure 50: Results showing max principle peak to peak and squeak limits for E-line 1 used in formula 3.

	20 DEGREES		80 DEGREES		60 DEGREES		40 DEGREES		0 DEGREES		~20 DEGREES		~40 DEGREES	
Measure	mP2P	SQ max 20	mP2P	SQ max 80	mP2P	SQ max 60	mP2P	SQ max 40	mP2P	SQ max 0	mP2P	SQ max -20	mP2P	SQ max -40
SEAM 2														
3001	0,00937	0,10	0,01369	0,10	0,01238	0,10	0,00909	0,10	0,00882	0,10	0,00893	0,10	0,00839	0,10
3002	0,00538	0,10	0,0076	0,10	0,00659	0,10	0,00523	0,10	0,00501	0,10	0,0051	0,10	0,00478	0,10
3003	0,00622	0,10	0,00879	0,10	0,00854	0,10	0,00597	0,10	0,00548	0,10	0,00571	0,10	0,00469	0,10
3004	0,0057	0,10	0,00769	0,10	0,00767	0,10	0,00547	0,10	0,00504	0,10	0,00524	0,10	0,00436	0,10
3005	0,0037	0,10	0,00517	0,10	0,00461	0,10	0,00358	0,10	0,0034	0,10	0,00349	0,10	0,00302	0,10
3006	0,00422	0,10	0,0058	0,10	0,00534	0,10	0,00408	0,10	0,00386	0,10	0,00398	0,10	0,00342	0,10
3007	0,00382	0,10	0,00511	0,10	0,00496	0,10	0,00368	0,10	0,00343	0,10	0,00354	0,10	0,0031	0,10
3008	0,00626	0,10	0,0084	0,10	0,00962	0,10	0,00596	0,10	0,00545	0,10	0,00567	0,10	0,00478	0,10
3009	0,00436	0,10	0,00598	0,10	0,00549	0,10	0,00432	0,10	0,00421	0,10	0,00426	0,10	0,00411	0,10
3010	0,00347	0,10	0,00491	0,10	0,00488	0,10	0,00344	0,10	0,0034	0,10	0,00341	0,10	0,00341	0,10
3011	0,00407	0,10	0,0056	0,10	0,0053	0,10	0,00402	0,10	0,00404	0,10	0,00401	0,10	0,0042	0,10
3012	0,00237	0,10	0,0036	0,10	0,00317	0,10	0,00236	0,10	0,00235	0,10	0,00235	0,10	0,00226	0,10
3013	0,00238	0,10	0,00324	0,10	0,003	0,10	0,00232	0,10	0,0022	0,10	0,00225	0,10	0,00198	0,10
3014	0,00589	0,10	0,00829	0,10	0,00767	0,10	0,00572	0,10	0,00547	0,10	0,00558	0,10	0,00515	0,10
3015	0,00786	0,10	0,0115	0,10	0,01097	0,10	0,0076	0,10	0,00716	0,10	0,00737	0,10	0,00642	0,10
3016	0,00143	0,10	0,00179	0,10	0,00177	0,10	0,0014	0,10	0,00137	0,10	0,00137	0,10	0,00141	0,10
3017	0,00159	0,10	0,00199	0,10	0,00183	0,10	0,00155	0,10	0,00151	0,10	0,00151	0,10	0,00148	0,10
3018	0,00245	0,10	0,00396	0,10	0,00349	0,10	0,00237	0,10	0,00223	0,10	0,00229	0,10	0,00206	0,10
3019	0,00919	0,10	0,01288	0,10	0,01135	0,10	0,00903	0,10	0,00876	0,10	0,00889	0,10	0,00849	0,10
3020	0,00857	0,10	0,01213	0,10	0,01088	0,10	0,00836	0,10	0,00802	0,10	0,00818	0,10	0,00753	0,10
3021	0,00871	0,10	0,01224	0,10	0,01124	0,10	0,00849	0,10	0,00802	0,10	0,00823	0,10	0,00728	0,10
3022	0,00762	0,10	0,01065	0,10	0,0099	0,10	0,0074	0,10	0,00697	0,10	0,00718	0,10	0,00628	0,10
3023	0,00533	0,10	0,00751	0,10	0,007	0,10	0,00519	0,10	0,0049	0,10	0,00502	0,10	0,00439	0,10
3024	0,00304	0,10	0,00432	0,10	0,00401	0,10	0,00298	0,10	0,00288	0,10	0,00294	0,10	0,00266	0,10
3025	0,00304	0,10	0,00394	0,10	0,00369	0,10	0,00297	0,10	0,00289	0,10	0,00292	0,10	0,00282	0,10
3026	0,00417	0,10	0,00577	0,10	0,0051	0,10	0,00408	0,10	0,00399	0,10	0,00403	0,10	0,00382	0,10
3027	0,00344	0,10	0,00436	0,10	0,00412	0,10	0,00329	0,10	0,00308	0,10	0,00318	0,10	0,0027	0,10
3028	0,00398	0,10	0,00523	0,10	0,00473	0,10	0,00385	0,10	0,00361	0,10	0,00374	0,10	0,00322	0,10
3029	0,00348	0,10	0,00464	0,10	0,00415	0,10	0,00335	0,10	0,00315	0,10	0,00326	0,10	0,00275	0,10
3030	0,00564	0,10	0,00706	0,10	0,00667	0,10	0,00543	0,10	0,00503	0,10	0,00521	0,10	0,00433	0,10
3031	0,00679	0,10	0,00886	0,10	0,00858	0,10	0,00651	0,10	0,00596	0,10	0,00622	0,10	0,00499	0,10
3032	0,00637	0,10	0,00847	0,10	0,0094	0,10	0,00605	0,10	0,00546	0,10	0,00573	0,10	0,00452	0,10
SEAM 3														
5001	0,01692	0,10	0,02309	0,10	0,02471	0,10	0,0164	0,10	0,01567	0,10	0,016	0,10	0,01484	0,10
5002	0,00609	0,10	0,00928	0,10	0,00899	0,10	0,00588	0,10	0,00556	0,10	0,00575	0,10	0,00501	0,10
5003	0,0028	0,10	0,00452	0,10	0,00386	0,10	0,00272	0,10	0,00256	0,10	0,00264	0,10	0,00226	0,10
5004	0,00197	0,10	0,00255	0,10	0,00242	0,10	0,00188	0,10	0,0017	0,10	0,0018	0,10	0,00136	0,10
5005	0,0016	0,10	0,00204	0,10	0,00208	0,10	0,00153	0,10	0,00138	0,10	0,00146	0,10	0,00114	0,10
5006	0,00134	0,10	0,00183	0,10	0,00186	0,10	0,00129	0,10	0,00119	0,10	0,00124	0,10	0,00106	0,10
5007	0,00372	0,10	0,00531	0,10	0,00556	0,10	0,00357	0,10	0,00325	0,10	0,00341	0,10	0,00275	0,10
5008	0,01352	0,10	0,0215	0,10	0,01871	0,10	0,01302	0,10	0,0121	0,10	0,01255	0,10	0,01075	0,10
5009	0,02531	0,10	0,04092	0,10	0,03481	0,10	0,02442	0,10	0,02273	0,10	0,02353	0,10	0,02027	0,10
5010	0,03646	0,10	0,05917	0,10	0,04984	0,10	0,03524	0,10	0,03285	0,10	0,03384	0,10	0,02945	0,10
5011	0,04546	0,10	0,07394	0,10	0,06211	0,10	0,04388	0,10	0,04092	0,10	0,04232	0,10	0,0368	0,10
5012	0,05003	0,10	0,08143	0,10	0,06852	0,10	0,04825	0,10	0,04483	0,10	0,04659	0,10	0,04041	0,10
5013	0,0501	0,10	0,08162	0,10	0,06887	0,10	0,04837	0,10	0,04492	0,10	0,04672	0,10	0,04047	0,10
5014	0,04587	0,10	0,07433	0,10	0,06293	0,10	0,04418	0,10	0,04109	0,10	0,04277	0,10	0,03676	0,10
5015	0,03688	0,10	0,05978	0,10	0,0505	0,10	0,0355	0,10	0,03311	0,10	0,03426	0,10	0,02956	0,10
5016	0,02563	0,10	0,04151	0,10	0,03506	0,10	0,02465	0,10	0,0231	0,10	0,02392	0,10	0,02065	0,10
5017	0,01356	0,10	0,02183	0,10	0,01829	0,10	0,01315	0,10	0,01246	0,10	0,01281	0,10	0,01118	0,10
5018	0,00386	0,10	0,00527	0,10	0,00465	0,10	0,00378	0,10	0,00363	0,10	0,0037	0,10	0,00335	0,10
5019	0,00157	0,10	0,0024	0,10	0,00218	0,10	0,00151	0,10	0,00144	0,10	0,00148	0,10	0,00136	0,10
5020	0,00133	0,10	0,00192	0,10	0,00164	0,10	0,00131	0,10	0,00124	0,10	0,00127	0,10	0,00114	0,10
5021	0,0018	0,10	0,00251	0,10	0,00221	0,10	0,00172	0,10	0,00159	0,10	0,00165	0,10	0,00134	0,10
5022	0,00272	0,10	0,00432	0,10	0,00346	0,10	0,00263	0,10	0,00246	0,10	0,00254	0,10	0,00221	0,10
5023	0,00523	0,10	0,00788	0,10	0,0066	0,10	0,00507	0,10	0,0048	0,10	0,00494	0,10	0,00425	0,10

Figure 51: Results showing max principle peak to peak and squeak limits for E-line 2 and 3 used in formula 3.

Appendix C – Expanded model verification

In this appendix the dynamic displacement simulation results for expanded and non-expanded models are shown.

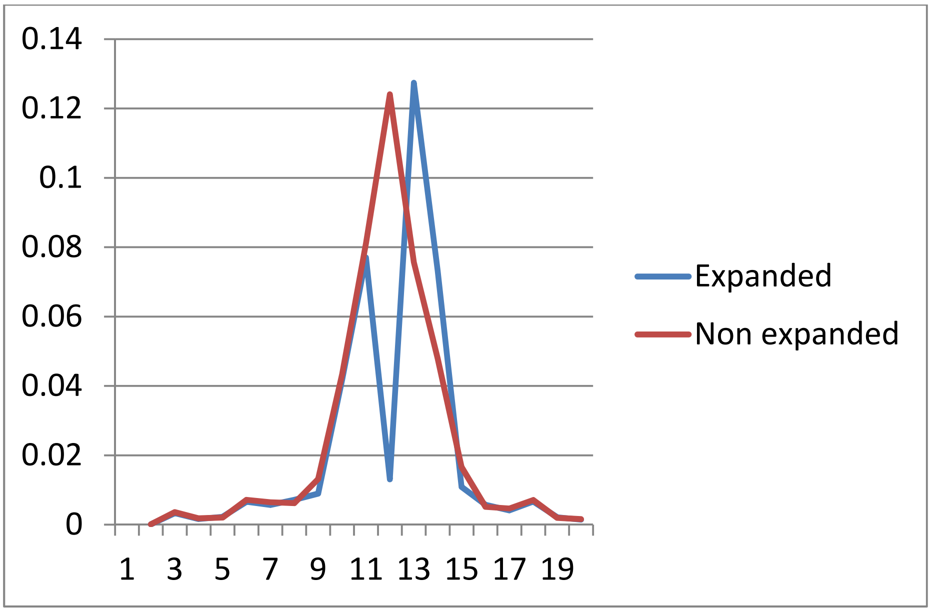

Figure 52: Dynamic displacement for E-line 1 in case 1.

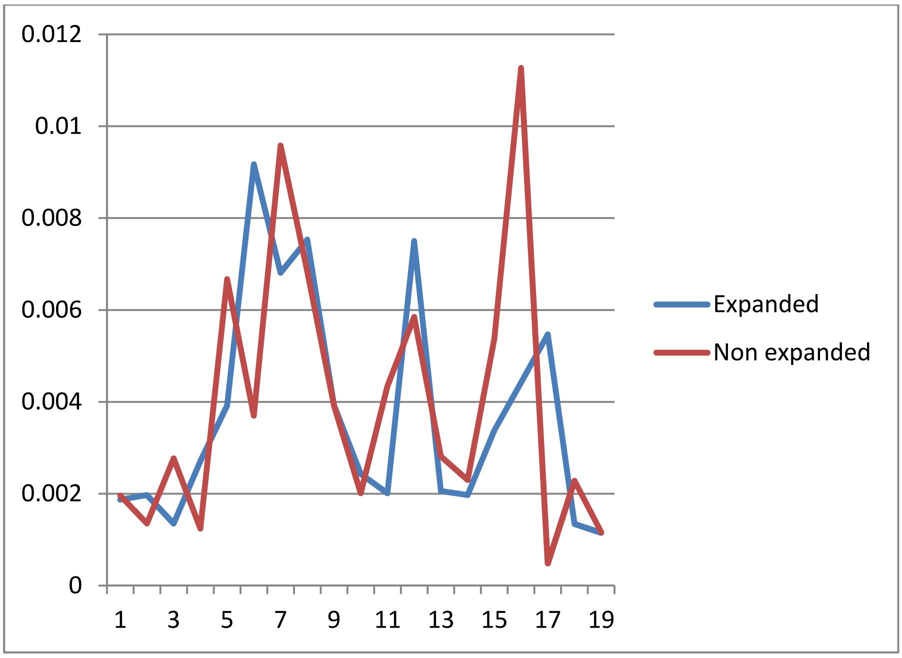

Figure 52: Dynamic displacement for E-line 2 in case 1.