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Multidisciplinary Optimization of Geometric Variation and Modal Behaviour for Squeak and Rattle Prevention

Master's thesis in Product Development

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**Multidisciplinary Optimization of Geometric
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Abstract

Squeak and Rattle are two undesired phenomenon that occurs when adjacent parts come into contact with each other either by sliding or impacting. The Squeak and Rattle directly affects the end user's perception towards the quality of the car which is not desirable for any automotive company. One of the main reason for the generation of Squeak and Rattle in a car is geometric variations which happen due to manufacturing tolerances, temperature etc. With modification in attachment points in an assembly, many other attributes like modal behaviour of the component are affected. This thesis aims to combine the design optimization process for geometric variation and modal behaviour for Squeak and Rattle prevention.

The study is carried out on a passenger car door and deco panel-IP assembly. Geometric variation analysis is performed in CAT software package of RD&T whereas the modal behaviour of an assembly is determined by doing FEM analysis. To couple the optimization process for two different disciplines, modeFRONTIER is used which is an integration platform for multi-objective and Multi Disciplinary Optimization (MDO). Initially, single discipline is framed in the optimization workflow to understand the optimum or best attachment points in an assembly. Further, MDO workflow is created and the results were compared with deco upled optimization to analyze its effects on the selection of optimum attachment points.

Multi Objective Genetic Algorithm (MOGA-II) is used as the optimization algorithm to find the best optimal positions within an assembly. The results show that the two objectives from MDO optimization workflow are conflicting with each other wherein the best solutions lie on a Pareto front. The MDO methodology can be applied for different types of geometries and attachment schemes. No experimental validation was done and could be considered as future scope of work.

Keywords: Squeak and Rattle, Multidisciplinary optimization, Modal behaviour analysis, Geometric variation, Tolerances, Resonance, MOGA-II

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Saiprasad Kulkarni, Dharun Velmani Thanga Ratnam, Gothenburg, September 2019

Nomenclature

Abbreviations

BSR	Buzz Squeak Rattle
CAD	Computer-Aided Design
CAT	Computer-Aided Tolerancing
DoE	Design of Experiments
FEM	Finite Element Method
GD&T	Geometric Dimensioning & Tolerancing
IP	Instrument Panel
ISF	Increment Space Filler
MDO	Multi-Disciplinary Optimization
MOGA-II	Multi-Objective Genetic Algorithm - II
RBE	Rigid Body Elements
RD&T	Robust Design & Tolerancing
S&R	Squeak & Rattle
ULH	Uniform Latin Hypercube
VCC	Volvo Car Corporation

Symbols

μ	Mean
ω	Eigen frequency
σ	Standard deviation
f	Force
k	stiffness
m	mass

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1

Introduction

This chapter aims at introducing the reader about the company and project background, along with the purpose of execution, scope, and the necessary delimitation's are presented followed by goal and key deliverables.

1.1 Project Background

In recent years, the automotive industry has seen a gradual increase in terms of driving demanded by customers. Growing demands from today's competitive market for improved perceived quality is pushing the automotive industries to break the barriers of excellence particularly in the Automotive Buzz, Squeak & Rattle (BSR) field. The sounds inside a car cabin comprises from different attributes which includes engine noise, tire noise and some irritating noises like Squeak & Rattle. Sounds from engine & tires are anticipated by the customers, however S&R is an attribute which occurs due to friction or impact of different interior parts within the cabin which is perceived as quality defects [1]. Digital simulations in the early product development phase helps the engineers to mitigate the S&R problems efficiently as well as cost effective.

Squeak is an acoustic phenomenon that is a friction induced noise between two different surfaces sliding in the opposite directions against each other. For the generation of Squeak, a relative motion between two surfaces must be there as shown in Figure 1.1. The intensity of generation of squeak is directly proportional with the loading conditions such as contact pressure, sliding speed, surface profiles, material properties and coefficient of friction. [2]

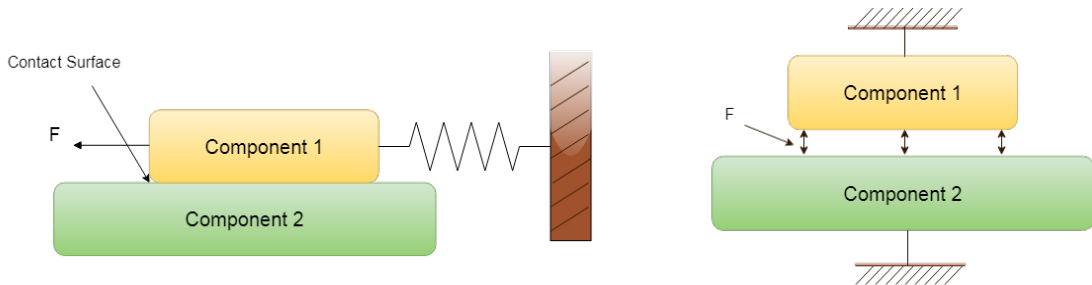


Figure 1.1: Phenomenon of Squeak & Rattle

Rattle occurs when two adjacent parts come in contact with each other due to an impact force. This can be due to the vibration between two components, deficient

tolerance ranges for complex geometries or also due to excitation of loose elements in a system as show in Figure 1.1. For the generation of rattles, road excitation to a vehicle is the primary source [2].

One of the main reasons for the generation of S&R in the passenger vehicle is geometric variations. This can be due to poor tolerances for complex geometries or other sources like atmospheric conditions, variation in process parameters, and additional human errors [3] . An important challenge in mass production is how to design a component so that they can be manufactured according to production plan and the desired properties such as functional and aesthetic aspects of the assembled product is ensured [3]. Thus variation in the final product influences both the cost and its quality during its launch to the market. Management of variation in a product, thus has been given utmost priority in most of the car manufacturing companies [3].

For geometric variation caused due to manufacturing tolerances is concerned, established approaches are available in the market to minimize the effect of product variation by choosing optimum attachment points in assemblies and adjusting the tolerance levels for a robust design. However, changing the position of assembly points have severe effects on other attributes of the product. The modal behaviour of the assembly is amongst the most influenced attributes by changing the assembly points of components. In early product development phase, the standard practice is to perform a decoupled design optimization for the location of attachment points to have a geometrically robust design and modal response. The main aim of this research is to perform multidisciplinary optimization for modal response and geometric variation for S&R prevention.

1.2 Volvo Car Corporation

This Master's Thesis has been performed in collaboration with Volvo Car Corporation (VCC), a Swedish car manufacturing company offering premium segments of cars like sedans, station wagon & Sport Utility Vehicle (SUV) to the customers. It's headquarters is located at Torslanda in Gothenburg, and is a subsidiary of the Chinese automotive company Geely Group.

1.2.1 Solidity Department

This Master thesis was carried out with Solidity department which is a subdivision of Craftsmanship & Durability Centre at VCC, who are responsible for eliminating Squeak & Rattle sounds and to secure a solid feeling in the car. The main scope of the department is to set the requirements and verification of S&R problems at the initial stages of product development to meet shorter lead times in order to avoid the late phase changes and reducing the need for physical prototypes.

1.3 Goals & Deliverables

The main goals identified for this project are outlined as follows:

- Perform Geometric variation by attachment location optimization in RD&T software.
- Perform modal response optimization to minimize the S&R risk in identified interfaces using Msc Nastran and Matlab.
- Perform a multidisciplinary optimization incorporating two design objectives.

Based on the outlined goals, The following milestones were expected to be met during the course of this thesis study:

- Planning report which will include specifications of the aim of the thesis, a description of how the work will be carried out
- Identify assemblies in the car cabin through previous studies and benchmark on the previous projects in the company.
- Prepare simplified geometries and finite element models representing the selected assemblies.
- Framework for Multidisciplinary Optimization
- Presentation of results at VCC & Chalmers University of Technology.
- Final Master Thesis Report.

1.4 Research Questions

With these goals in mind, the following research questions have been drafted to steer the research in this thesis:

- With the aim of S&R prevention by geometric variation and modal analyses, how different the results of a decoupled or multidisciplinary optimisation are?
- For different assemblies, how the above difference vary? Can the findings be clustered for different types of geometries and attachment schemes?

1.5 Scope and Delimitations

The project is mainly focused on:

- Geometry variation analysis using the RD&T software and optimizing the attachment points with the aim of controlling the displacement levels at selected interfaces vulnerable for generating S&R.

The main goal is to perform a multi-disciplinary optimisation of the attachment points of selected assemblies in a car cabin to improve geometric variation and modal behaviour of the assemblies for S&R sound prevention.

In order to focus towards scope of the project, certain delimitations were set and are as follows:

- To perform this research study, the assemblies will be selected as advised by the supervisor.
- The Finite Element Model of the assemblies will be provided by the supervisor.
- The Master Thesis is not expected to investigate if the number of assembly points can be reduced.
- Framework for Multidisciplinary optimization will be developed only for the side door and deco panel-IP assembly. Deco panel - IP assembly is selected to give a head-start for defining the methodology for MDO whereas the side door assembly is selected because it is more prone for S&R.

2

Theory

This chapter aims at providing the reader with a basic understanding of the theories relevant to carry out the the study for this thesis topic.

2.1 Robust Design

Edward Deming, an American statistician, a forefront figure in quality engineering declared "Uncontrolled variation is the enemy of quality" [4]. Previous research shows that variation is one of the most crucial aspect for product failure. The approach to reduce the variation without eliminating the causes of variation is called as robust design. A product design is said to be geometrically robust only if it satisfies the requirements and constraints, even though the geometry is affected with certain variations [5].

Placement of attachment points in an assembly is a key factor to control the contribution of variation [7]. The relationship between robustness and sensitivity can be illustrated by using a beam and a support as illustrated in Figure 2.1 & 2.2

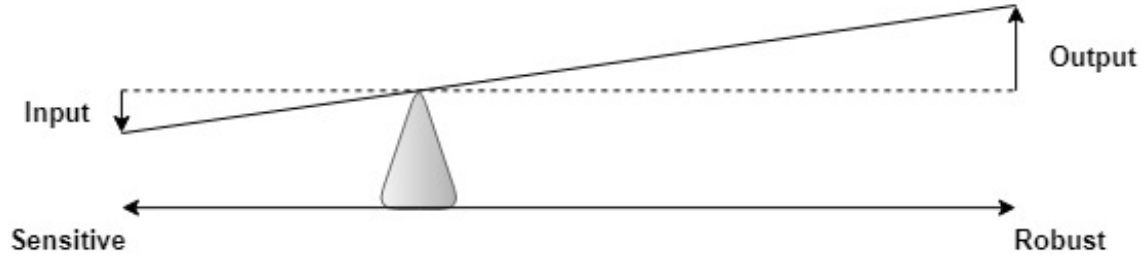


Figure 2.1: Illustration of a sensitive system, inspired by Lindkvist, L. (2017), [8]

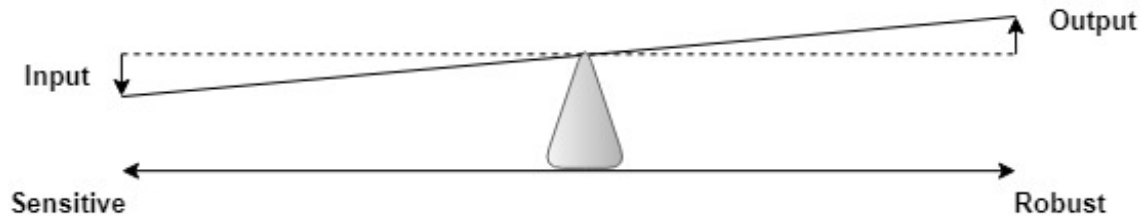


Figure 2.2: Illustration of a robust system, inspired by Lindkvist, L. (2017), [8]

The support stand in the above illustrated example dictates the robustness of the system since it contributes to the relation between input and output parameters. In

Figure 2.1, the attachment point(i.e. support stand) position contributes to higher variation resulting to a sensitive system whereas in Figure 2.2 , variation observed is quite low which signifies as a robust system [6] [7].

2.1.1 Variation Analysis

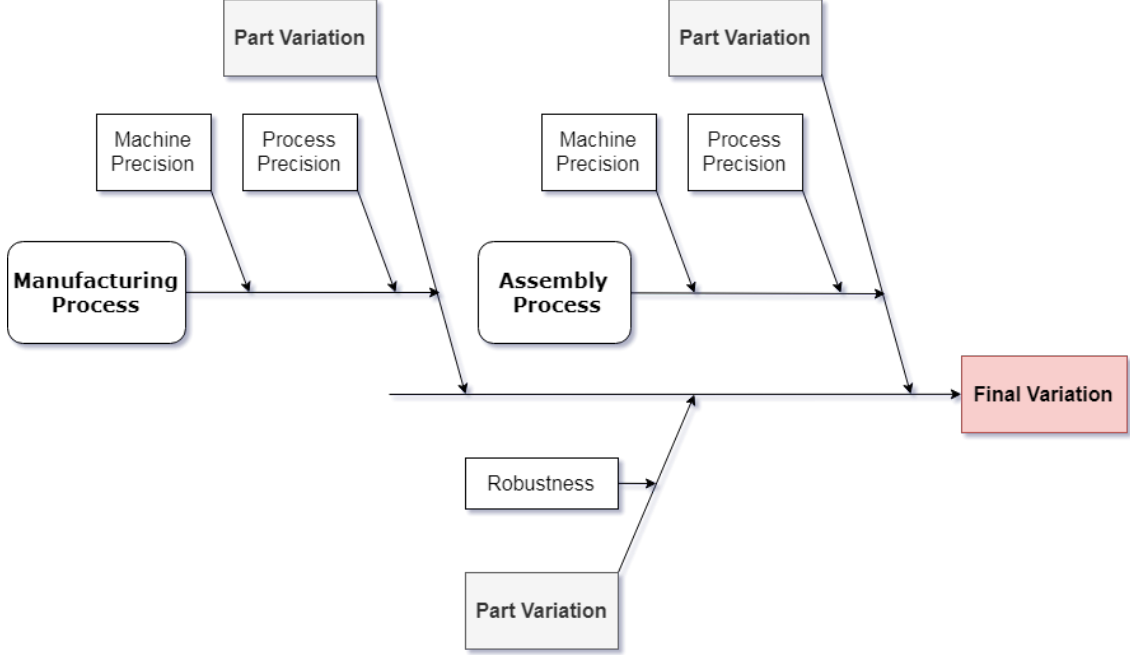


Figure 2.3: Possible Variations from manufacturing to final product, inspired by Lindkvist, L. (2017), [8]

Variation of parts and process should be identified during the early stages of product development. Cost involved in changing the design during early stages is more feasible than changing the design in the final stages. As shown in Figure 2.3, production process involved and wear & tear in manufacturing tools are the key contributors for part variation. Along with part variation, there is assembly variation which includes the variation in fixtures and jigs involved in the assembly process, altogether which constitutes to final geometric variation.

2.1.2 CAT Simulation

CAT Simulation is performed by using RD&T, a commercial software package developed by RD&T Technology AB [13] [14]. This tool is used in the early product development phase for statistical variation simulation based on digital CAD models in Robust Design Tolerancing discipline. RD&T is a beneficial software package which supports the geometrical assurance process throughout the product realization loop i.e. from early concept stages to final production [13]. RD&T is based on Monte-Carlo simulation which also has the Finite Element Analysis capability to simulate non-rigid geometries. [13]

2.1.3 Locating Schemes

Locating schemes have an important role of locking the position of a part in the space. The general principle for assigning the locating schemes is to spread the locators proportionally all over the geometrical surface of the component in order to obtain a robust solution.

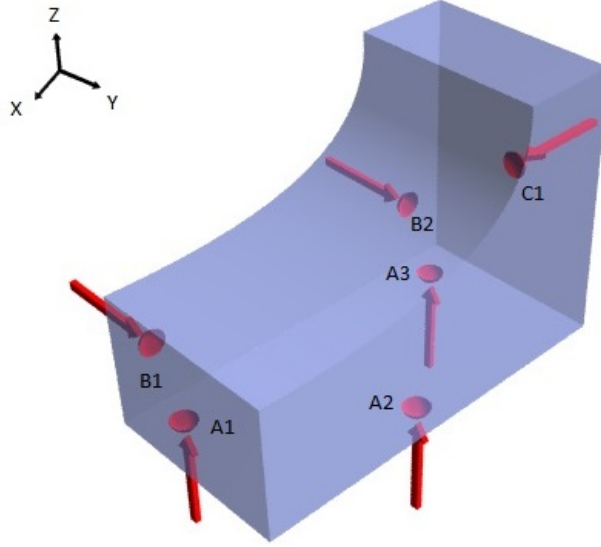


Figure 2.4: The 3-2-1 locating scheme, inspired by Lindkvist, L. (2017), [8]

As shown in Figure 2.4, a rigid body has six degrees of freedom i.e 3 translation & 3 rotational. Fundamentally, a rigid body can be locked in all directions by using 3-2-1 locating scheme principle. The primary points A1, A2 & A3 in Figure 2.4 represents a plane, which locks the component in space in translation in Z and rotation around X and Y directions. The locators B1 & B2 locks the component in translation in Y and rotation around Z directions. The final locator C1, locks the component in translation in X direction [8].

Positioning system is the most influential parameter for a geometry's variation. Figure 2.5 illustrates how locators influences the geometry to be robust or sensitive to variation by using 3-2-1 principle. Figure 2.5 shows a manufactured component i.e. a blue rectangle while the dotted black rectangle represents the nominal design. From the Figure 2.5 it is clear that the left reference system is more sensitive to variation compared to the right reference system due to position of its locators. This indicates that it is better to have locators as far away from each other as possible spread over the entire geometry [10].

For geometry with non rigid parts, sometimes it is not possible to use traditional 3-2-1 locating scheme due to component's complex and irregular shapes. For such situations, it is possible to define a 6-direction locating scheme, with 6 different directions. For some cases which has non rigid parts, number of support points exists in addition to the six main locators, to counteract the effect of gravity and other forces [9].

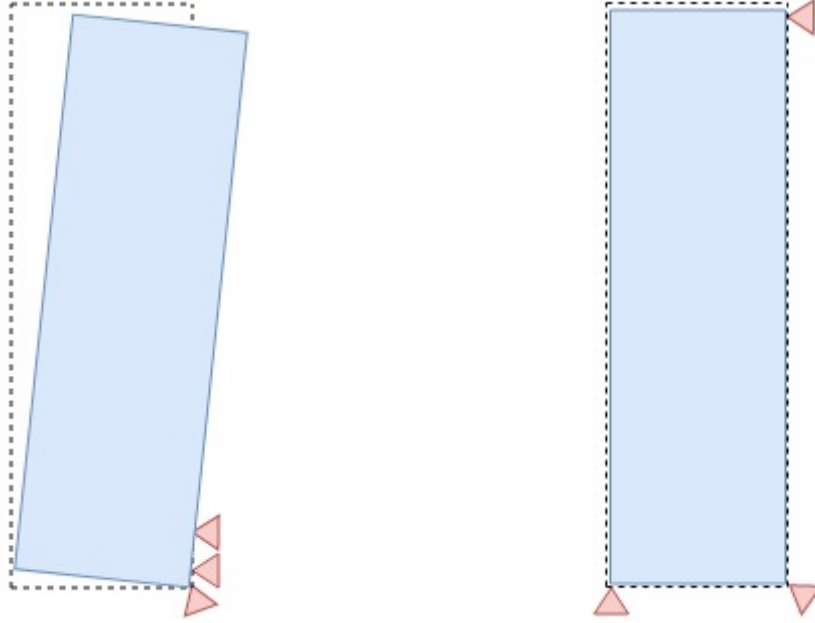


Figure 2.5: Illustration of sensitive & robust systems, [10]

2.1.4 Tolerances

Tolerance is termed as the range of allowable variations in the dimensions of a geometry and in the positioning of parts in a mechanical assembly to achieve desired function [11]. It is also specified as the allowed geometrical variation from its nominal value for a feature which can include in the form of size, orientation or its location [12].

Along with the locating schemes, tolerances are one of the key factors affecting the overall geometrical variation. To overcome the variation, position of the locators in the assembly can be optimized during early product development phase without any additional costs. Another way of reducing geometrical variation is by giving tight tolerances which will increase the manufacturing costs and is generally desirable to avoid [9].

GD&T is a symbolic language that defines the allowed variation with respect to nominal value [12]. GD&T is also said to be a communication tool between designers and manufacturing personnel's about how much precision is required for each part of a geometry [12]. GD&T also helps to understand how the geometry may vary and still can be able to achieve its desired function.

In RD&T, there are many ways to define tolerances according to the requirements for a geometry. For this particular research, linear tolerances are used for geometry assurance simulation.

2.1.5 Measures

A critical point or dimension where variation of geometry is to be analyzed is called as a Measure. The Measures are decided and defined beforehand where the dimen-

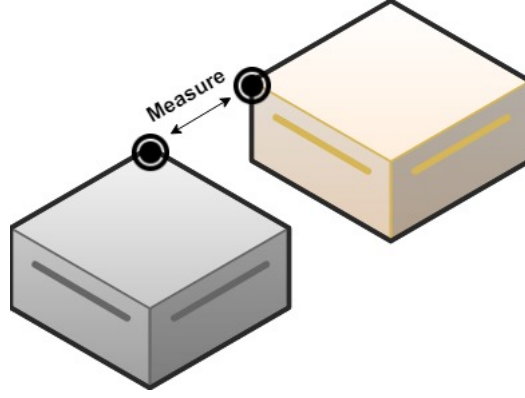


Figure 2.6: Illustration of a measure

sions or points to be analyzed are critical to variation of geometry. In RD&T, there are many ways to define a measure but for this particular research, Point-Point measure is used to analyze variation. As shown in Figure 2.6, Point-Point Measure is defined as the distance between two points or nodes [13].

2.1.6 Standard Deviation

Standard deviation is a statistical term which is a measure of how a set of data varies to its nominal value and is represented by the Greek letter " σ ". If the data is close to the mean value, it indicates a very small distribution whereas high value indicates a large spread of data.

Standard variation is calculated by Equation (2.1), where x represents a value in a data-set, μ represents the mean and N represents the number of values in data-set. [15]

$$\sigma = \sqrt{\frac{\sum (x - \mu)^2}{N}} \quad (2.1)$$

2.2 Modal Analysis

Modal analysis is the process to calculate the essential dynamic characteristics of a system in the forms of natural frequencies and modes shapes by generating a mathematical model to illustrate its dynamic behaviour [16]. Modal analysis is one of the steps in performing a dynamic analysis by determining the natural frequencies and mode shapes. These results helps to understand how the system will respond to the dynamic loading conditions. The modes are inherent properties of a structure which are determined by the material and geometrical properties like damping, mass, stiffness and also the boundary conditions applied to the system. For instance, if certain mass is added to the structure, the behaviour of structure vibrates differently [17].

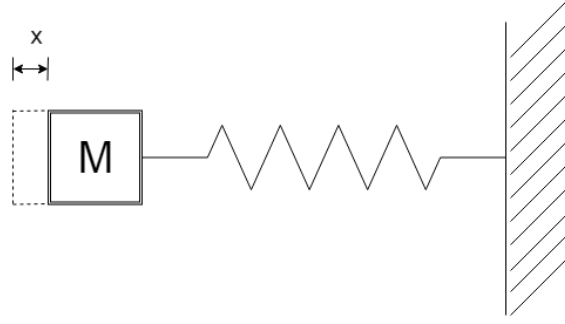


Figure 2.7: Undamped system, inspired by Fu, Zhi-Fang, and Jimin He. *Modal Analysis*, [16]

Consider the undamped simple mass and spring system as show in Figure 2.7. Newton's second law of motion derives the Equation (2.2) with displacement x .

$$m\ddot{x} + kx = 0[16] \quad (2.2)$$

where \mathbf{m} represents the mass and \mathbf{k} represents the stiffness of the spring. The mathematical representation for an undamped system is given by the Equation (2.3)

$$(k - \omega^2 m)X = 0[16] \quad (2.3)$$

where ω represents the natural frequency of the system whereas X represents the eigen vectors.

2.2.1 Eigen Modes & Eigen Frequencies

The eigen frequencies are the frequencies at which the system vibrates. It is the square root of the ratio of stiffness and mass for a linear undamped system. For an undamped system, eigen frequency is determined by the Equation (2.4).

$$\omega = \sqrt{\frac{k}{m}} \quad (2.4)$$

Eigen frequencies can be illustrated by taking an example of a musical instrument guitar where strings are tuned in such a way that they vibrate at a certain frequency.

Eigen modes are defined as the deformed shapes of the structure at a specific eigen frequency. Each mode shape relates with its specific eigen frequency. The reason to compute the eigen frequencies and eigen modes is to determine the dynamic interaction between a component and and its supporting structure. [18]

2.2.2 Dynamic Stiffness

When a car starts moving on the road, vibration is transmitted from road to the vehicle. The dynamic stiffness is defined as the frequency dependant ratio between a dynamic force and the resulting dynamic displacement. Dynamic loads applied are applied in terms of frequency. This time varying load application induces time

varying responses for different characteristics like displacements, velocities, accelerations, forces, and stresses [18]. The formula for dynamic stiffness is shown below in the Equation (2.5).

$$k(freq) = \frac{f(freq)}{s(freq)} \quad (2.5)$$

where $\mathbf{k}(\mathbf{freq})$ is the stiffness, $\mathbf{f}(\mathbf{freq})$ is the force and $\mathbf{s}(\mathbf{freq})$ is the displacement.

An increase in the dynamic stiffness of a component will result in the reduction of overall vibration in the system. Figure 2.8 below shows the relationship between force and displacement for a spring-damper system.

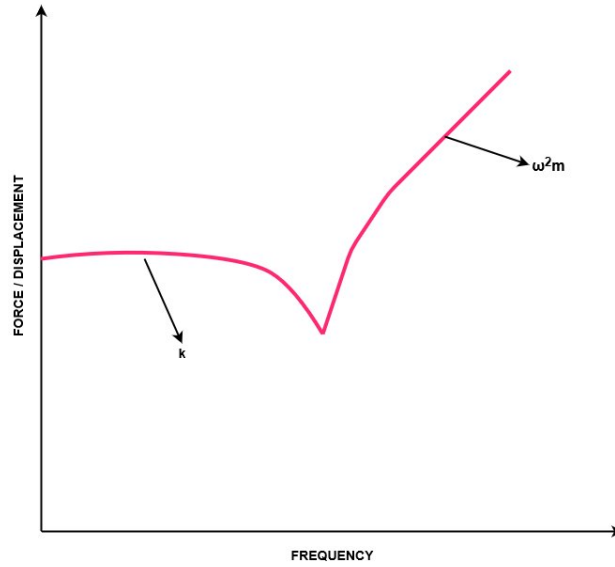


Figure 2.8: Relationship between force and displacement for spring-damper element [29]

2.2.3 Resonance

Resonance is a phenomenon that occurs when the frequency at which a force is periodically applied is almost equal or equal to the natural frequencies of the system where it acts. This further results in oscillation of system with larger amplitude than compared when the force is applied at other frequencies. The frequency at which the resonance amplitude is maximum is called as the resonant frequency [25].

In the Figure 2.9, how the amplitude increases as damping decreases and how the frequency shifts towards resonant frequency is shown.

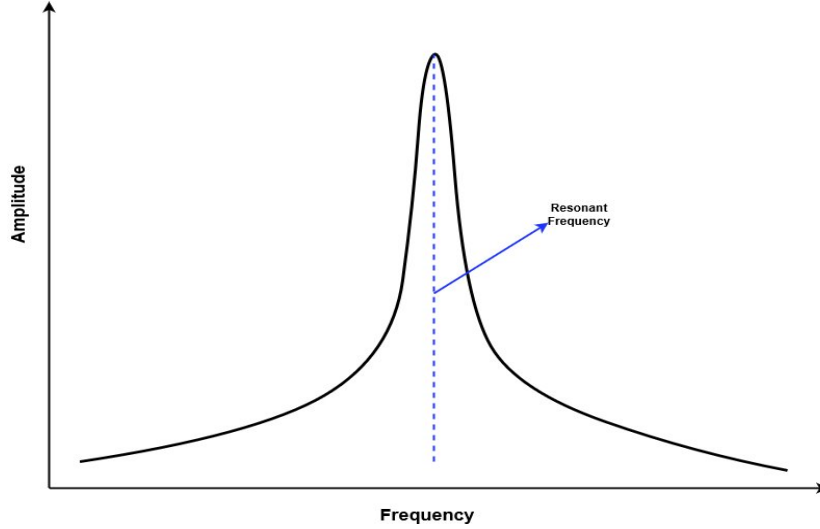


Figure 2.9: Resonant Frequency [30]

2.3 Multidisciplinary Optimization

2.3.1 modeFRONTIER

modeFRONTIER is an integration platform for multi-objective & multi-disciplinary optimization developed by Italian company named ESTECO which enables the users to streamline the engineering design process to cut time and cost while securing optimum results [21]. The workflow in modeFRONTIER enables the execution of a series of design samples for optimization framework. With innovative optimization algorithms introduced in this software package, this helps the user to determine the set of best possible solutions combining conflicting objectives. The post-processing tools helps the user to perform sophisticated statistical analysis and visualize the output results for decision making process.

2.3.2 Design of Experiments

The framework on where the design points should be positioned in a specified design space to get the best results with limited sample size is called as design of experiments. DoE is a series of experimental tests in which the input variable values are varied to identify the output behaviour. The main advantage of DoE is to perform a smart exploration of the available design space and extract as much as information as possible from the outputs [22]. Following are the types of DoE used for this study:

2.3.2.1 Full Factorial Design

Full factorial designs consist of all possible combination of levels for all input variables. It is suitable for statistical analysis wherein interactions between variables can be analyzed by measuring the response of every possible combination of factors.

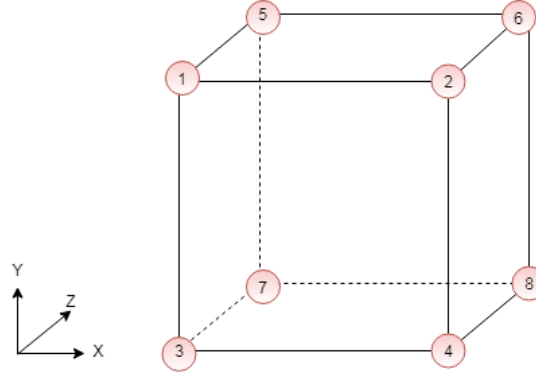


Figure 2.10: Full factorial design with two levels [28]

The sample size for full factorial can be computed by Equation (2.6) [22].

$$N = \prod_i^k n_i \quad (2.6)$$

2.3.2.2 Space Filler Designs

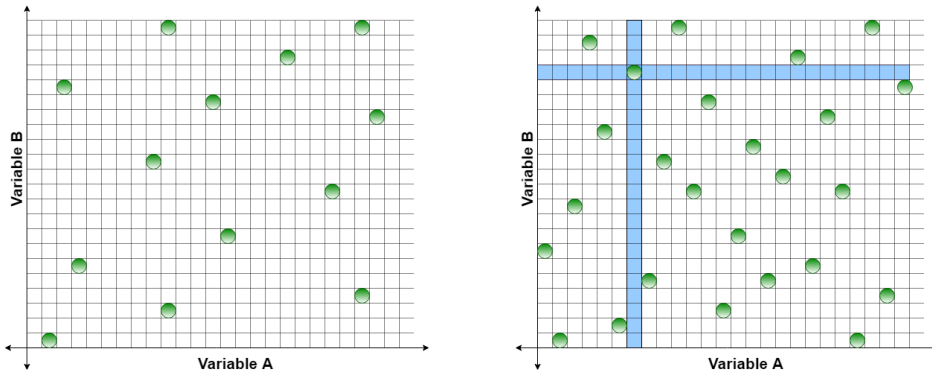


Figure 2.11: Space fillers [26]

- Increment Space Filler(ISF)

ISF is a DOE algorithm that sequentially adds new design samples by maximizing the minimum distance of the variables from the existing points as shown in Figure 2.11. This algorithm is mostly suited to generate a response surface model between input and output variables [22].

- Uniform Latin Hypercube(ULH)

ULH is an algorithm that generates random numbers uniformly, minimizes correlations between input variables and maximize the distance between generated designs. The algorithm works by dividing the design space into orthogonal grids. The amount of orthogonal grids depends upon the number of input variables and the algorithm tries to explore the design space as far as possible. After setup of grids, the algorithm picks one design from one row

and one column as shown in Figure 2.11. This ensures well spread of design samples in design space [23]. This algorithm is also suitable for discrete input variables [22].

2.3.3 Optimization

Optimization in engineering discipline is termed as the formulating of a design problem into a mathematical problem to attain optimum results. With the application of optimization concept in product development process will result in reduction of time and cost dramatically to find a profitable design. Different algorithms have been derived which are favourable for different levels of complexity problems.

2.3.3.1 Multi Objective Genetic Algorithm

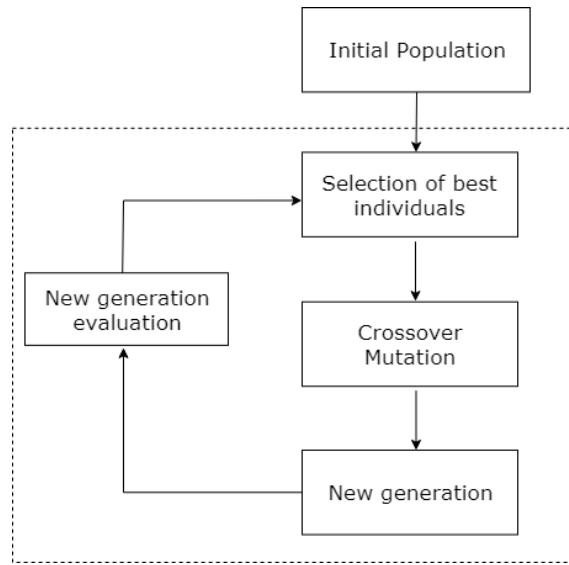


Figure 2.12: Genetic Algorithm concept, [26]

Genetic Algorithm was developed in 1960 which represents a different approach to evolutionary computation in which the the evolution of population is initiated due to the effect of cross-over operator. MOGA-II is the advanced version of multi-objective genetic algorithm that uses a smart and efficient multi-search elitism which helps to reach optimal solutions without converging at local optimum [24]. The operating principle of MOGA-II is as follows:

- Selection: Initialize the starting population in the data-set and evaluate the fitness function for each individual in the population.

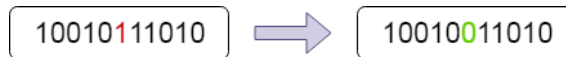


Figure 2.13: Mutation [24]

- Mutation: Mutation is an operator which ensure diversity in the generations of population. New designs of genes are created by random mutation. It ensures the MOGA-II algorithm robustness [24].

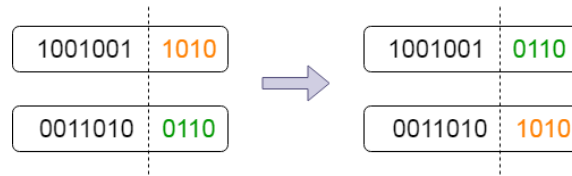


Figure 2.14: Crossover [24]

- Classical Crossover: An offspring is created by exchanging the genetic material of two parents in order to produce an offspring with better characteristics than the parent [24].

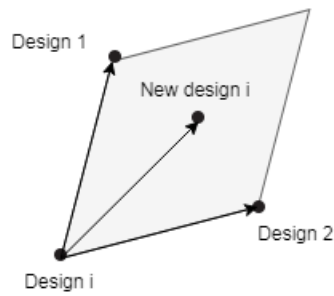


Figure 2.15: Directional crossover [24]

- Directional Crossover: Direction of reaching optimal design could be found by comparing the fitness value of the corresponding individuals. New designs in the next generation is created by moving in a randomly weighted direction computed based on the direction vector [24].

3

Methodology

In this chapter, the research methodology implemented and its significance over the course of period will be presented.

3.1 Research Methodology

"Aims against Stages" methodology is used to evaluate the performance of the research work and also to reach the intended milestones set at the start of the project. The questions are assigned in accordance with different stages and at the end of each research question, the answers are sought to understand the performance of the process [27]. Following questions were formulated to monitor the deliverables and develop the knowledge within this study :

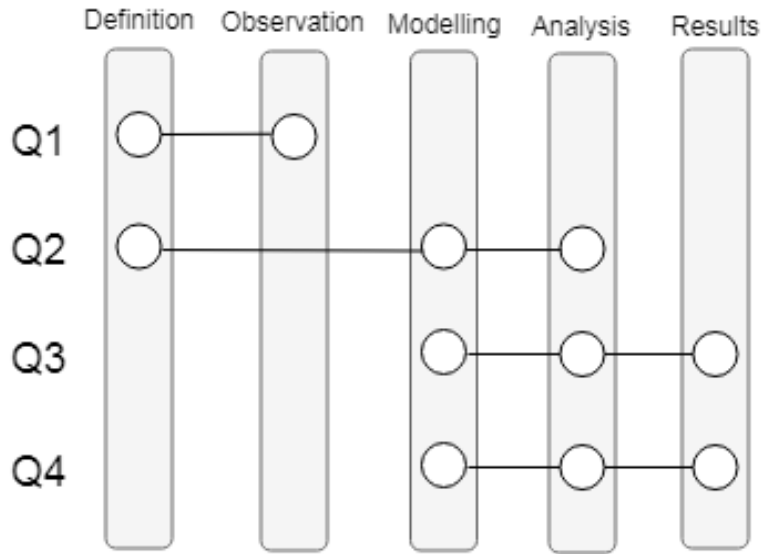


Figure 3.1: Aims against Stages [27]

- Q1 - Which assemblies in the car cabin is subjected to S&R ?
- Q2 - What results are obtained when combining the static geometric variation with the dynamic response of a system to predict and evaluate S&R ?
- Q3 - With the aim of S&R prevention, how different the results of a decoupled or multidisciplinary optimization are for geometric variation and modal analysis ?
- Q4 - Can the findings be clustered for different geometries and attachment points ?

The various stages in the research method is described below :

- **Defining the problem**

The problem to be investigated usually falls in the category of performance/-functionality failure of a product or further improving the functionality and performance of the product. One of the main sources of Squeak & Rattle generation in the car cabin is geometric variations whose primary sources are manufacturing tolerances, temperature or aging. With different methodologies for reducing geometric variation by adjusting tolerance levels or moving the attachment points, it will have severe effects on other attributes of the product. The modal behaviour of the assembly is amongst the most influenced attributes. The main aim of this research work is to analyze and combine the design optimization for modal response and geometric variation optimization for S&R prevention.

- **Observing the problem**

The problems were investigated by carrying out a literature study, in which the prime focus was set to determine how S&R occurs. The problem of S&R was further investigated by conducting one to one discussions with team members of the Solidity department of VCC. Assemblies mentioned in Table 3.1 subjected to S&R was formulated. While selecting the assemblies for this study, great importance was given to those assemblies with different material combinations. Material compatibility, temperature, forces, loads and relative motion are significant parameters for the choice of materials to avoid S&R. For example, the Instrument Panel in a car cabin is exposed to high temperatures for which material selection should be based on thermal properties to avoid S&R. To make this research work more widely, different combinations of materials within an assembly were selected to observe their behaviour.

Table 3.1: Assemblies selected for research work

Sr.No.	Element Type	Material Combination	Assembly Name
1	Panel - Panel	Plastic-Steel	Side Door
2	Panel - Structure	Steel-Steel	Tailgate
3	Panel - Beam	Metal - Metal	Door Outer body - Crash Beam
4	Panel - Structure	Plastic - Plastic	IP Top Cover - IP Deco Panel
5	Bracket - Panel	Metal - Metal	A Pillar - IP Bracket
6	Glovebox	Panel - Structure	Plastic - Metal

- **Modelling**

With the FE models of Side Door and IP assembly already provided, large amount of time was saved in modelling which allowed to focus on the research work. To carry out this study, the FE models were simplified to an extent. The FE model consisted of numerous complex surfaces. However to perform the

required analysis some modifications were done in the model. The parts that is of primary interest for simulation was taken into account, since having redundant parts for this particular study would increase the complexity and the total time for simulation.

To carry out geometric variation analysis, RD&T software a commercial package for CAT Simulation was used where specific boundary conditions were defined to the model according to the requirements. Tolerances were defined for attachment points to be analyzed and measure points were defined to analyze variation analysis. For modal analysis, commercial software package for pre-processor ANSA is used and for post processing the results META is used whereas NASTRAN is used as the FE solver.

modeFRONTIER software is used to carry out the optimization process with different DoE & optimization algorithms. The ultimate goal for using the modeFRONTIER was to find the optimal design with less number of samples. A workflow was created in modeFRONTIER to calculate variation analysis and response from modal analysis by NASTRAN solver for each iteration of design defined in the DoE.

- **Analysis**

Geometric variation analysis was performed to analyze variation in critical dimensions (measures) of the design using RD&T software. The variation analysis in RD&T uses Monte Carlo Simulation technique to analyze the variation in the defined measures. Dynamic Stiffness analysis was carried out to find the displacement due to applied force in an assembly. Matlab tool is used for post processing the displacement values.

Single discipline optimization with conflicting objectives was performed to understand the optimal attachment positions according to respective discipline's requirement. Multidisciplinary optimization was performed by using evolutionary algorithm to find the behaviour of the optimal positions when two disciplines are integrated with each other with contrasting objectives.

- **Results**

Various post-processing tools available in modeFRONTIER software were used to interpret the final outcomes of the analysis.

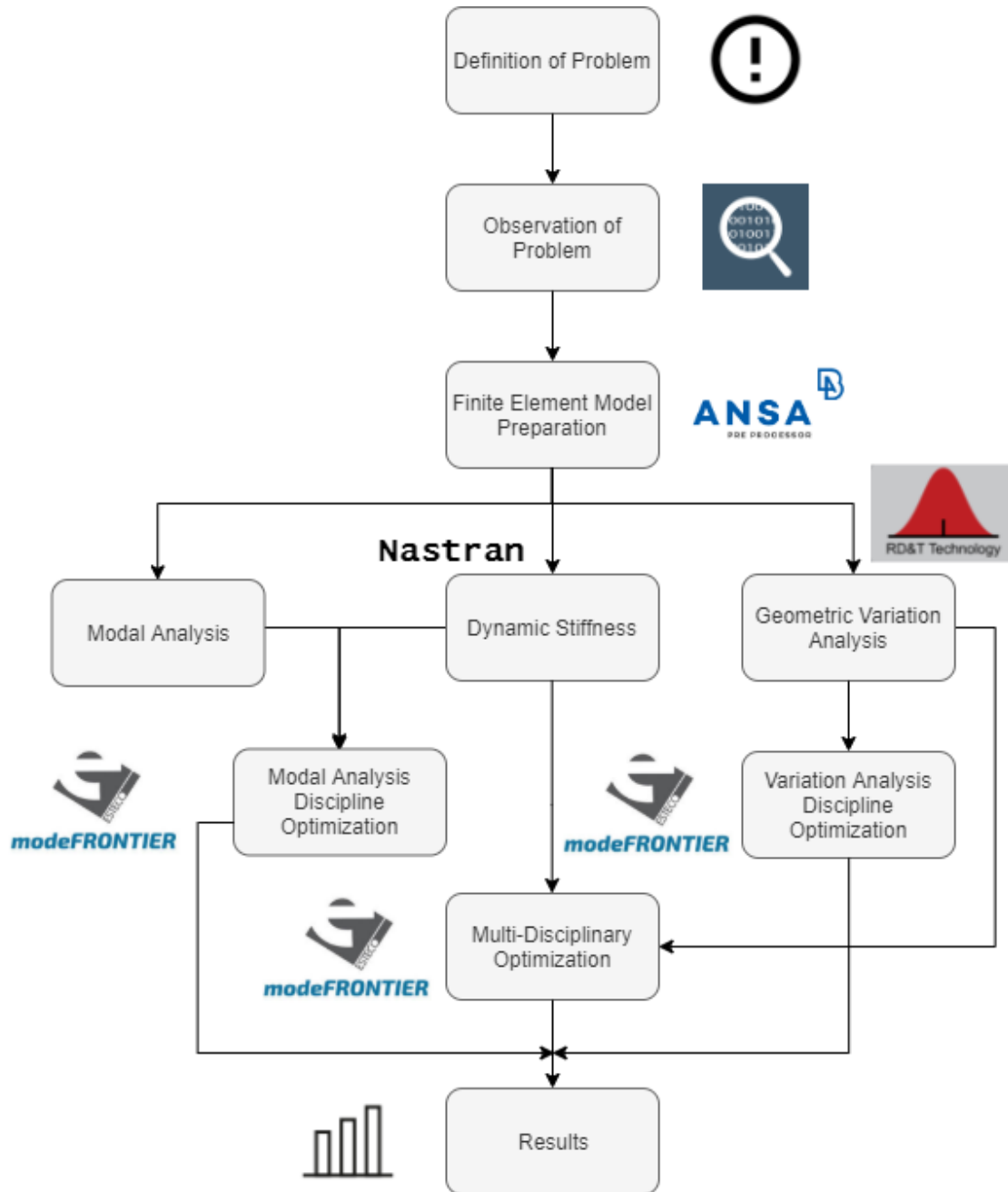


Figure 3.2: Schematic workflow

4

Workflow

In this chapter the work flow for two different assemblies will be explained. The ways by which the problem was formulated, the tools used to satisfy the goals of the project will be explained in detail.

4.1 Assembly 1 : IP Top Cover - Deco Panel

4.1.1 FE Model



Figure 4.1: IP Assembly

The FE model of IP as shown in Figure 4.1 was provided by the Solidity department at VCC. It was represented by mid surface meshed components, with material and properties included in it. The FE model has a high level of modelling details and simplification of model was necessary for our research work to save time. Since the goal of this thesis was just to identify the optimal attachment points within the assembly, the complex model with irregular surfaces and parts were excluded. This paved the way to reduce simulation time for further analysis.

Due to the size and complexity of the IP model, it is reduced to two main parts i.e. deco panel and IP Top cover as show in Figure 4.2. It has 4 attachment points in

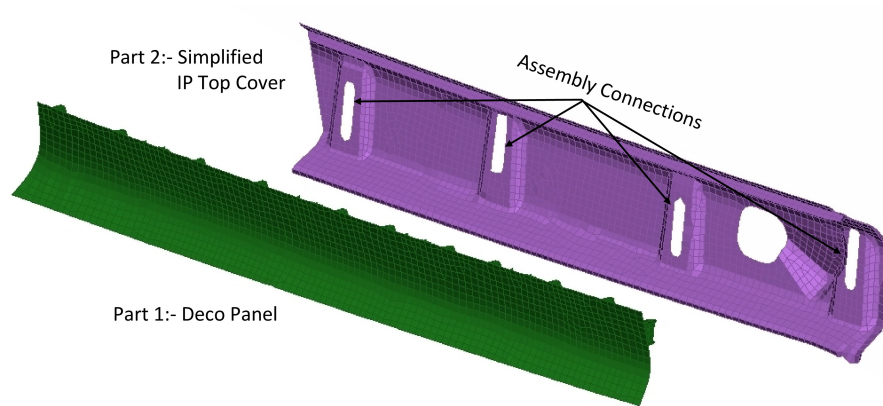


Figure 4.2: Assembly of deco panel & IP Top cover

the assembly as shown in the Figure 4.2 with slots to accumulate the clips attached to the deco panel. Parts associated with the IP top cover were taken into account to make the results more realistic as shown in Figure 4.3. RBE2 is used to represent a rigid connection whereas RBE3 is used for load distribution or a flexible connection. Redundant RBE2 & RBE3 elements which didn't constitute for our research work were removed from the model.

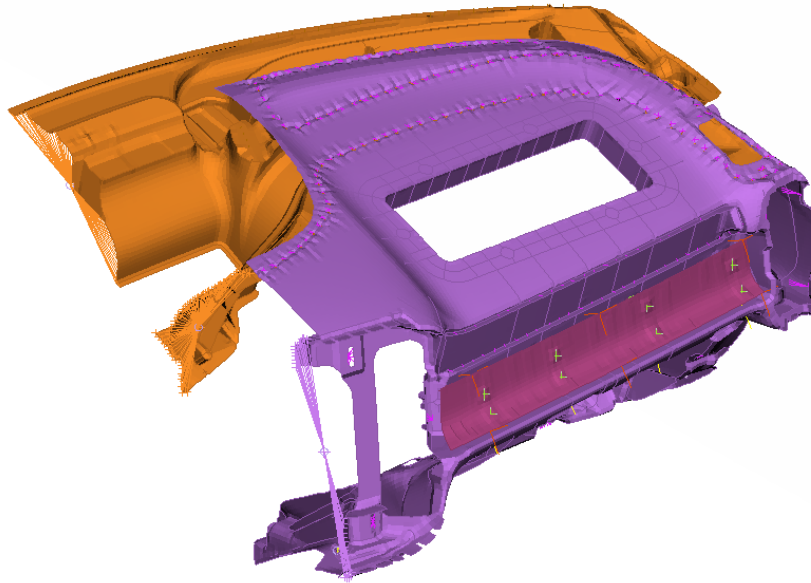


Figure 4.3: Final model of Deco panel & IP assembly considered for this study

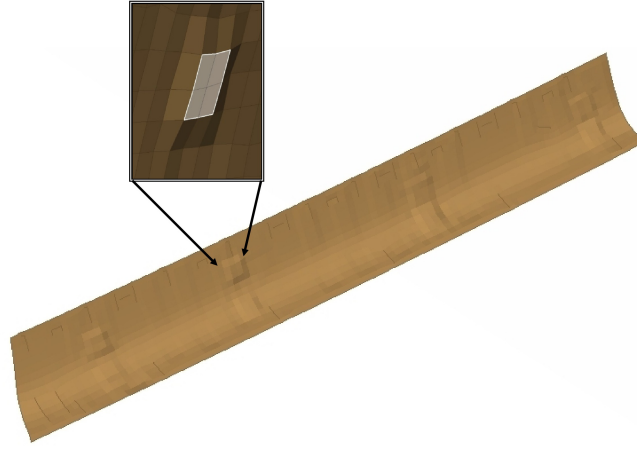


Figure 4.4: Extruded Patches

Steps for creating the attachment points between the assembly was defined by creating patches on the respective parts. This is done to make sure that the CAT software i.e. RD&T for variation analysis and FEM software for modal analysis, replicate the attachment points in an assembly exactly at exact same position (i.e. exact node). In this method, an offset of 4 elements of a part where an attachment point is to be defined is created with 1mm normal to the shell element as show in Figure 4.4. Similar patch is created on the other part of the assembly normal to the patch created in the first part. The quality of the mesh of the assembly is checked in the pre-processor software in order to avoid warping, mesh distortion, triangles and to maintain aspect ratio for the entire assembly. The next step is to perform modal analysis and dynamic stiffness calculation using FEM package of BETA Simulation Solutions.

4.1.2 Modal Behaviour Analysis

The workflow for the modal behaviour analysis and dynamic stiffness calculation of an assembly is performed as shown in the Figure 4.5. A modal analysis is performed to determine the natural frequencies and mode shapes of a structure. After performing the modal analysis with satisfactory results, the next step is to perform a dynamic stiffness calculation with SOL111 using Nastran solver. The idea behind this method is to determine the displacement values in terms of magnitude when a force F is applied at specific eigen-frequencies. With satisfactory results from dynamic stiffness calculation, the outputs are read through a Matlab script for post processing.

4.1.2.1 Modal Analysis

A modal analysis SOL 103 was performed on the assembly with free-free boundary conditions to compute the natural frequencies and mode shapes of a structure.

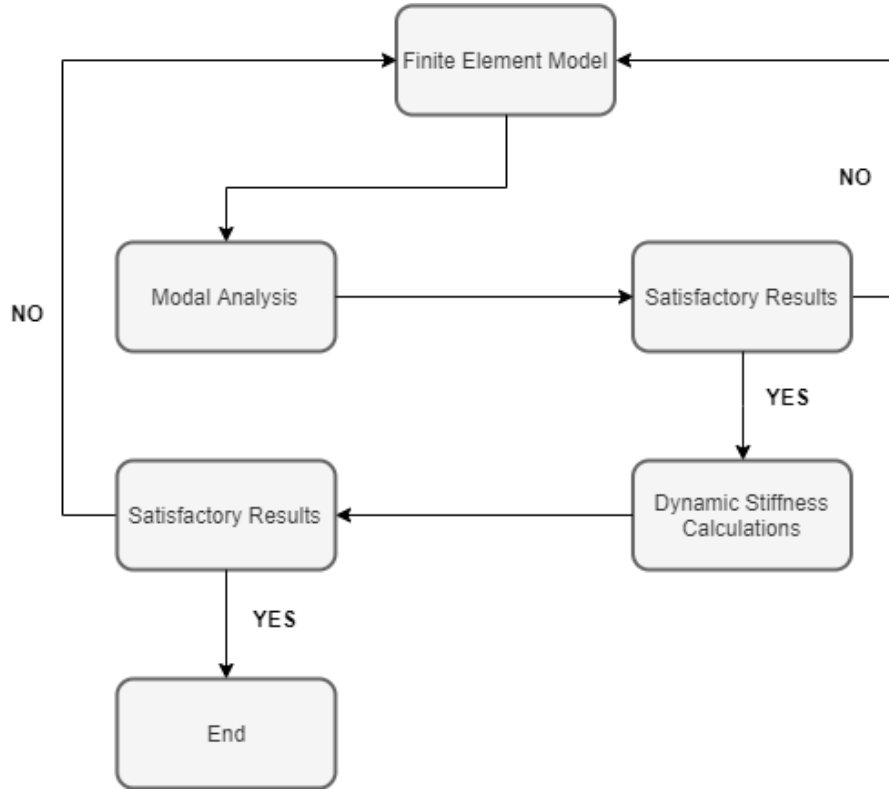


Figure 4.5: Modal Behaviour analysis

This means that an assembly will not undergo any internal deformation but will be able to move or rotate freely in 6 rigid modes which have absolutely zero modal frequency. Identifying rigid body modes helps to determine the modelling errors or an inadequate constraint set in a particular assembly.

To perform a modal analysis on a structure an input file is defined in the form of *.ecd format which consist of model data i.e. information about the finite element model, including geometry, elements. It also contains the type of analysis to be performed as well as the type of data the output is required. For SOL 103, when input file is submitted to the Nastran solver, the software generates several output files like *.f04, *.f06 & *.op2. The *.op2 file contains the set of eigen frequencies that is read by the Meta. After getting the satisfactory rigid modes for a particular assembly, the next step is to perform dynamic stiffness calculation by using Nastran SOL 111.

4.1.2.2 Dynamic Stiffness Calculations

Initially, RBE3 elements was defined as connection between two parts in an assembly. Since it is very complicated to activate and deactivate RBE3 elements which is important for optimization process, CBUSH elements were introduced instead of RBE3 elements. A CBUSH element is a generalized spring and damper element which is defined between two nodes in Nastran. These CBUSH elements act as an attachment point between two parts in an assembly. While defining the properties for a CBUSH element, the stiffness values can be defined along the 6 degrees of

freedom. The stiffness value is defined as 100000 N/m (Newton per meter) for each CBUSH element to make the attachment point activate and 0 N/m to deactivate.

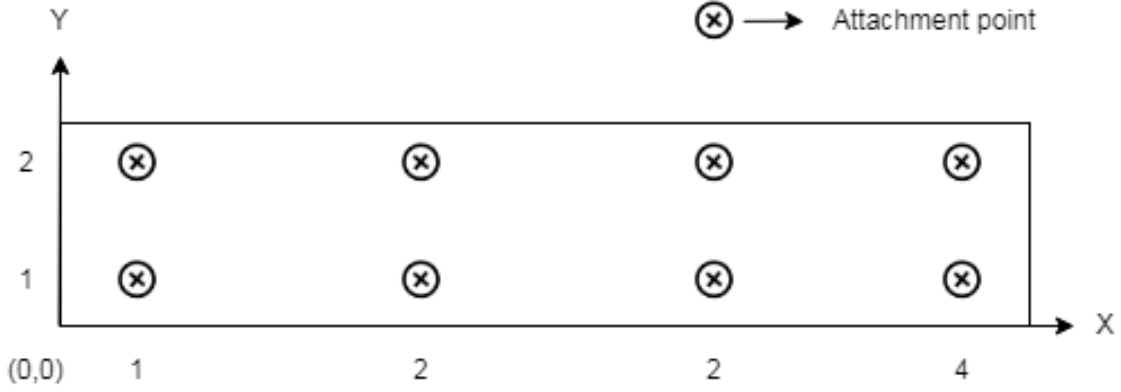


Figure 4.6: Numbering scheme for CBUSH elements

For better understanding of exact location of weld points activated and interpret the results while post processing, a numbering system was developed in such a way that the results from the analysis could be interpreted easily as shown in Figure 4.6. Along the row, the ID of the CBUSH element increase in x direction whereas along the column it was increased in y direction. Each element was defined as "5XY", where 5 represents CBUSH element whereas X & Y represent its location as per the local coordinate system.

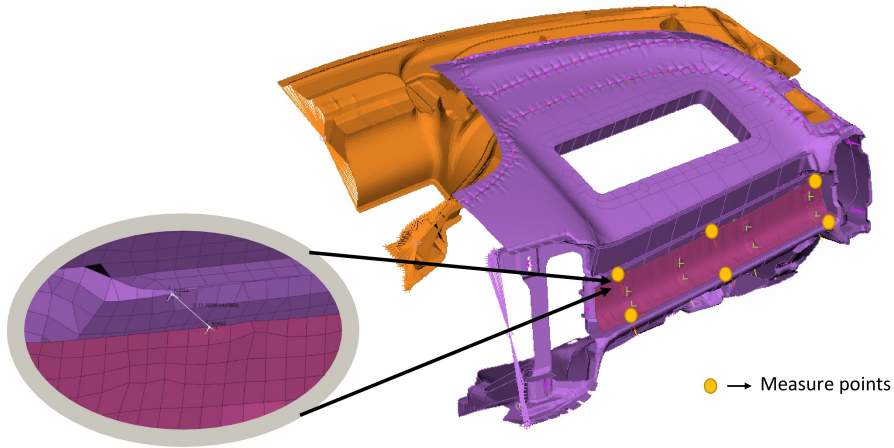


Figure 4.7: Measures defined for Deco panel & IP assembly

Measures were defined at six different locations within the assembly of Deco panel - IP top cover as shown in Figure 4.7. A local coordinate system CORD1 is defined at each particular measure between two nodes of respective parts within an assembly. While selecting the nodes for a measure, it is very important to check the orientation of measure normal to the model. The measures were defined at the minimal distance between two parts which might be subjected to rattle.

Similar to CBUSH elements, measures were defined with numbering schemes as shown in Figure 4.8. Since measures were defined between two nodes, it is very important to distinguish two different parts with part number. Measures are defined

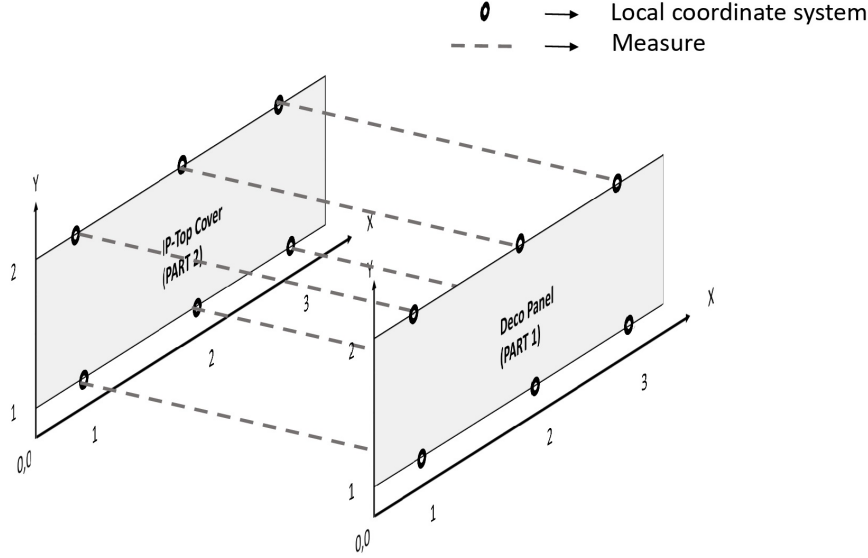


Figure 4.8: Numbering scheme for Measures

as "1XY-2XY" where 1 & 2 depicts the respective part number whereas X & Y represents its location as per the local coordinate system.

Dynamic stiffness was calculated by using Nastran solver which has an ecd file that contains the type of analysis to be performed as well as the type of data the output is required. For this study, limit of 300 Hz was set for identifying the eigen frequencies. The dynamic stiffness is calculated at defined measure points with Nastran solver by activating CBUSH elements with specified stiffness value with an applied force and a damping ratio. With this dynamic displacement is observed between two parts in an assembly which gives output in the form of *.pch file. The output file consist of critical eigen frequencies at which the displacement occurs in terms of magnitude and phase angle. For this research work, only magnitude was taken into consideration and was read by using a Matlab script which is used to determine the resonant frequencies.

4.1.3 Geometric Variation Analysis

The software package used to simulate the part variation that occurs due to dimensional and geometrical tolerances was RD&T. Each Monte Carlo simulation in RD&T represents one assembly of deco panel - IP top cover being manufactured. The assembly in RD&T was simulated with 1000 runs.

The parts i.e. deco panel & IP were loaded separately into RD&T in *.nas format. The mesh elements of both the parts were set to compliance since the parts to be analyzed are non rigid parts. The IP is positioned by using 6 directions positioning system with added support points as shown in Figure 4.9. A 6 direction positioning system is used to position an assembly where the positioning planes are not perpendicular [13]. The 6 direction positioning system is defined by six local and six target locating points similar to 3-2-1 positioning system with 12 support points fixed for

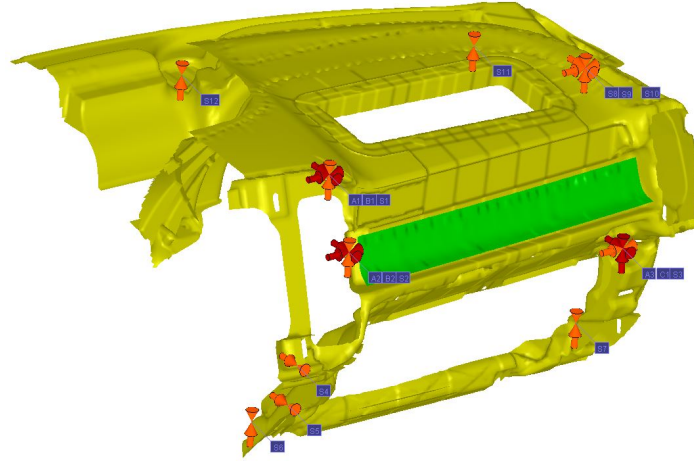


Figure 4.9: Positioning system of deco panel - IP assembly for Variation Analysis

realistic analysis [13].

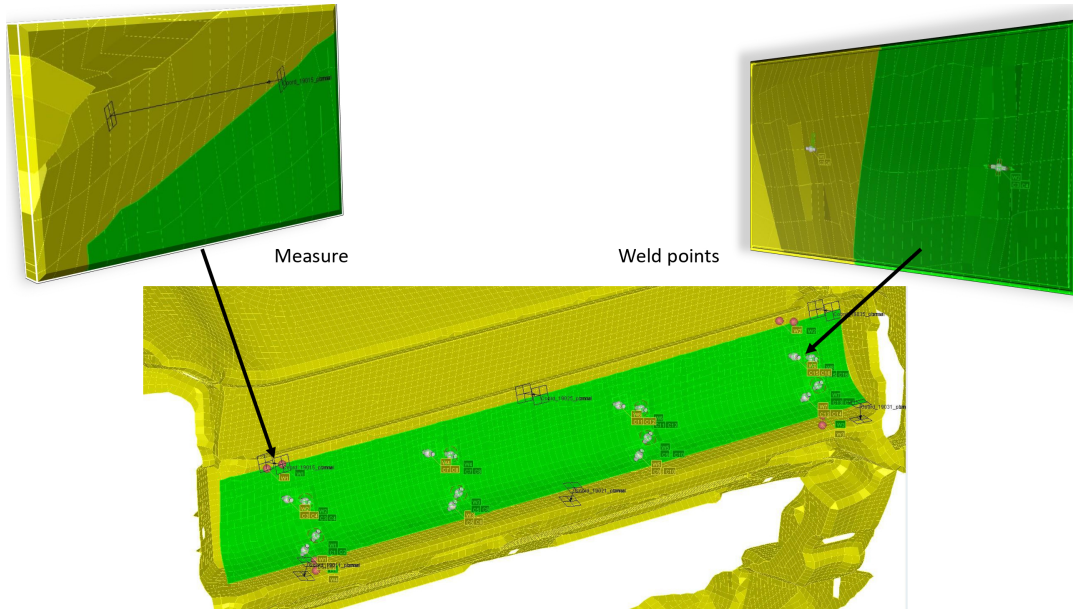


Figure 4.10: Weld point and Measure details for deco panel - IP assembly

For each location, measure was defined 1 in normal direction and 1 in planar direction (total 12 measures). The type of measure used to define in this assembly is Point-Point i.e. using two nodes from respective parts. Measures were defined using the numbering scheme as explained in Figure 4.8.

To create attachment points between the deco panel - IP assembly, weld points were used to carry out geometric variation simulations as shown in Figure 4.10. In RD&T, weld points are created by selecting two corresponding nodes of different parts of an assembly. A local and target node is selected for creating weld point using balanced gun as a type of weld. Weld points with balanced gun means that the two weld points are forced together with equal opposite forces which acts as an

attachment point within the assembly [13]. A total of 8 weld points were defined with 16 contact points within the assembly as show in Figure 4.10 with the same numbering scheme as previously defined to CBUSH elements as explained in Section 4.1.2.2. To facilitate the research work initially, weld points are used in RD&T software instead of fasteners.

The tolerance for the attachment points. i.e. weld points in RD&T were defined based on the details provided by VCC. The tolerances were defined only in the normal direction of attachment points. Tolerances in planar direction of attachment points were not considered because the results didn't contribute to any variation in the geometry.

For variation analysis, it is very important to have all the parts assembled during simulation. To achieve this, both parts i.e. deco panel and IP were defined in the sub-assembly which in turn was connected to a fixture via locating scheme. During the simulation of variation analysis, the parts are placed and held together due to locating scheme.

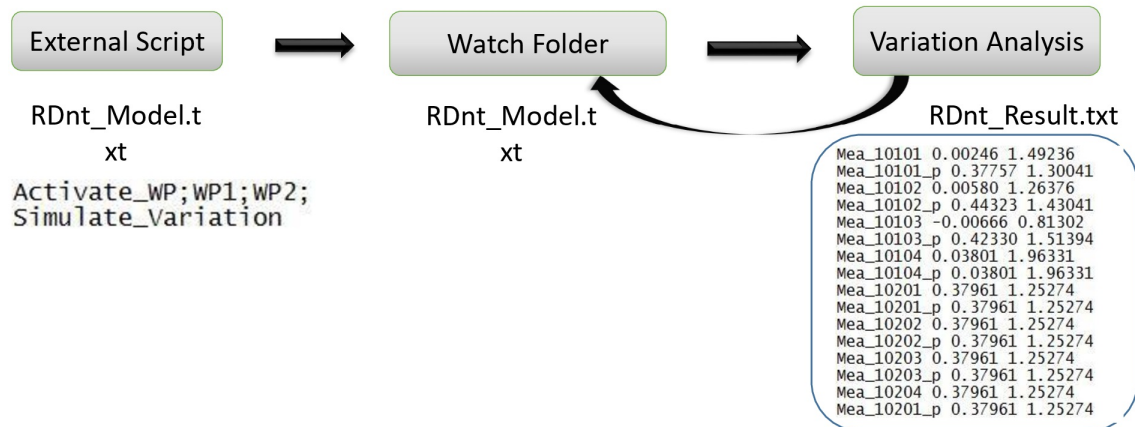


Figure 4.11: Methodology for performing variation analysis in RD&T in batch mode

After performing various iteration on how to perform the geometric variation analysis in batch mode, a macro is used which is readily available to run RD&T by means of a model script in *.txt format. When a design sample is initiated in the RD&T software to run variation analysis in batch mode, a text file which instructs to activate the set of weld points is generated in the watch folder, and it is read by RD&T to simulate variation at defined measures as shown in Figure 4.11. A result file in the form of *.txt is generated which contains the measure details and their corresponding 6 sigma and mean shift values for an assembly.

4.1.4 Optimization

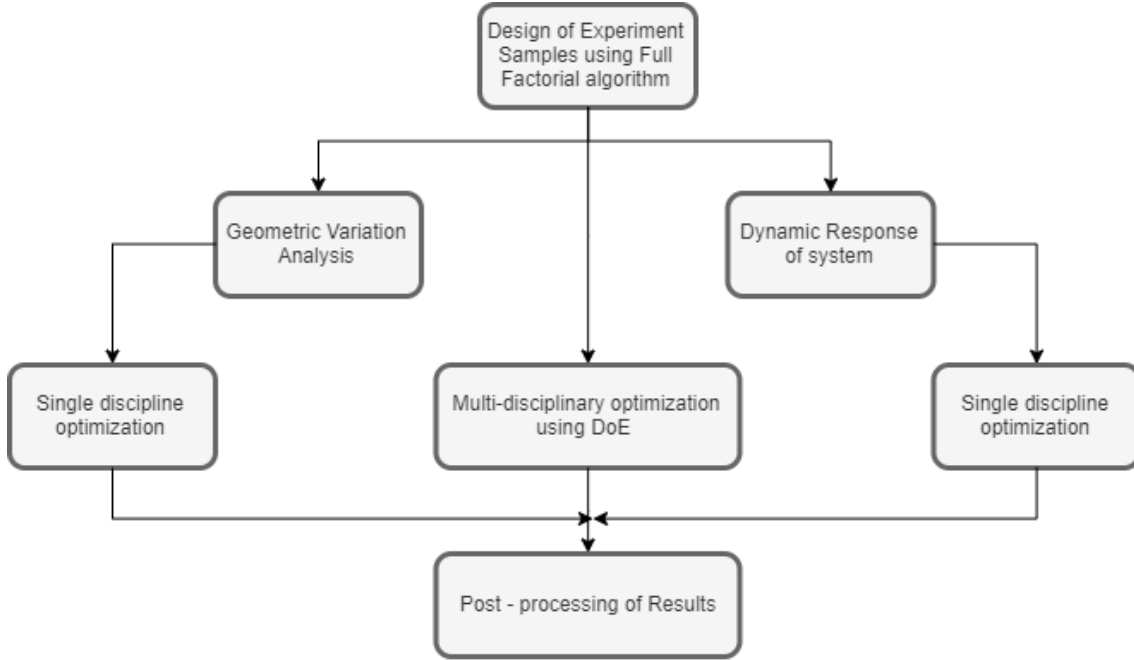


Figure 4.12: Optimization workflow for deco panel - IP assembly

Through the graphical interface of modeFRONTIER, a workflow can be established consisting of different nodes which are connected with each other to constitute a logical scheme of an optimization process. For deco panel - IP assembly, a methodology is followed as shown in Figure 4.12. Initially, a DoE is performed with respect to the input variables and constraint using Full Factorial algorithm. With 8 input variables and two levels for each input variable i.e. activate & deactivate weld points, 256 design combinations is generated using Equation (2.6). With a constraint applied to the input variables stating that only 4 weld points should be active as mentioned in Equation (4.1), only 70 designs resulted to feasible designs. Table 4.1 shows the effect of constraint applied on the input variables for determining feasible and unfeasible designs.

$$w1 + w2 + w3 + w4 + w5 + w6 + w7 + w8 = 4 \quad (4.1)$$

Table 4.1: Constraint applied for deco panel - IP assembly

w1	w2	w3	w4	w5	w6	w7	w8	$\sum_{i=1}^8 w(i)$	DoE feasibility
1	0	1	0	1	0	1	0	4	Feasible design
1	1	1	1	1	1	0	0	6	Unfeasible design

After the generation of DoE for the assembly, the next step is to perform a single discipline multi-objective optimization for geometric variation analysis and modal behaviour analysis. Results are analyzed from optimization process for conflicting

objectives for respective disciplines. A multidisciplinary optimization workflow is created taking into account the conflicting objectives i.e variation in normal and planar direction & total number of resonant frequencies in normal and planar direction. Here objectives defined for planar direction are termed as assembly subjected to squeak whereas for planar direction it is termed as assembly subjected to rattle.

4.1.4.1 Optimization for Geometric Variation Analysis

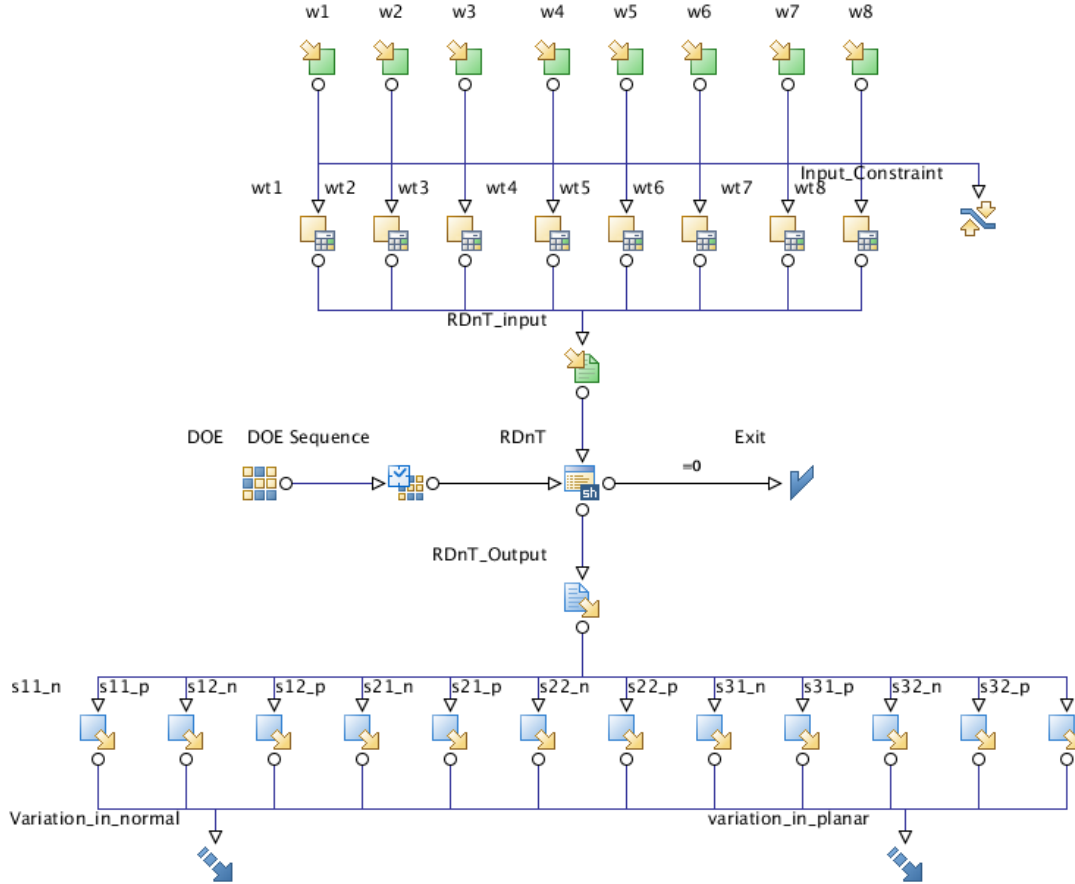


Figure 4.13: Workflow in modeFRONTIER for optimization of Geometric variation for deco panel - IP assembly

A graphical interface of optimization workflow for Geometric variation for deco panel - IP assembly is shown in Figure 4.13. The number of input variables defined is 8 weld points denoted by w1 to w8 as shown in Figure 4.13 which has a lower bound as 0 and upper bound as 1 with a step size of 1. The idea behind defining the lower bound and upper bound with value 0 and 1 is to ensure for any design sample, if the value of input variable is 1 it states that the weld point for that particular variable is active whereas on the other hand 0 indicates the weld point is deactivated. A transfer variable is assigned for each input variable to ensure that RD&T will understand the lower bound and upper bound and relate it with the numbering schemes defined as explained in Section 4.1.2.2.

As explained earlier in Section 4.1.4, only 70 feasible designs were initiated in the DoE table using Full Factorial algorithm. The reason behind not using any optimization algorithm for this assembly is that since all the possibilities from DoE is covered which itself will give the optimum results based on the objectives defined. A shell script node stores and configures scripts using UNIX supported languages which is used for initiating geometric variation analysis in RD&T software in batch mode using the methodology as explained in Figure 4.11.

The output results i.e. 6 sigma values are stored for each design sample in a node called output variable. The design objective nodes are the goal nodes used for identifying numerical variables computed in data flow as a function of Input and Output variables. Objective can be expressed in mathematical function of input/output variables using a JavaScript along with defining the type of optimization i.e. whether the objective should be maximized or minimized. For this assembly, the objectives for geometric variation are defined in terms of variation in normal direction i.e. rattle and variation in planar direction i.e. squeak. The root mean square is calculated for all the measures subjected to variation in normal direction for defining the objective of minimization of rattle. On the other hand, root mean square of all measures subjected to variation in planar direction is defined with the objective of minimization of squeak. The definition of each node in modeFRONTIER is explained in Appendix A.1.

4.1.4.2 Optimization for Modal Behavior Analysis

A schematic workflow of optimization setup in modeFRONTIER for modal behaviour analysis is shown in Figure 4.14. The input variables remains the same as explained in Section 4.1.4.1 whereas the input files required to run modal analysis are FE-model in the form of *.nas format and a separate CBUSH file in the form of *.nas format which includes the properties and stiffness values. To submit the model for execution of modal analysis on the assembly as a batch process in NX Nastran, an *.ecd file is required which contains the model data i.e. information about the finite element model, including geometry, elements, materials, loads as well as analysis data, type of output required. The *.ecd file is generated by using python script provided by VCC for calculating dynamic stiffness.

As explained earlier in Section 4.1.4, only 70 feasible designs were initiated in the DoE table using Full Factorial algorithm. A Matlab script was created to read the output file from Nastran i.e in the form of *.pch format, wherein normal & planar displacements for a particular measure is plotted with respect to eigen frequencies.

The output results i.e. total number of resonant frequencies are stored for each design sample in a node called output variable. For this assembly, the objectives for modal behavior are defined in terms of minimizing total number of resonant frequencies subjected to normal & planar direction. Along with number of resonant frequencies, it was important to identify the which of the measures is subjected to S&R . The definition of each node in modeFRONTIER is explained in Appendix A.1.

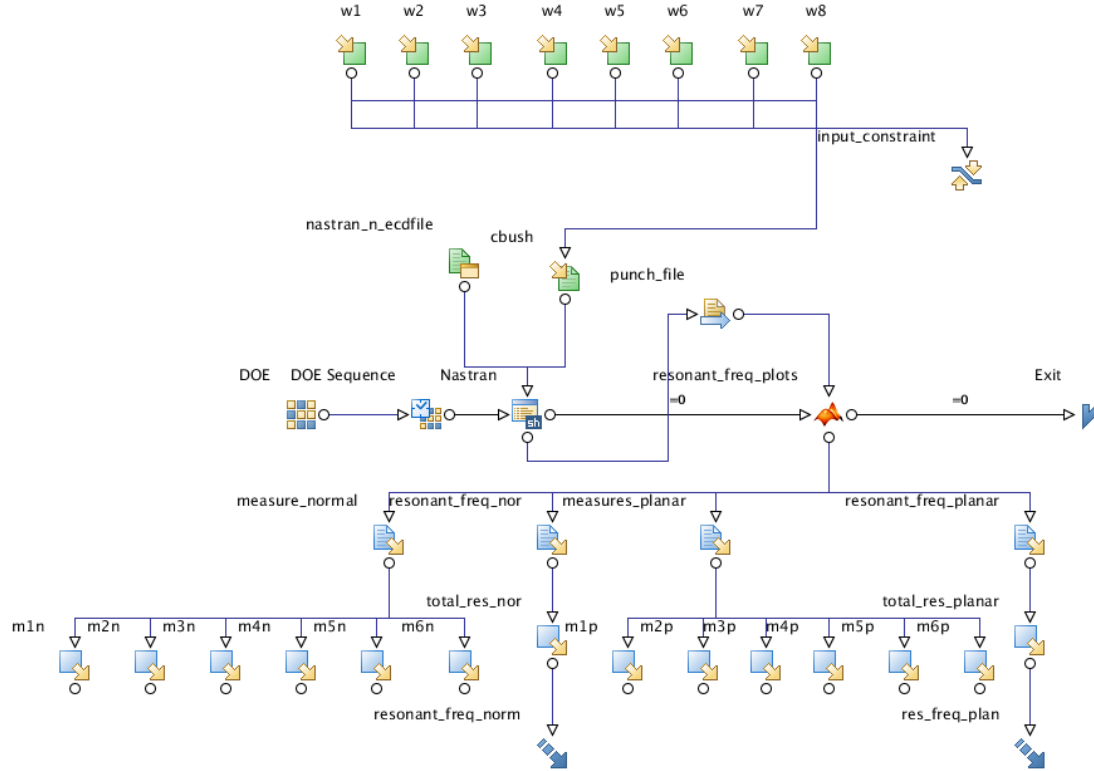


Figure 4.14: Workflow in modeFRONTIER for optimization of Modal Behavior analysis for deco panel - IP assembly

4.1.4.3 Multi-Disciplinary Optimization for Geometric Variation & Modal Behavior Analysis

A graphical representation for an MDO approach for deco panel - IP assembly is shown in Figure 4.15. Here both the disciplines i.e geometric variation and modal behaviour are integrated together within modeFRONTIER workflow. As explained in Section 4.1.4, the DoE sequence is generated by using full factorial algorithm.

The objectives defined in the geometric variation optimization as explained in Section 4.1.4.1 i.e variation in normal and variation in planar are summed up as shown by Table 4.2 when introduced to the MDO framework. Similarly, the objectives defined for modal behaviour analysis optimization i.e total number of resonant frequencies in normal and planar direction are summed together as shown in Table 4.2 for defining the objective in MDO workflow.

Table 4.2: Objectives formulation for MDO

Minimize	Description
Objective 1	6 sigma (variation) in normal + 6 sigma (variation) in planar
Objective 2	Resonant frequencies in normal + Resonant frequencies in planar

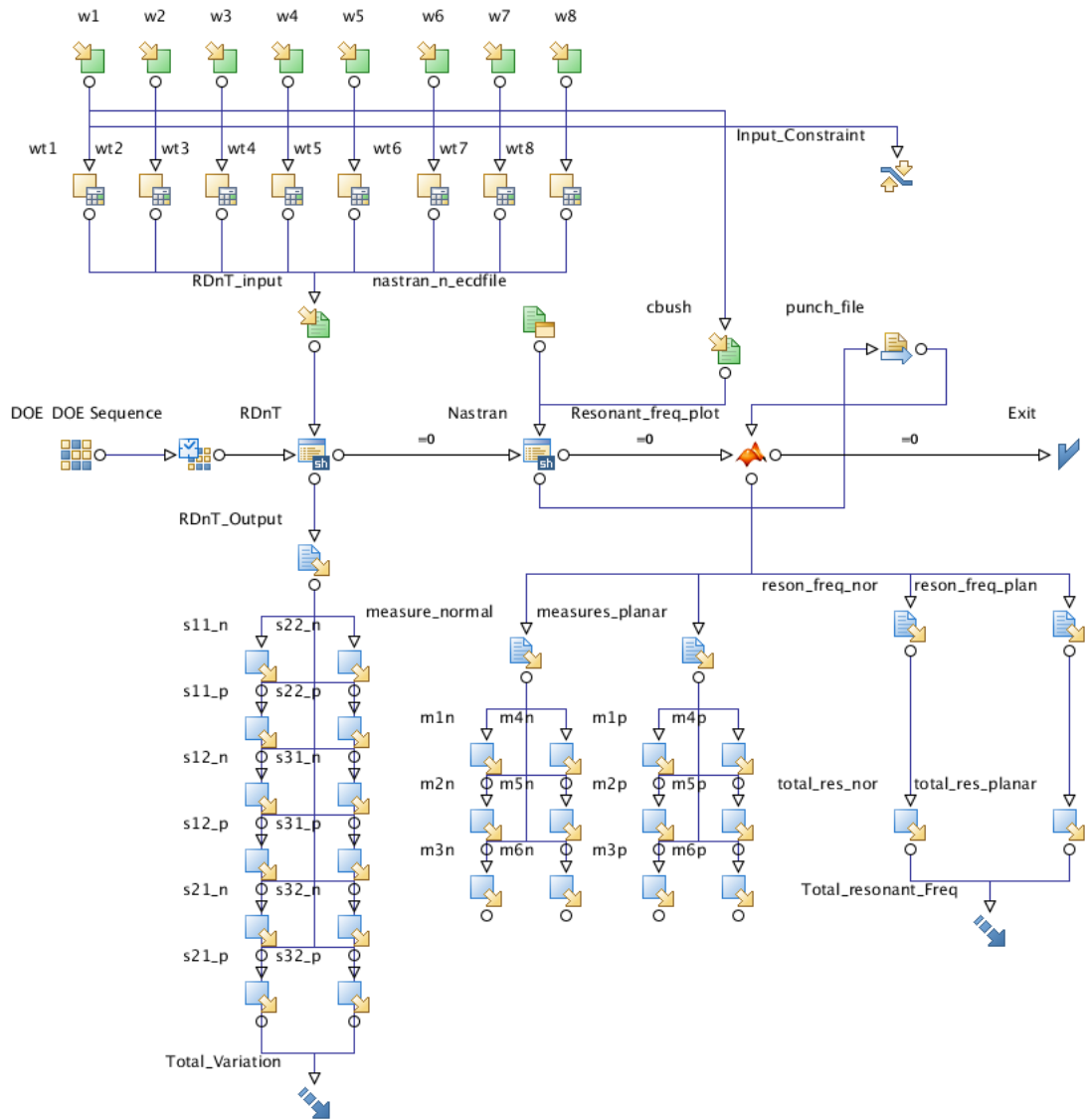


Figure 4.15: Workflow in modeFRONTIER for MDO of Modal Behavior & Geometric variation analysis for deco panel - IP assembly

4.2 Assembly 2 : Side Door Structure - Door Panel

4.2.1 FE Model

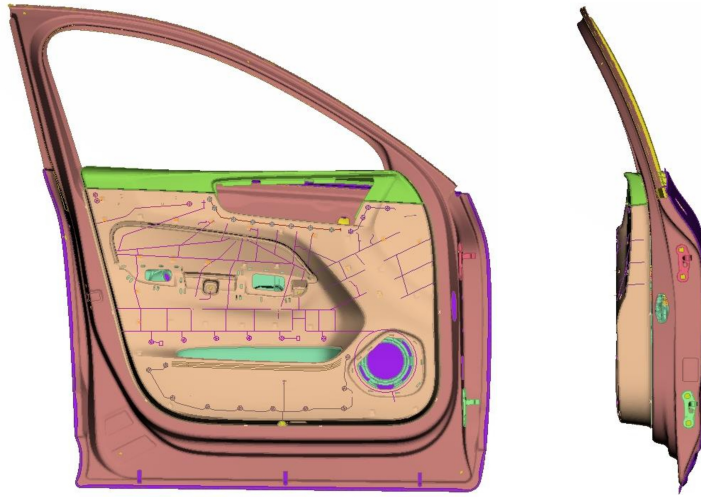


Figure 4.16: FE model of Side door structure - door panel assembly

The FE model of Side door structure - Door panel as shown in Figure 4.16 was provided by the Solidity department at VCC. As described in Section 4.1.1, patches were created on door panel as well as the door structure. An offset of 4 elements of a part where an attachment point is to be defined is created with 1 mm normal to shell element as shown in Figure 4.17. The quality of mesh is inspected to make sure that warping, mesh distortion and triangles are avoided for further analysis.

4.2.2 Modal Behaviour Analysis

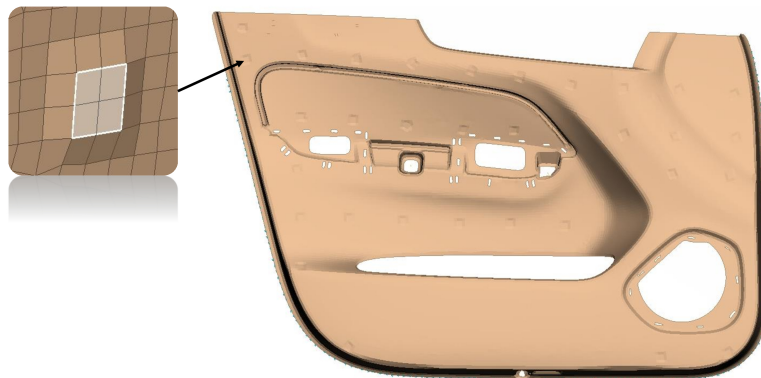


Figure 4.17: Extruded patches for side door assembly

Similar steps were followed as explained in the Section 4.1.2 in order to determine the natural frequencies and mode shapes of an assembly followed by dynamic stiffness calculation using Nastran solver.

4.2.2.1 Dynamic Stiffness Calculations

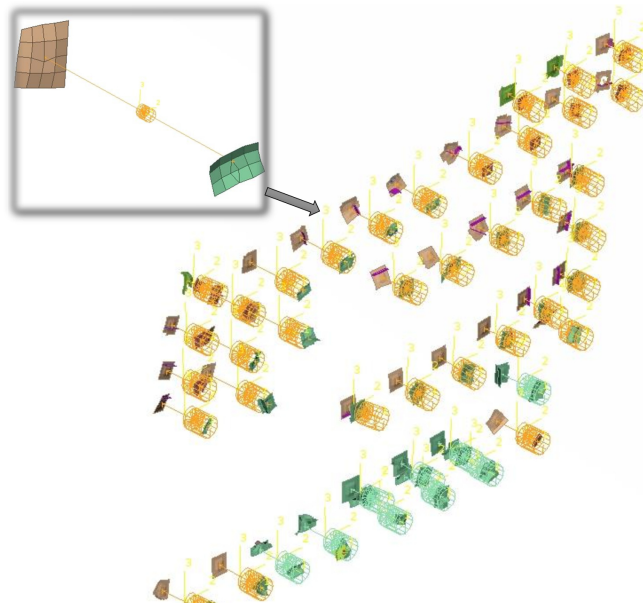


Figure 4.18: CBUSH elements for Side door assembly

A total of 44 CBUSH elements are defined exactly at the location where patches are defined as shown in Figure 4.18. These CBUSH elements were defined with stiffness value of 100000 N/m along the six degrees of freedom. The numbering scheme is followed in similar way as defined for deco panel - IP assembly as shown in Figure 4.6.

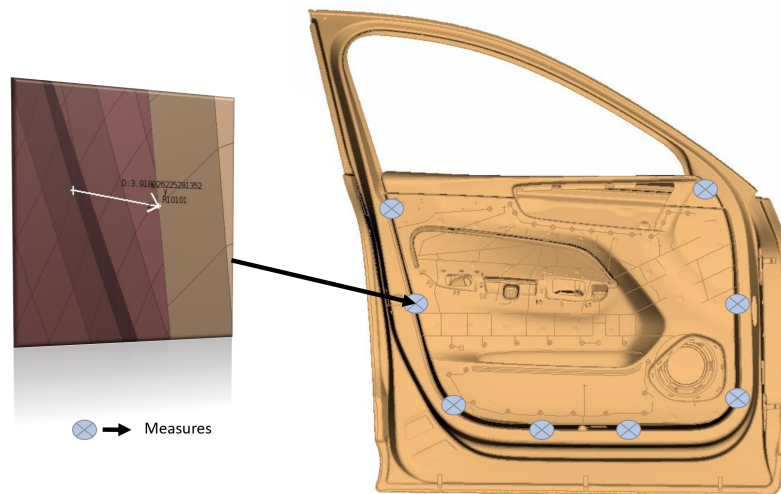


Figure 4.19: Measures defined for Side door assembly

Measures were defined at 8 different location as shown in Figure 4.19. Measures were defined with similar pattern of numbering scheme as shown in Figure 4.8.

4.2.3 Geometric Variation Analysis

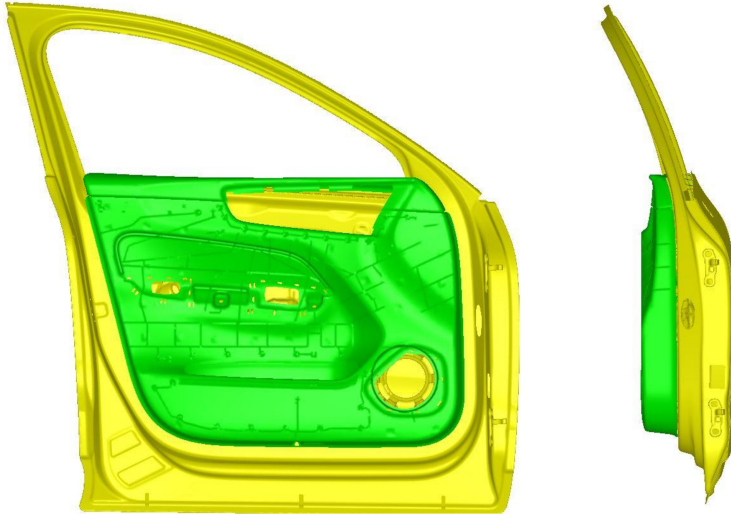


Figure 4.20: RD&T model for side door assembly

RD&T software package is used for simulating part variation that occurs due to dimensional and geometric tolerances. To perform variation analysis on side door assembly, 100 runs were defined because of the complexity of model. The door panel and the door structure are imported into RD&T as shown in Figure 4.20 in *.nas format. The door structure is positioned by using 6 directions positioning system with added support points as shown in Figure 4.21.

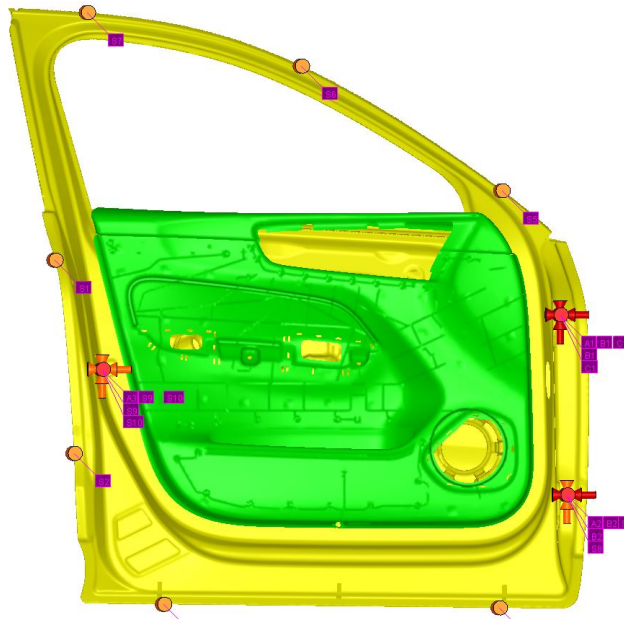


Figure 4.21: Positioning system

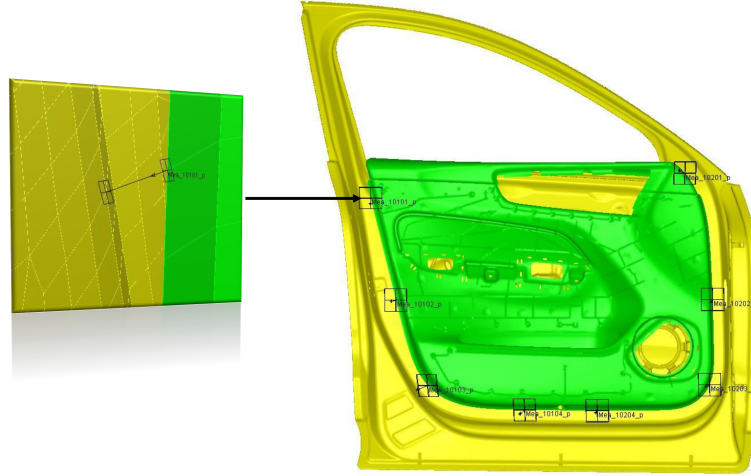


Figure 4.22: Measures defined for side door assembly

For side door assembly, measures are defined at 8 different locations as shown in Figure 4.22. For each location, measures are defined 1 in normal direction and 1 in planar direction (total 16 measures). Measures are defined using the numbering scheme as shown in Figure 4.8.

As shown in Figure 4.23, a total of 44 weld points are defined with 88 contact points within the assembly with same numbering scheme as previously defined to CBUSH elements. Weld point "A" is defined additionally at the bottom of the door assembly as per the requirement. The weld point "A" is defined without any tolerance value which will always be active and is not considered for optimization process. The tolerances for the attachment points were defined only in normal direction based on the details provided by VCC.

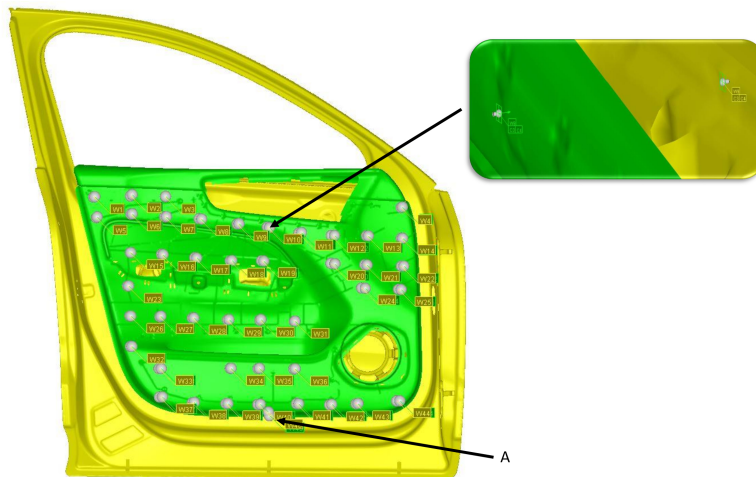


Figure 4.23: Weld points defined for side door assembly

4.2.4 Optimization

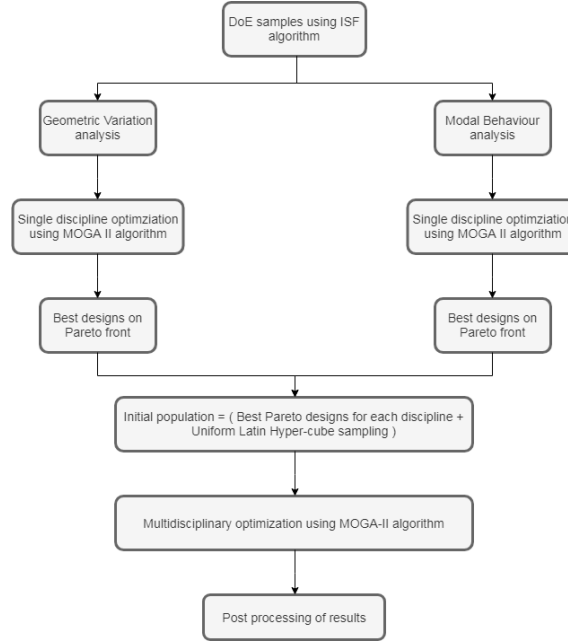


Figure 4.24: Optimization workflow for side door assembly

For optimization of side door assembly, a methodology is followed as shown in Figure 4.24. Initially, a DoE is performed with respect to input variables and constraint using Increment Space Filler (ISF) Algorithm. 10 input variables are defined with lower bound as 1 and upper bound as 44 with a step size of 1. A constraint is applied to the input variables which make sure that while generating a DoE, same attachment points are not repeated within a design sample. An example of feasibility of DoE is explained in Table 4.3.

Table 4.3: Constraint applied for side door assembly

w1	w2	w3	w4	w5	w6	w7	w8	w9	w10	DoE Feasibility
50101	50204	50302	50307	50307	50607	50705	51002	50908	51008	Unfeasible design
50101	50204	50302	50307	50405	50607	50705	51002	50908	51008	Feasible design

After the generation of DoE, the next step is to perform single discipline multi-objective optimization for geometric variation analysis and modal behaviour analysis. Results are analyzed for single discipline optimization using post processing tools available in modeFRONTIER. Best designs are selected on the Pareto front with two conflicting objectives for each discipline. A MDO workflow is created taking into account the two objectives i.e. variation in normal and planar direction & total number of resonant frequencies in normal and planar direction. For setting up of initial population in MDO, best designs on Pareto front and Uniform Latin hyper-cube algorithm is used. An accountability of simulation time is considered by defining it as a constraint and number of generations for the population is calculated. The results are analyzed by post processing tools and are explained further in Results section.

4.2.4.1 Optimization for Geometric Variation Analysis

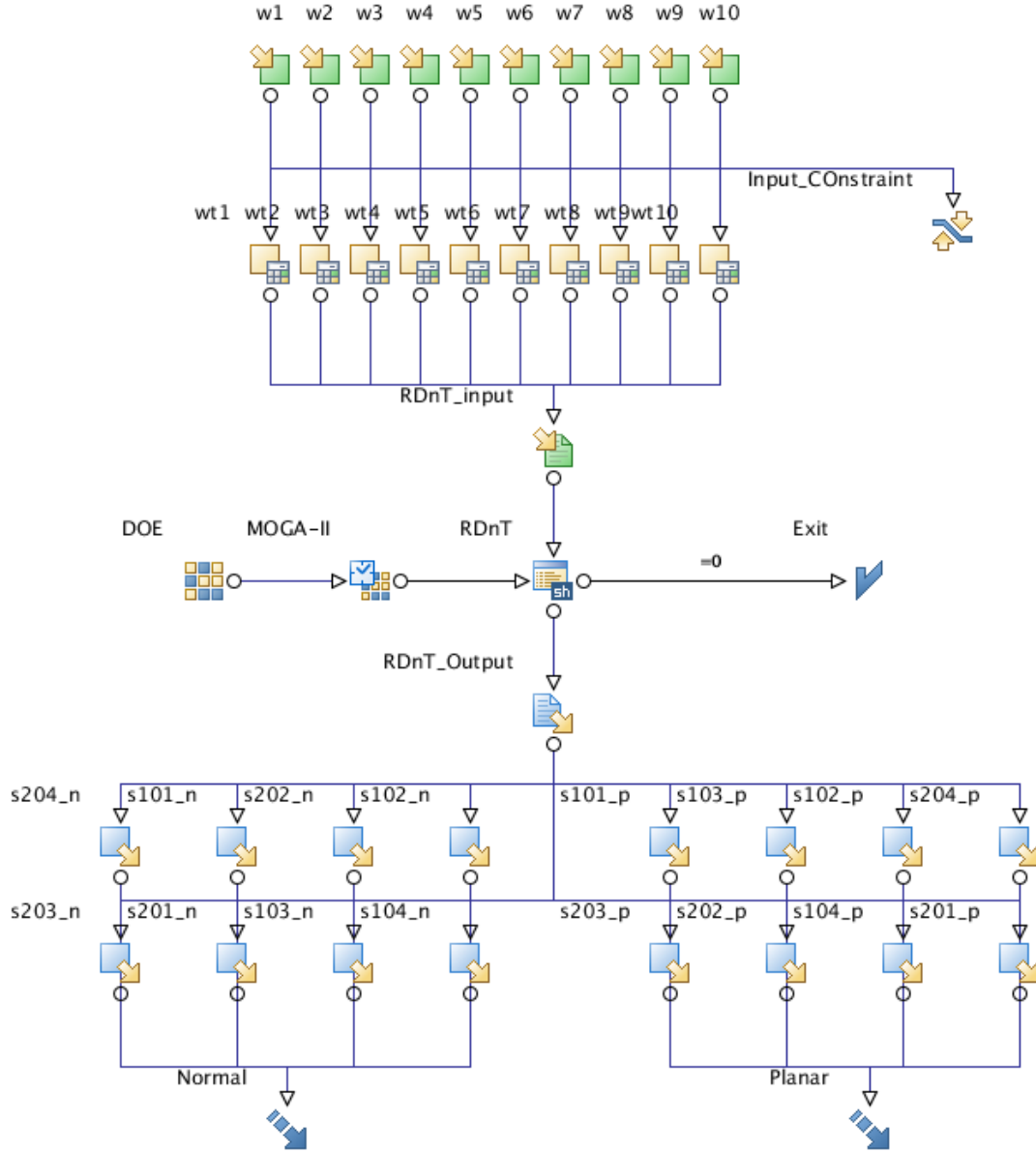


Figure 4.25: Workflow in modeFRONTIER for optimization of Geometric variation analysis for side door assembly

A graphical interface of optimization workflow for Geometric variation analysis for side door assembly is shown in Figure 4.25. The number of input variables defined is 10 weld points denoted by w1 to w10. A step input is defined in the input variables with lower bound as 1 and upper bound as 44 with step size of 1. This means that each step value i.e. 1 to 44 is defined with a weld point.

The number of designs generated in DoE is 200 by using ISF algorithm. The simulation time for the optimization process is considered and a constraint is defined by keeping number of generations for MOGA-II depending upon the the total simulation time available. 20 generations is set for MOGA-II algorithm which means that the the total number of simulations is counted as 2000 runs i.e. (initial DoE(200)

* number of generations(20) = 2000 runs). A shell script node is used to run the geometric variation analysis in batch mode in RD&T using the methodology as explained in Figure 4.11.

The output results i.e 6 sigma values are stored for each design sample in output variable. For side door assembly, the objectives for geometric variation are defined in terms of variation in normal direction i.e. rattle and variation in planar direction i.e.e squeak. The root mean square is calculated for all measures subjected to variation in normal direction for defining the objective of minimization of rattle. Similarly, root mean square is calculated for all measures subjected to variation in planar direction for defining the objective of minimization of squeak.

4.2.4.2 Optimization for Modal Behavior Analysis

A schematic workflow of optimization setup in modeFRONTIER for modal behaviour analysis is shown in Figure 4.26. The input variables remains the same as explained in Section 4.2.4.1 whereas the input files required to run modal analysis are FE- model in the form of *.nas format. A separate CBUSH file is also required in the form of *.nas format which includes CBUSH properties and stiffness values. Modal analysis is performed in batch mode by using an *.ecd file.

The output results from the modal behaviour analysis is read by a Matlab script wherein normal and planar displacements for a particular measure is plotted with respect to eigen frequencies. The output results i.e. total number of resonant frequencies are stored for each design sample in output variable. For this assembly, the objectives are defined in terms of minimizing total number of resonant frequencies in normal and planar direction.

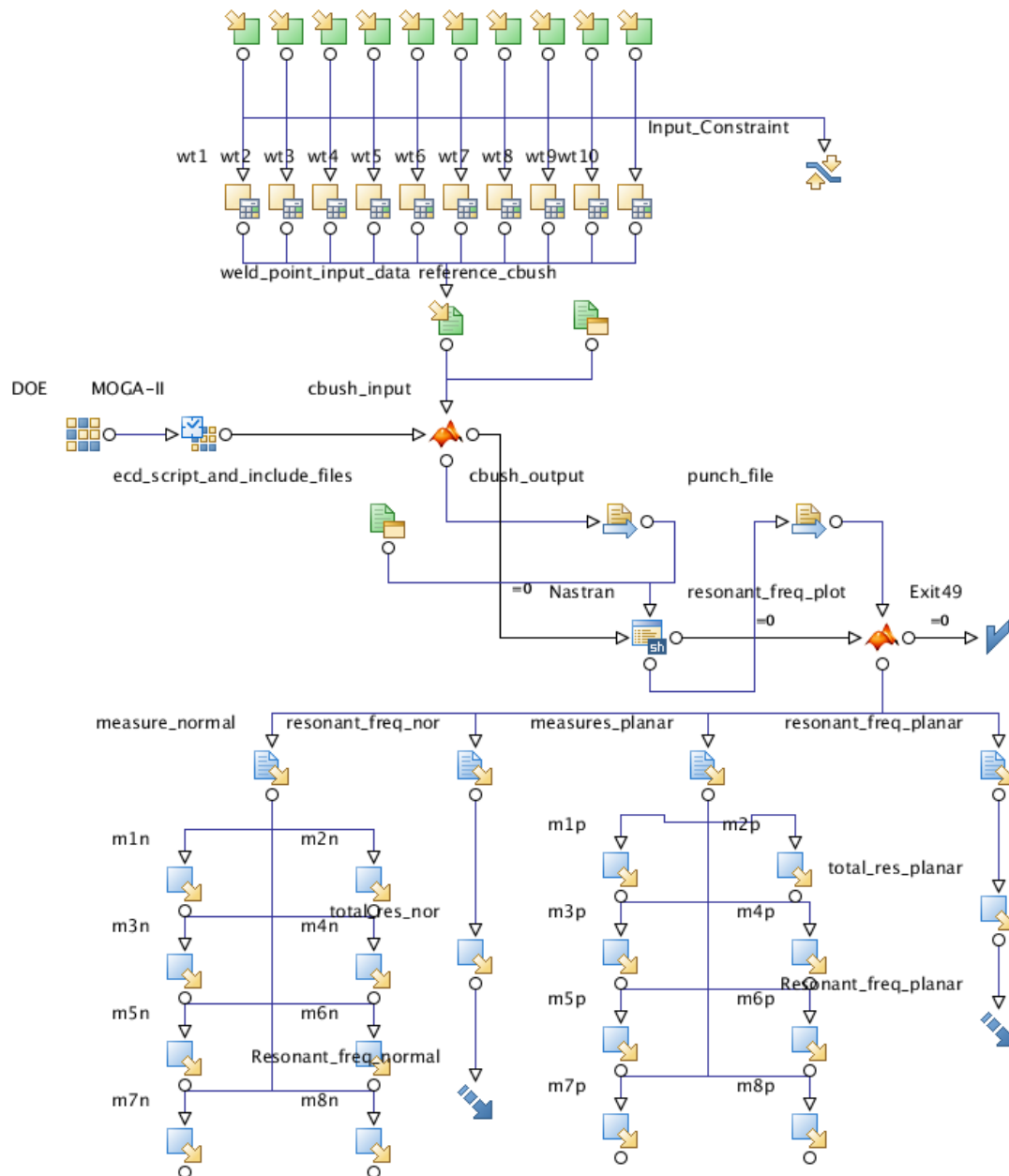


Figure 4.26: Workflow in modeFRONTIER for optimization of Modal Behavior analysis for side door assembly

5

Results and Discussion

In this chapter, the results for geometric variations, modal behaviour and optimization outcomes will be presented for different assemblies.

5.1 Deco panel and IP assembly

5.1.1 Single discipline optimization for Geometric variations

The optimization methods for variation analysis was performed and the 6σ values for the best designs along measures in normal (Rattle) and planar (Squeak) is tabulated as shown in Table 5.1.

Table 5.1: Results for geometric variation optimization

Measure	Design 1	Design 2	Design 3	Design 4
19011_normal	0.60821	0.55306	0.56322	0.48878
19011_planar	0.55457	0.41381	0.36969	0.23485
19012_normal	0.48816	0.41081	0.41327	0.53214
19012_planar	0.61351	0.47331	0.41441	0.25706
19021_normal	0.28437	0.35891	0.42062	0.40416
19021_planar	0.61218	0.3079	0.2538	0.11224
19022_normal	0.36555	0.5927	0.57337	0.43059
19022_planar	0.62034	0.31457	0.28662	0.12943
19031_normal	0.23138	0.19842	0.25251	0.72749
19031_planar	0.58514	0.27829	0.23711	0.21817
19032_normal	0.35108	0.35948	0.41637	0.4879
19032_planar	0.62482	0.27176	0.20395	0.4063

A Scatter plot is a post-processing tool available in modeFRONTIER which suggests a correlation between the objectives defined. The scatter plot for the design is plotted by having the results for squeak in X direction and the results for rattle in Y direction. After observing the scatter plot for geometric variation optimization as shown in Figure 5.1, it is clear that all the best designs lie on a Pareto front which means no objective can be improved without sacrificing at least one another objective.

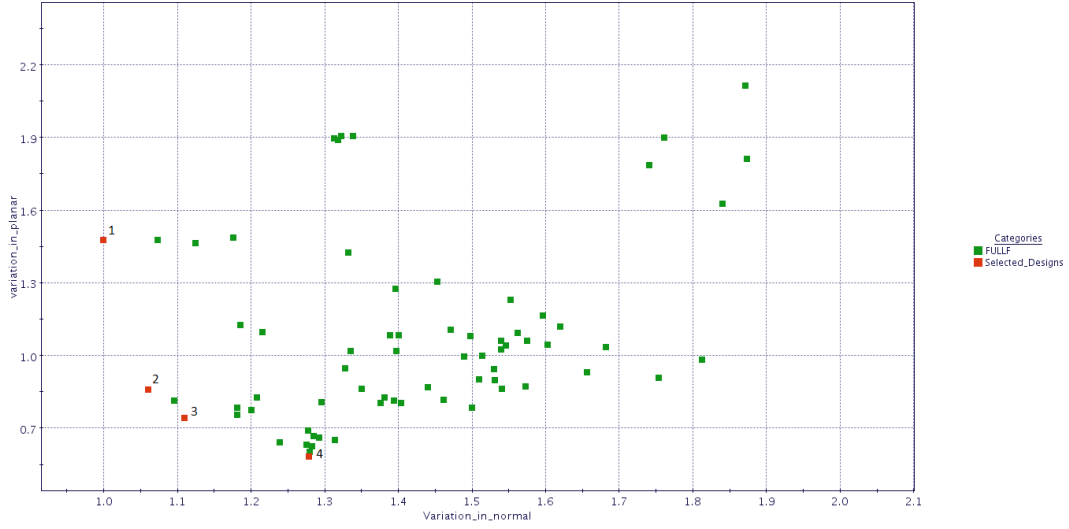


Figure 5.1: Scatter plot for single disciple optimization for variation analysis

Design visualization is done for the best combinations of attachments points in the assembly as shown in Figure 5.2, Figure 5.3, Figure 5.4, Figure 5.5.



Figure 5.2: Attachment points plot for design 1



Figure 5.3: Attachments points plot for design 2



Figure 5.4: Attachment points plot for design 3



Figure 5.5: Attachment points plot for design 4

5.1.2 Single discipline optimization for modal behaviour analysis

The optimization methodology for modal behaviour analysis was performed and the number of resonant frequencies in normal (rattle) & planar (squeak) for the best designs along measures is tabulated as shown Table 5.2. The objective for this optimization process is to minimize the possibilities of resonant frequencies which might be subjected to S&R at defined measures.

Table 5.2: Results for modal analysis optimization

	Design 1	Design 2	Design 3	Design 4	Design 5
Total Resonant Frequencies- normal	2	4	5	6	9
Total Resonant Frequencies- planar	12	10	9	7	6

The scatter plot for the designs is plotted by having the results for squeak in X direction and the results for rattle in Y direction. After observing the scatter plot for modal behaviour optimization as shown in Figure 5.8, it is clear that all the best designs lie on a Pareto front which means no objective can be improved without sacrificing at least one another objective.

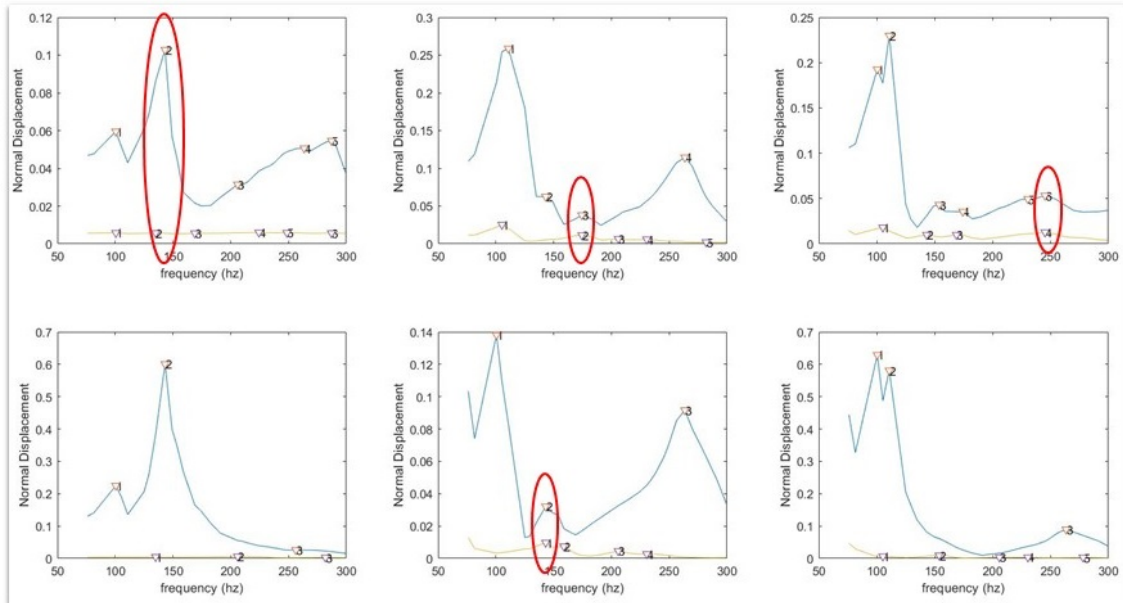


Figure 5.6: Matlab plot for identifying resonant frequencies for Rattle

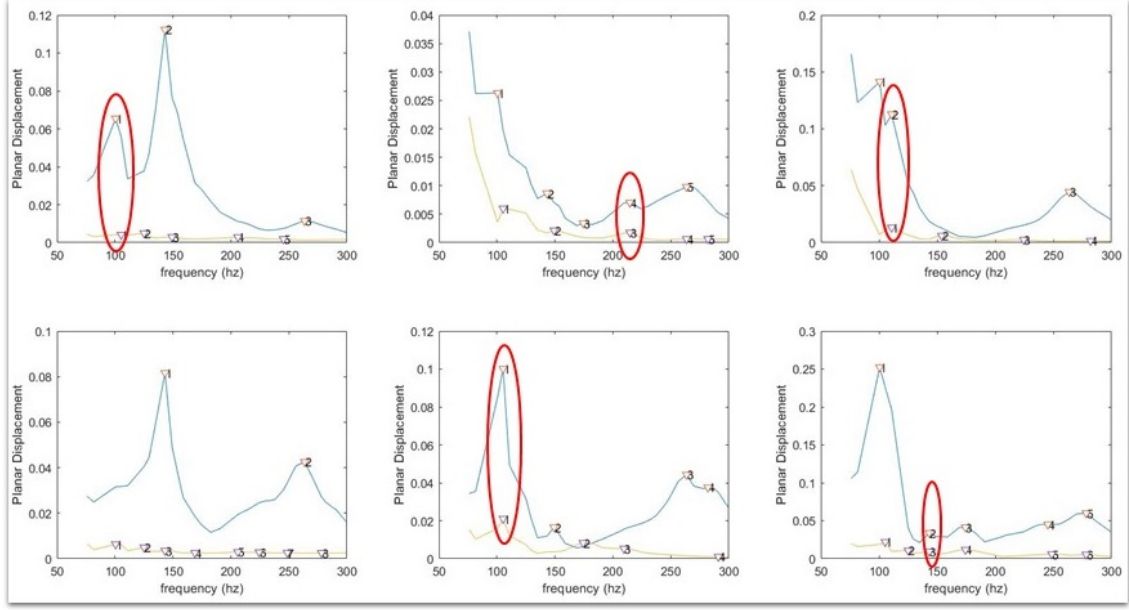


Figure 5.7: Matlab plot for identifying resonant frequencies for Squeak

The output file from NASTRAN is read by a Matlab script which calculates the dynamic stiffness along the measures and is plotted for normal displacement i.e.(rattle) as shown in Figure 5.6 and for planar displacement i.e.(squeak) as shown in Figure 5.7. The plots are for the Design number 3 as shown in Table 5.2. To calculate the resonant frequencies, the peak values were initially identified for deco panel and IP as shown in Figure 5.6 & Figure 5.7. A range of $\pm 2\%$ was defined for the peak values of IP which were then compared with the peak values of deco panel to check whether they fall in this range. If they happen to fall in that defined range, it means that at that particular frequency, the two components will be subjected to rattle which is highlighted by red marks in Figure 5.6. Similar procedure is carried out to identify the resonant frequencies for squeak which is highlighted by red oval shapes as shown in Figure 5.7.

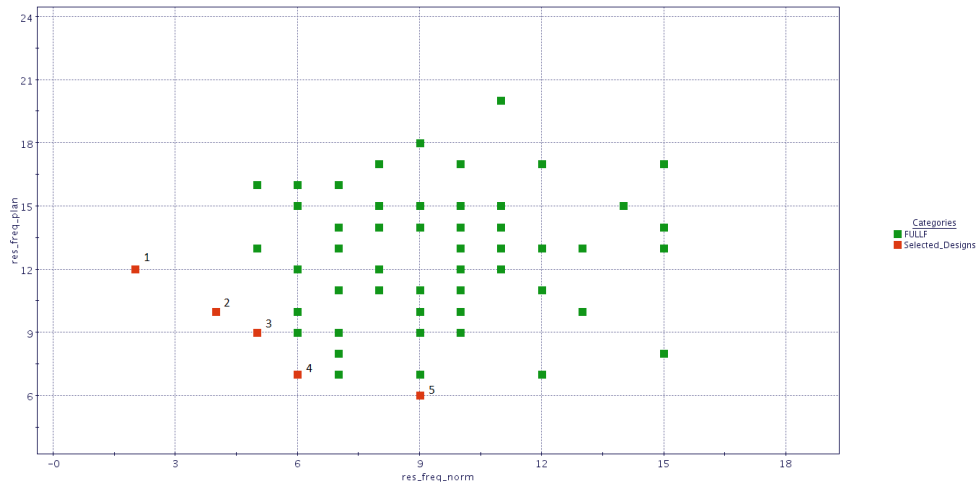


Figure 5.8: Scatter plot for single discipline optimization for modal analysis

The attachment points for the best selected designs is plotted as shown in the Figure 5.9, Figure 5.10, Figure 5.11, Figure 5.12, Figure 5.13.



Figure 5.9: Attachment points plot for design 1



Figure 5.10: Attachment points plot for design 2



Figure 5.11: Attachment points plot for design 3



Figure 5.12: Attachments points plot for design 4



Figure 5.13: Attachment points plot for design 5

5.1.3 Multidisciplinary optimization

The initial population for MDO workflow is the same as generated for single disciplines. None of the available optimization algorithms is used for this assembly since DoE covered all the possibilities of designs. The results for MDO is plotted as

shown in the Figure 5.14 where X axis indicates the total variation in normal and planar direction whereas Y axis indicates total number of resonant frequencies in normal and planar direction. After observing the scatter plot for MDO as shown in Figure 5.14, it is clear that all the best designs lie on a Pareto front which means no objective can be improved without sacrificing at least one another objective.

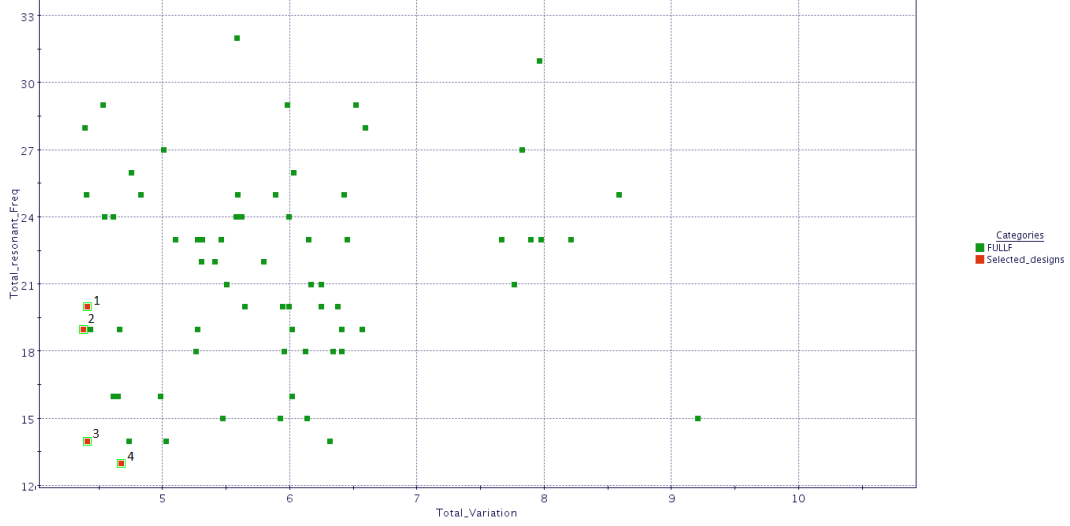


Figure 5.14: Scatter plot for MDO

Design visualization is done for the best combinations of attachments points in the assembly as shown in Figure 5.15, Figure 5.16, Figure 5.17, Figure 5.18.



Figure 5.15: Attachment points plot for design 1



Figure 5.16: Attachment points plot for design 2



Figure 5.17: Attachment points plot for design 3



Figure 5.18: Attachment points plot for design 4

5.2 Side Door Assembly

5.2.1 Single discipline optimization for Geometric variations

The variation analysis was performed and the results of variation for the measures in normal (Squeak) and planar (Rattle) is tabulated as shown in Table 5.3.

Table 5.3: Results for Geometric variations optimization

Measure	Design 1	Design 2	Design 3
10101_normal	0.71701	0.74083	0.74765
10101_planar	0.27182	0.2798	0.27548
10102_normal	0.48834	0.48675	0.49895
10102_planar	0.09593	0.09157	0.09415
10103_normal	0.3052	0.29323	0.29085
10103_planar	0.11218	0.11479	0.11454
10104_normal	0.09832	0.09665	0.08082
10104_planar	0.01962	0.01959	0.02459
10201_normal	0.93902	0.97041	0.94915
10201_planar	0.25474	0.2633	0.24565
10202_normal	0.63392	0.63051	0.65022
10202_planar	0.09537	0.09582	0.1085
10203_normal	0.4424	0.42065	0.47789
10203_planar	0.05503	0.05712	0.05557
10204_normal	0.10246	0.0955	0.13441
10204_planar	0.02144	0.02017	0.03316

The scatter plot for the design is plotted by having the results for rattle in X direction and the results for squeak in Y direction. After observing the scatter plot for geometric variation optimization as shown in Figure 5.19, it is clear that there is a linear correlation between the two objectives defined for this assembly. The designs with red boxes indicates the initial DoE whereas pink boxes indicates the MOGA-II which is converging to the optimal solutions. The 3 best designs selected are indicated by the blue boxes of which the results are shown in Figure 5.3.

The selected best designs from the optimization is visualized in Figure 5.20, Figure 5.21, Figure 5.22.

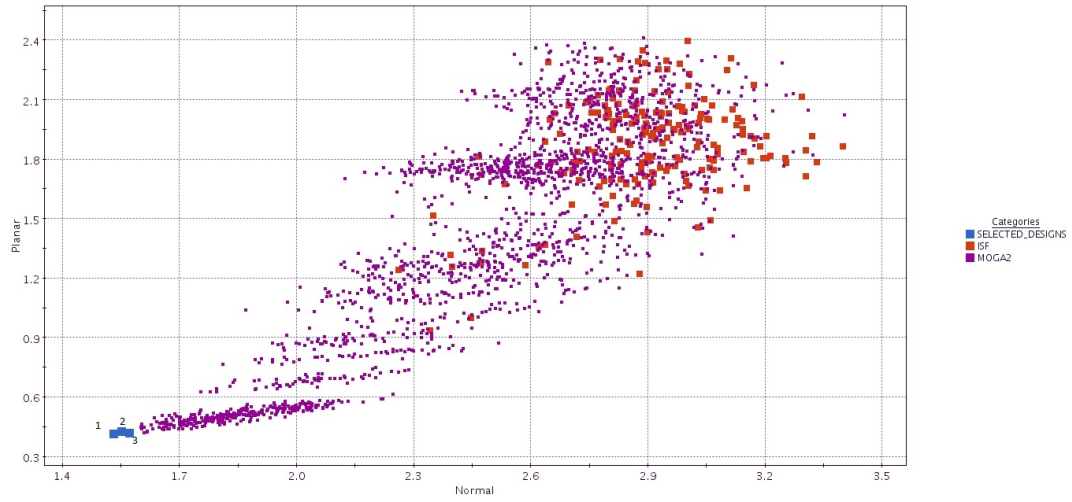


Figure 5.19: Scatter plot for single discipline optimization for variation analysis

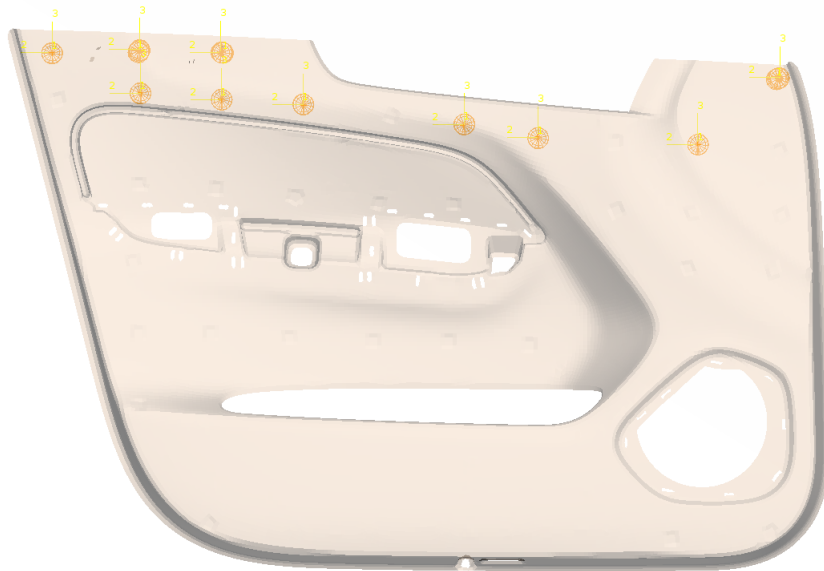


Figure 5.20: Attachment points plot for design 1

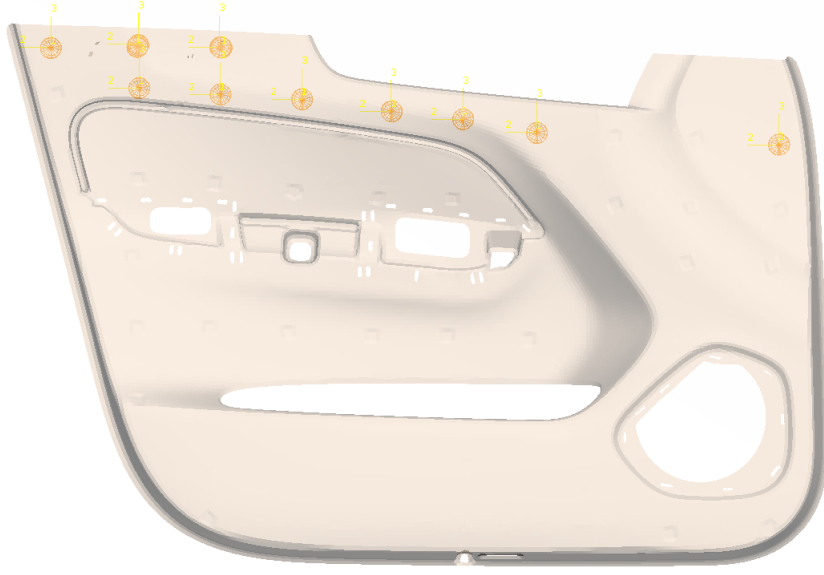


Figure 5.21: Attachment points plot for design 2

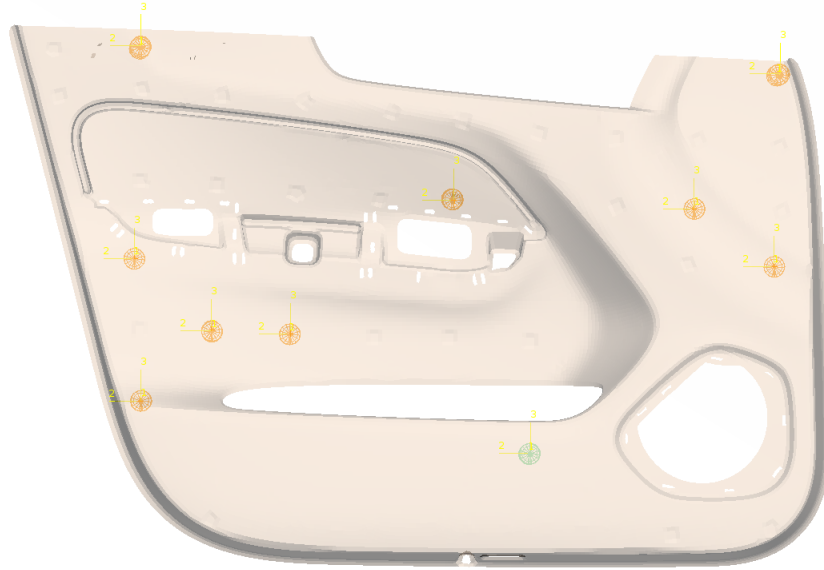


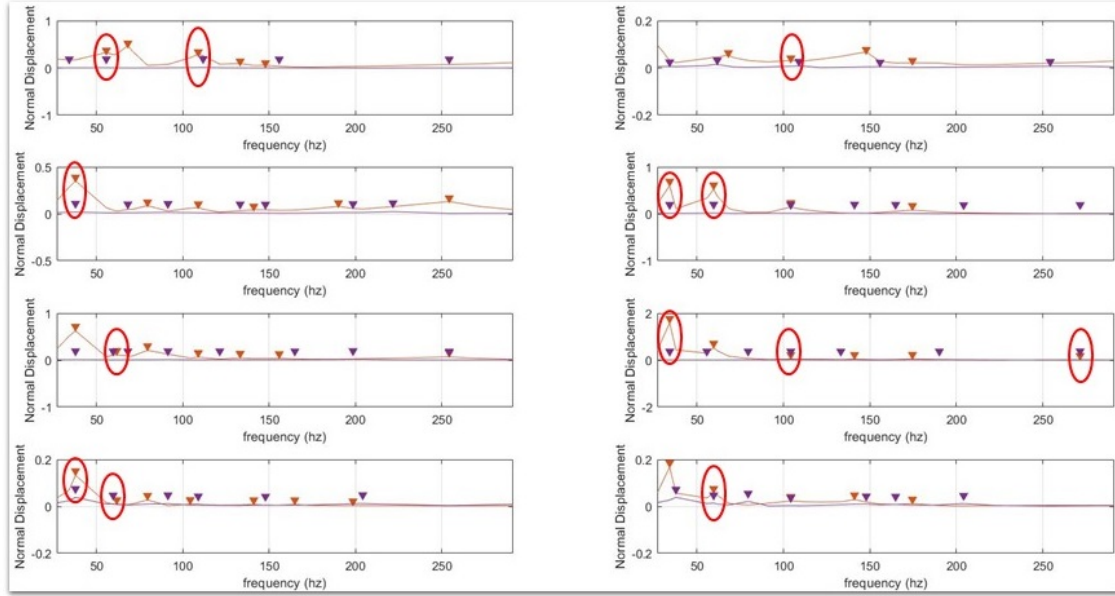
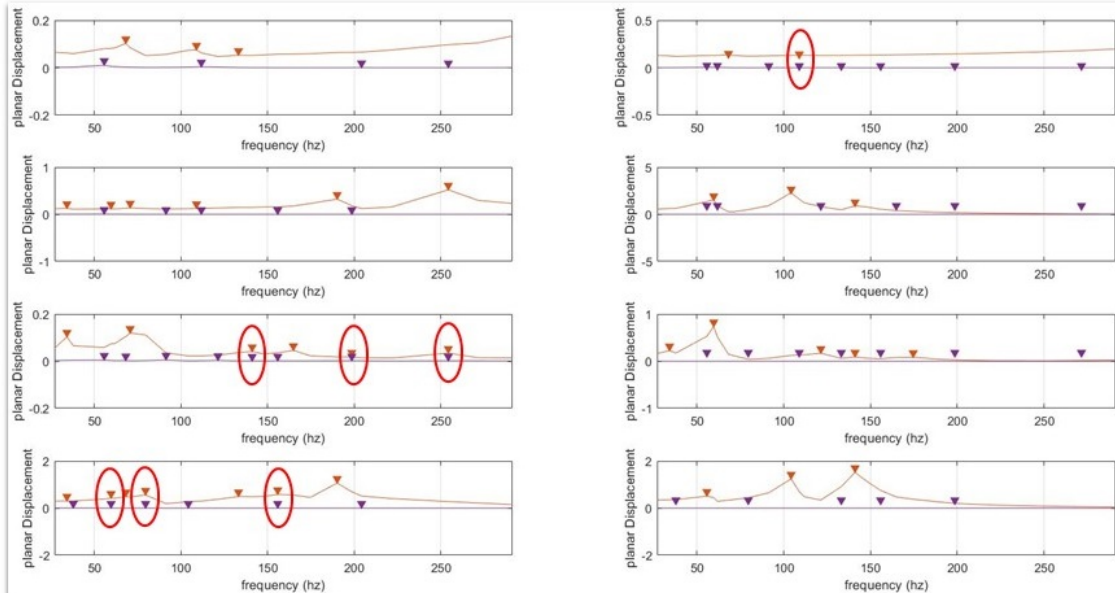
Figure 5.22: Attachment points plot for design 3

5.2.2 Single discipline optimization for modal behaviour analysis

The optimization methodology for modal behaviour analysis was performed and the number of resonant frequencies in normal (rattle) & planar (squeak) for the best designs along measures is tabulated as shown Table 5.4. The objective for this optimization process is to minimize the possibilities of resonant frequencies which might be subjected to S&R at defined measures.

Table 5.4: Results for modal behaviour optimization

	Design 1	Design 2
Total resonant frequency normal	9	13
Total resonant frequency planar	14	7


Figure 5.23: Matlab plot for identifying resonant frequencies for Rattle

Figure 5.24: Matlab plot for identifying resonant frequencies for Squeak

The output file from NASTRAN is read by a Matlab script which calculates the dynamic stiffness along the measures and is plotted for normal displacement i.e(rattle)

as shown in Figure 5.23 and for planar displacement i.e.(squeak) as shown in Figure 5.24. The plots are for the Design number 2 as shown in Table 5.4. To calculate the resonant frequencies, the peak values were initially identified for door panel and door structure as shown in Figure 5.23 & Figure 5.24. A range of $\pm 2\%$ was defined for the peak values of door structure which were then compared with the peak values of door panel to check whether they fall in this range. If they happen to fall in that defined range, it means that at that particular frequency, the two components will be subjected to rattle which is highlighted by red marks in Figure 5.23. Similar procedure is carried out to identify the resonant frequencies for squeak which is highlighted by red oval shapes as shown in Figure 5.24.

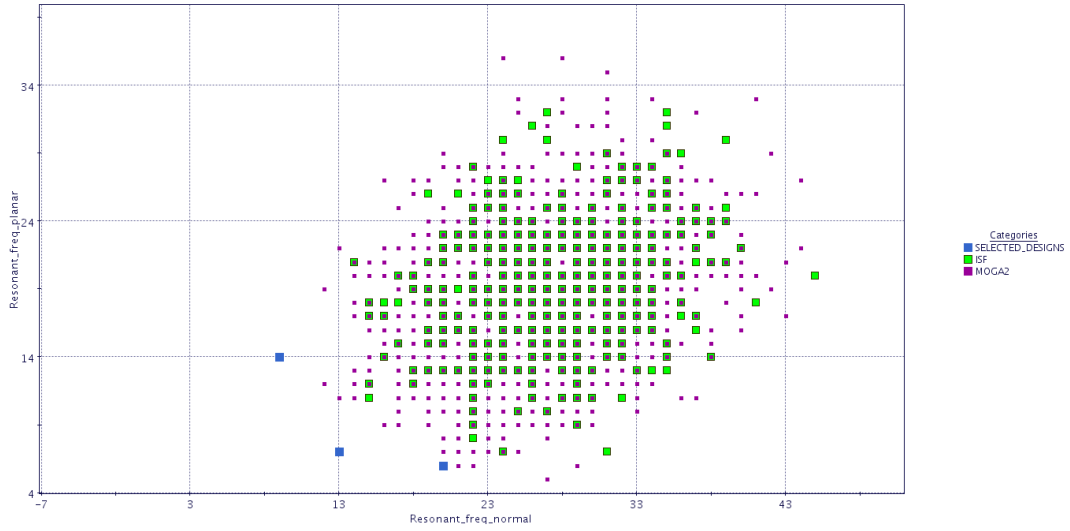


Figure 5.25: Scatter plot for single discipline optimization for variation analysis

The scatter plot for the designs is plotted by having the results for squeak in X direction and the results for rattle in Y direction. After observing the scatter plot for modal behaviour optimization as shown in 5.25, it is clear that all the best designs lie on a Pareto front which means no objective can be improved without sacrificing at least one another objective. The green boxes highlighted in the scatter chart defines the initial population of DoE whereas the purple marks indicates the MOGA-II which indicates that the algorithm is trying to converge for best optimal solutions. The blue boxes are the best designs which are selected and are presented in Table 5.4.

The best designs as shown in the from the scatter plot are visualized in Figure 5.26, Figure 5.27, Figure 5.28 .

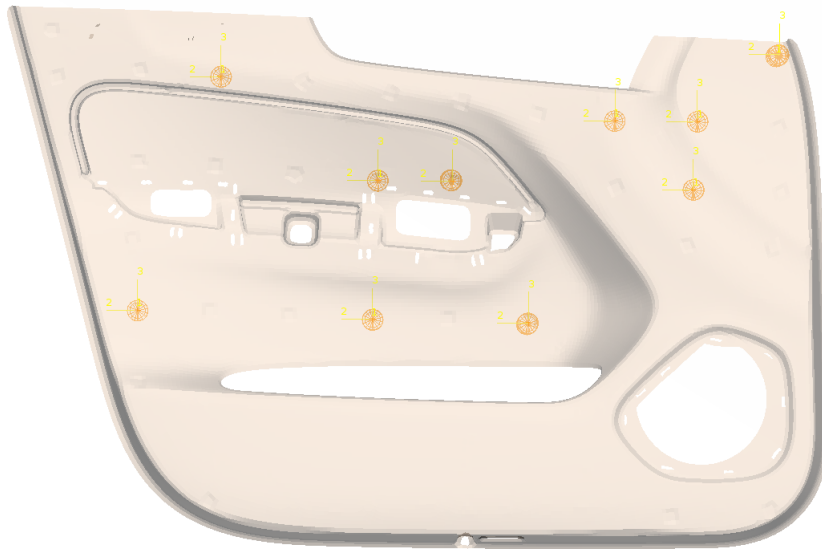


Figure 5.26: Attachment points plot for design 1

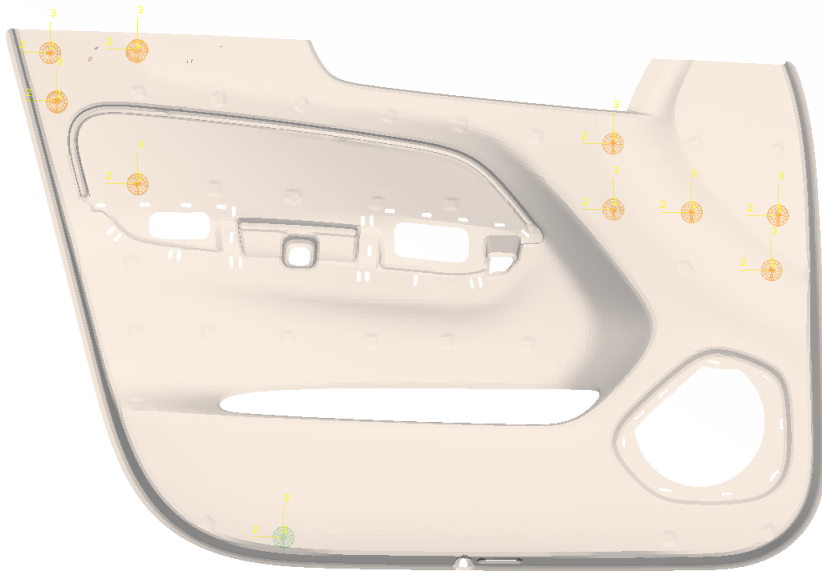


Figure 5.27: Attachment points plot for design 2

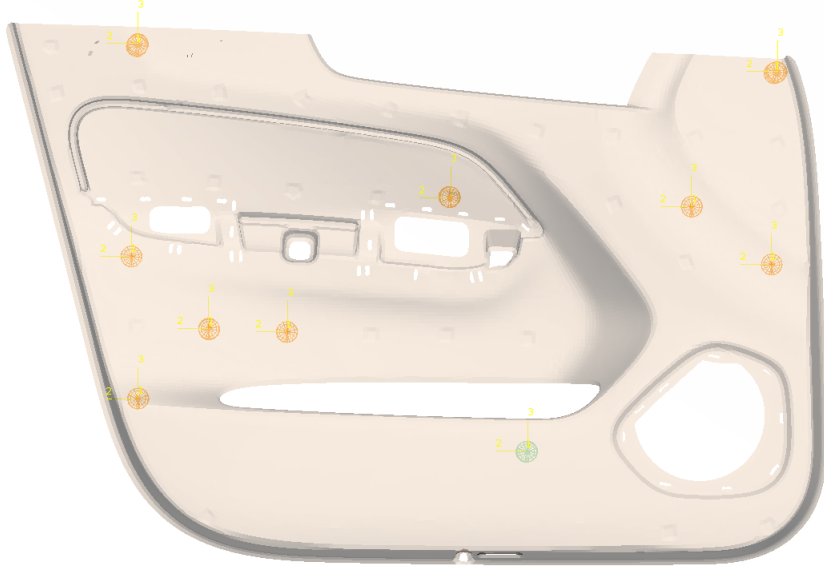


Figure 5.28: Attachment points plot for design 3

5.2.3 Multidisciplinary optimization

For MDO, the initial population was defined by taking the best designs from each disciple along with some designs generated from ULH algorithm. The results for MDO is plotted as shown in the Figure 5.29 where X axis indicates the total variation in normal and planar direction whereas Y axis indicates total number of resonant frequencies in normal and planar direction. After observing the scatter plot for MDO as shown in Figure 5.29, it is clear that all the best designs lie on a Pareto front which means no objective can be improved without sacrificing at least one another objective. The blue boxes indicates the initial population generated by ULH algorithm and the yellow boxes indicates the best designs from each discipline. The pink boxes represents the MOGA-II which is converging with respect to the objectives defined. The best designs selected are depicted by green boxes as shown in Figure 5.29.

The attachment points for the best designs from MDO is shown in Figure 5.30, Figure 5.31, Figure 5.32.

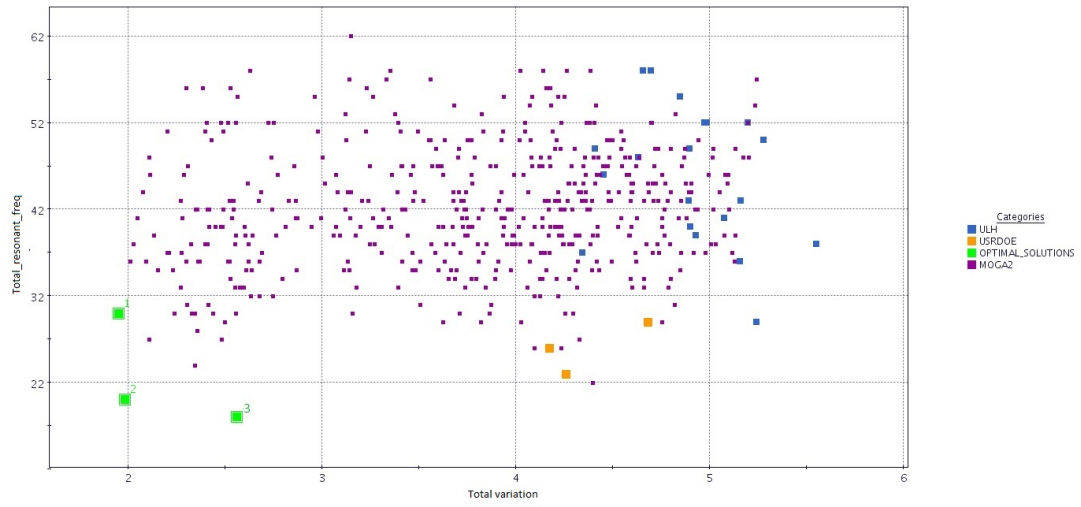


Figure 5.29: Scatter plot for MDO

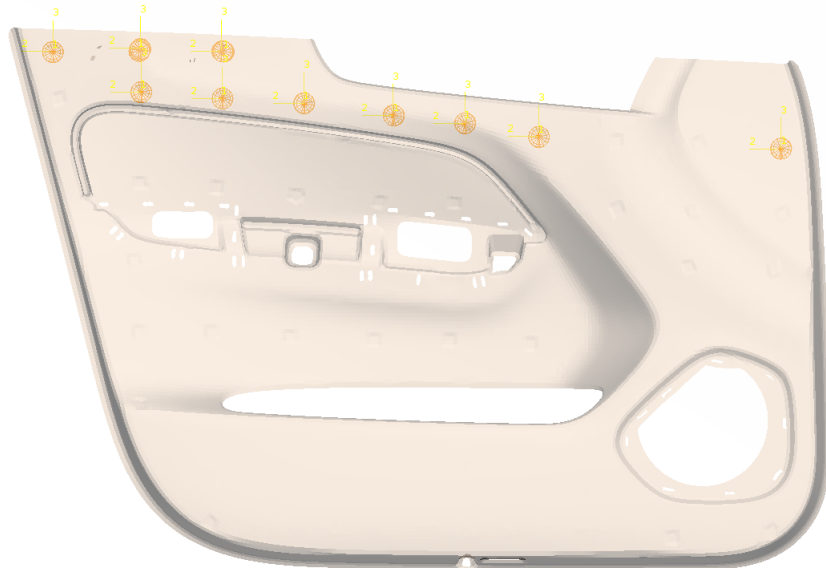


Figure 5.30: Attachment points plot for design 1

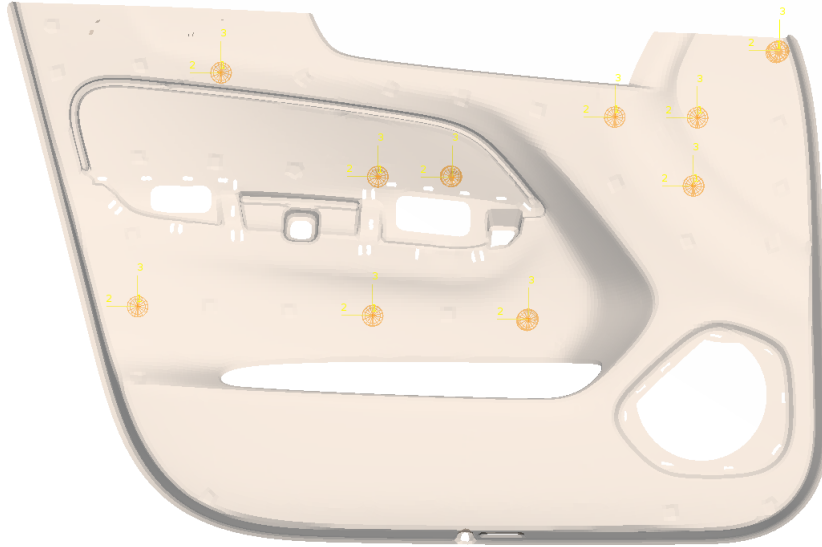


Figure 5.31: Attachment points plot for design 2

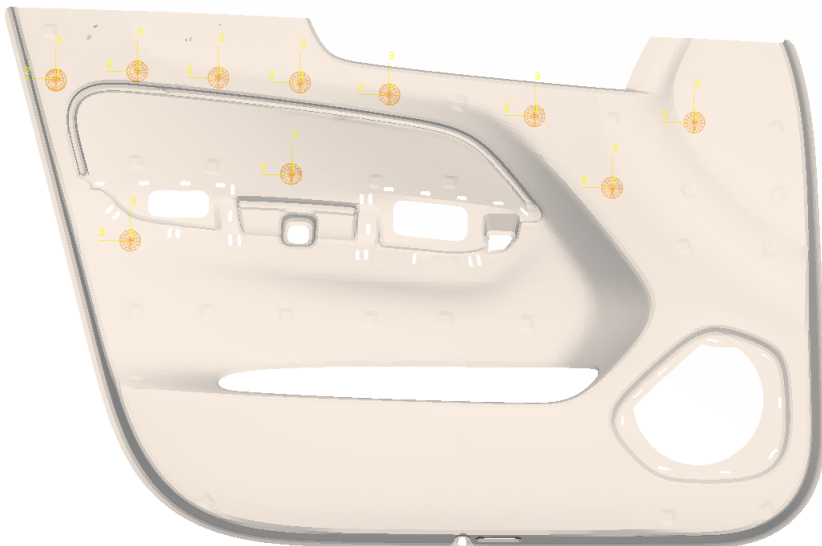


Figure 5.32: Attachment points plot for design 3

6

Conclusions & Recommendations

6.1 Conclusions

The purpose of this thesis was to perform a multi-disciplinary optimization of the attachment points of selected assemblies in a car cabin to improve geometric variation and modal behaviour of the assemblies for Squeak and Rattle sound prevention. The results clearly showed that the optimal designs lie on a Pareto front which means no objective can be improved without sacrificing at least another objective. This proves that geometric variation play a key role in generation of S&R. The results obtained from single discipline optimization was compared with multi-disciplinary optimization results to observe the effects for generation of S&R.

A literature review is done for MOGA-II algorithm for optimization process because of its robustness in reaching global optimum. Different DoE algorithms like ISF & ULH were thoroughly studied and applied depending upon the requirement of the model. The proposed optimization strategy is able to converge to the optimal solutions but the required computational resources are still a demanding aspect.

The MDO framework is applied for two different assemblies i.e. deco panel - IP assembly & side door assembly. This MDO technique developed can be clustered for other types of geometries and attachment schemes.

6.2 Recommendations

The current study was performed by introducing weld points as attachment point within an assembly. Instead of weld points, fasteners can be used to obtain more realistic results. This option is already available in the RD&T software package to determine geometric variations.

A study could be performed to reduce the total number of attachment points in the assembly by using optimization strategies as it would reduce the manufacturing time and overall manufacturing cost of an assembly.

The definition of objectives for MDO workflow can be made more robust by introducing more advanced topics like threshold for identifying resonant frequencies.

Although it can be considered that the results are accurate, there were lot of factors that could contribute error to the final result. One of the factors is defining the weld

points in RD&T and CBUSH elements in ANSA. For easy identification of possible attachment points, patches were created within the model. This can be eliminated by integrating both the softwares for defining the attachment points.

A study can be performed by comparing different optimization algorithms available in modeFRONTIER in order to reach global optimum in efficient way.

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A

Appendix

A.1 Node Details

NODE	ICON	DESCRIPTION
Input Variable		Input variables are the parameters of a model you can change. They are used to make changes in design parameters like geometric dimensions, forces etc.
Transfer Variable		The Transfer Variable Nodes is used to identify a variable as a function of input or output variables. The input and output variables in workflow are linked to
Input File		The input file node contains the input file that has to be fed to the process. The input variable node or transfer variable node is connected to the input file node to assign the variable position in the input file.
Output Variable		The output variable measure the system response of the entire workflow. It is totally dependent on the values of the input variable.
Output File		The output file node contains the output file is obtained after the analysis is completed. The output variable node is connected to the output file node to assign the variable position in the output file.
Transfer File		The Transfer File Node is a node that is used to identify a set of files that should be transferred from one application to another to continue the process flow.
Support File		The Support File Node is a node used to identify a set of files that should be copied in the working directory of an application that is linked to this node before the application is processed.
SH Shell Script		The SH Shell Node is a script node which stores and configures scripts in one of the UNIX-supported languages. It indicates the process that has to be run with the help of the input file to generate the required output file
Matlab Scrip		The Matlab Node is a node that integrates Matlab with modeFRONTIER. It stores and configures Matlab scripts and specifies the files and variables that has to be received and sent to other application nodes in the workflow.
Objective		Objective is used to maximize or minimize an input or output variable.
Scheduler		It is connected to the DOE table tool. Here the type of optimization that has to be performed, the analysis settings, RSM tools are available.
DOE		The DOE table creation tool helps to create new DOE sequences by marking the type of DOE algorithm to be chosen and the total designs to be created according to the required criteria.
Exit		This marks the end of the entire process flow that has been defined.
Sync Node		The Synchronizer Node consists of a pair of nodes which indicates two or more different processes to be executed in parallel. The parallel execution begins with the Synchronizer Start node and ends with the Synchronizer End node.
Design Contrain		The Design Constraint Nodes are nodes used to identify constraints of the optimization problems that should not be violated by any design. Designs which follow these constraints are feasible and the other designs are unfeasible.