# Project 2: Brake Disc Optimization Using ANSYS

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## 1 Introduction

In this project, we are tasked with optimizing a brake disc of an automobile with respect to multiple objectives. A brake disc should not only withstand high temperatures but should also be immune to engine's natural frequency, be lightweight to save fuel and resist high stresses. In the following problem, we analyze one such brake disc in three domains, i.e. Structural, Modal and Transient Thermal. We then utilize the information of these analyses to build a Design of Experiments and perform Multi-Objective Optimization to achieve the optimum design that:

- Minimize maximum equivalent (Von - Misses) Stress.
- Minimize brake disc volume.
- Maximize first natural frequency of brake disc.
- Minimize maximum temperature in the brake disc.

The optimum design is then compared against the initial design to check the performance improvement in the above objectives.

## 2 Initial Design

The initial design of the brake disc consists of three fundamental parameters:

- Inner Diameter (ID) in mm.
- Outer Diameter (OD) in mm.
- Thickness (t) in mm.

The default values of these parameters are given below:

| ID (mm) | OD (mm) | t (mm) |
|---|---|---|
| 75 | 125 | 25 |

# 3 Analysis: Static Structural

Static Structural analyses is used to evaluate the stresses that the brake disc will undergo during the operation. We also parameterize volume of the disc through geometry in this analysis.

## 3.1 Materials

The two sub-geometries for this project are brake disc and brake pads. The material chosen for brake disc is **Gray Cast Iron** and the material chosen for brake pads is **Structural Steel**.

## 3.2 Importing and Geometry Preparation

The geometry is gracefully provided in this project by Dr. Ren and his group. An **.agdb** file can be imported in any analysis chosen in the ANSYS Workbench.

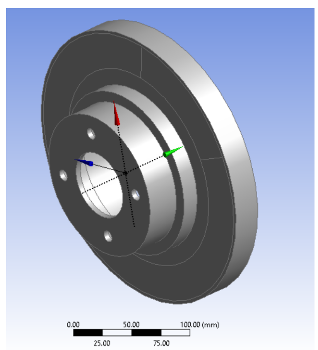


Figure 1: 3D CAD of Brake Disc

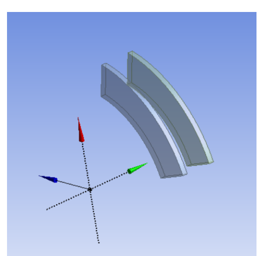

Figure 2: 3D CAD of Brake Pad

## 3.3 Connections

### 3.3.1 Contacts

Since the pads contact the disc, it is highly important to define the frictional surface in contact accurately. Thus the face of each pad that contacts the disc on either side is selected individually (in pad-disc face pair) and the co-efficient of friction $\mu = 0.22$. The nature of contact is **Solid To Solid**.

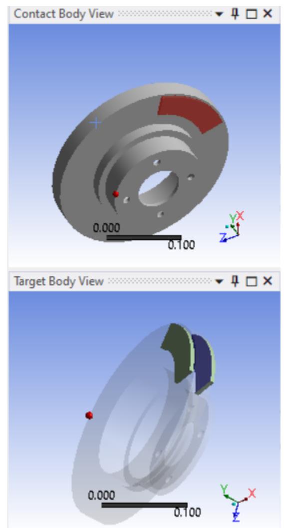


Figure 3: Definition of frictional surface between pad and disc.

### 3.3.2 Joints

Since the disc rotates freely about a hub in an automobile, this joint between hub and disc needs to be modelled in order to simulate the disc rotating. Thus, a **revolute** joint is modelled at the location where a hub bearing could potentially lie. The nature of the joint is **Body-Ground**.

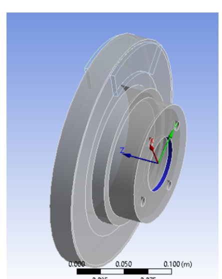

Figure 4: Revolute joint definition

This joint allows the disc to only rotate about the Y - axis and restricts motion in any other direction to allow it to only rotate in the required direction.

## 3.4 Mesh

In order to solve the problem, the object needs to be divided into small chunks called mesh. Each mesh is a sub-problem that when integrated gives fine discrete information of each analysis. The mesh chosen for this problem is different for the disc and the pads.

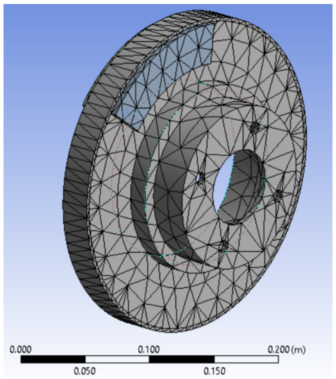


Figure 5: Patch Conforming Method

For the entire assembly, Patch Conforming method was used to perform mesh. The type of mesh chosen is tetrahedron. The size of mesh chosen due to system limitations is 5 mm. For the inner side of the brake pads, the face that touches the disc, Face Sizing method was used. This method allows higher refinement on the surface where detailed information is required.

## 3.5 Analysis

### 3.5.1 Rotational Velocity

A rotational velocity of 250 $rad/s$ is applied to the disc. All the other components of the velocity are set to 0. This ensures that the disc only rotates in the same manner as the wheel in this analysis.

### 3.5.2 Displacement

A constraint of displacement is applied on the pads. The pads are not allowed to move in any direction but Y - axis. This ensures that when load is applied on the pads, they only move in the direction parallel to the axis of rotation to make contact with the disc with the intention of stopping its motion.

### 3.5.3 Pressure

In order for the brake pads to make contact with the disc, a pressure of $1.0495 \times 10^7\ Pa$ is applied on each pad such that the direction of pressure helps them make contact with the disc. This pressure is assumed to be the pressure brake-fluid when squeezed through tubes from reservoir to the pads generates.

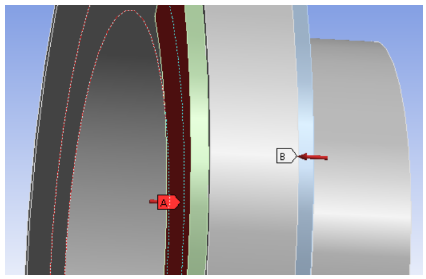


Figure 6: Direction of pressure.

## 3.6 Solution

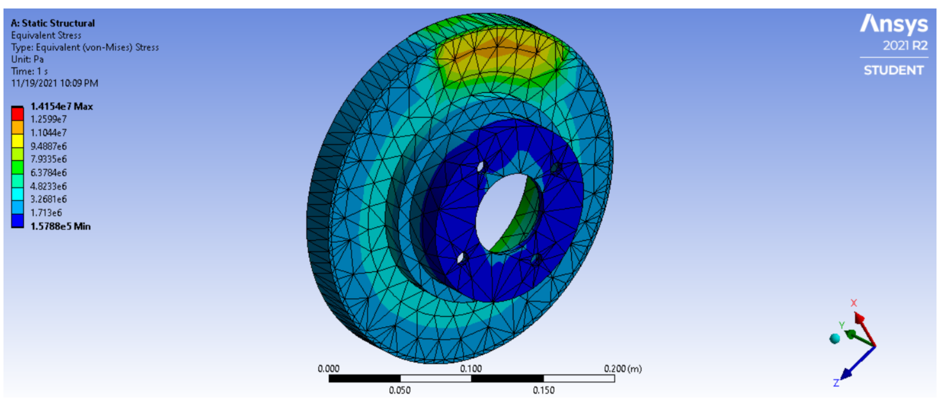


Figure 7: Static Structural Analysis. One Pad is hidden for better visualization.

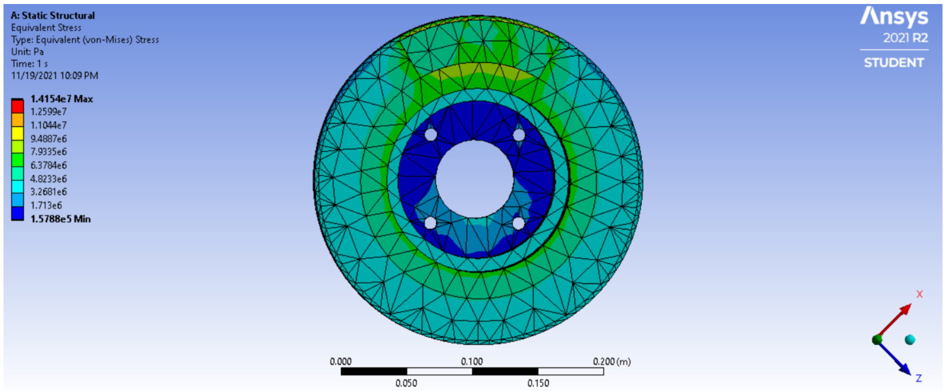


Figure 8: Static Structural Analysis. Back Side.

In this analysis, the maximum Equivalent (Von - Misses) Stress observed was $1.4154 \times 10^7 \ Pa$. The volume of the initial design was found to be $9.9667 \times 10^-4 \ m^3$. Both these values are parameterized for future analysis.

# 4 Analysis: Modal

The Modal Analysis is performed so that the brake disc does not fair due to resonance from engine vibration frequency. Hence, it is important to maximize the natural frequency of the disc as much as possible to avoid any conflict with the engine frequency. To do so 10 modes of the disc are calculated. Since the first 6 modes are rigid body modes, we evaluate and maximize the $7^{th}$ mode for Total Deformation. All the mesh and contact settings are copied and implemented from structural analysis.

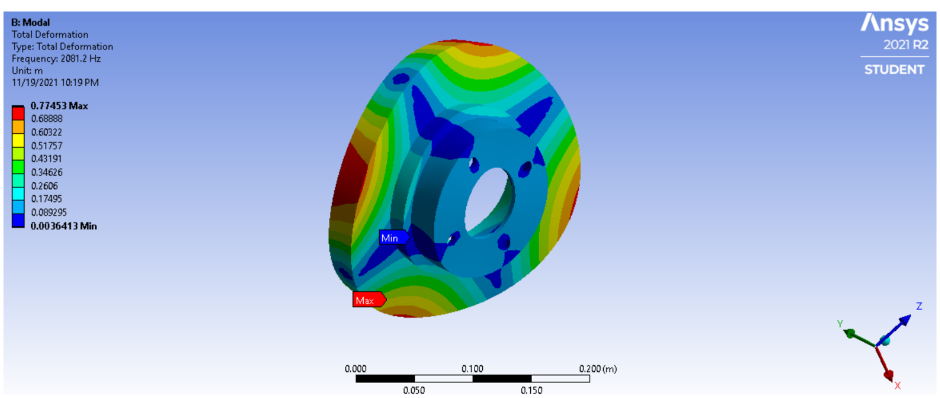


Figure 9: Total Deformation in Modal Analysis

It was found that the natural frequency of the disc is 2081.2 Hz. This value is parameterized for future analysis.

# 5 Analysis: Transient Thermal

The Transient Thermal Analysis is performed to find the maximum temperatures on the brake disc. In order to achieve high efficiency and product lifecycle, one needs to manage the temperatures reached on the disc to minimum. Thus, the aim of thermal analysis is to find a combination of parameters where the maximum temperature is minimized. All mesh and contact settings are copied from the structural analysis.

## 5.1 Analysis

The initial temperature settings for the analysis are set to 35°C (uniform).

### 5.1.1 Convection

The surface of the brake disc is assumed to transfer heat through convection only. The film co-efficient is chosen as 5 $W/m^2.°C$.

### 5.1.2 Heat Flux

The heat flux is modelled on both the brake disc and brake pads. Only the surface of disc and pads that would be in contact are subjected to flux. The flux on each surface is $1.5395 \times 10^6$ $W/m^2$.

## 5.2 Solution

The temperature analysis of the disc-pad system reveals maximum temperature on the disc to be 311.51°C. We should try and minimize this temperature as much as possible. Thus, maximum temperature is parameterized.

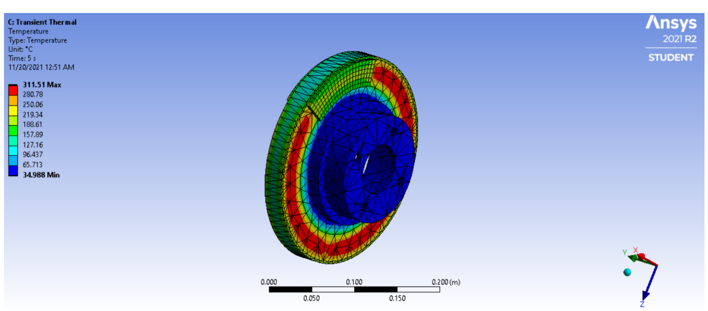


Figure 10: Temperature profiles in the disc

# 6 Workflow

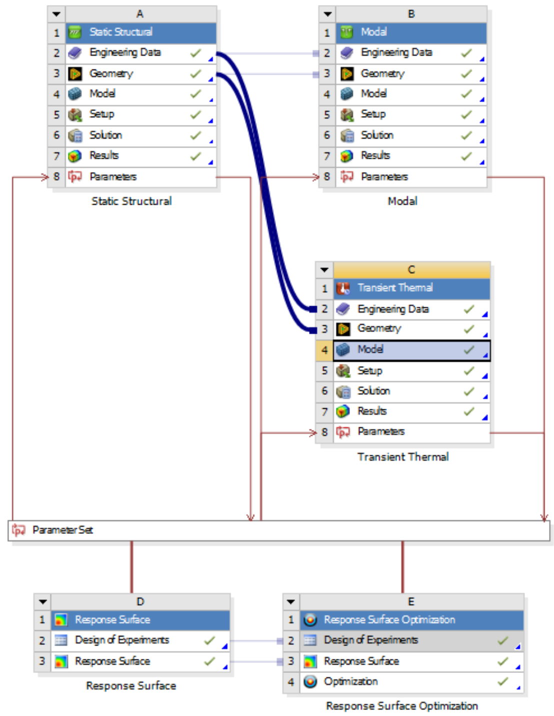


Figure 11: Workflow of Design Optimization

This workflow shows the structural, modal and transient thermal analysis where the material data and geometry is shared between each other. The parameter set consists of all the parameters from individual analyses in the form of inputs and outputs. The input parameter set is:

1. Disc Inner Diameter (ID) mm.
2. Disc Outer Diameter (OD) mm.
3. Disc Thickness (t) mm.

The output parameters are:

1. Volume of disc in $mm^3$.
2. Maximum Equivalent Stress in Pa.
3. Frequency of deformation in Hz.
4. Maximum disc temperature in °C.

These parameters are used in design of experiments and a response surface is characterized out of it. Later the response surface is optimized. Here the DOE and Response Surface is shared with the Response Surface Optimization block.

# 7 Response Surface Optimization

The response surface plots variation of various inputs and outputs to give an understanding of how varying parameters affects the objective.

## 7.1 Design of Experiments

The Design of Experiments (DOE) allows the users to select and analyze various combination of inputs selected from a finite domain bounded by their individual upper and lower limits. Due to this bounding, the said combinations can yield outputs that are different from the initial combination tested. Understanding how varying inputs can yield different outputs ultimately helps one shape a desired output by refining inputs based on the knowledge derived from DOE. Another great use of DOE is that, one need not do all infinite possible combinations to derive information of output variation corresponding to input variation. Instead, one needs to carefully select a few experiments that are a subset of all experiments whose results are acceptably equivalent to the total experiments.
The technique chosen in this project for DOE is Sparse Grid Initialization. The reason to choose this technique is multi-fold:

- Firstly, SGI only uses a few points to interpolate the multivariate regression function. It adds more points if deemed necessary. This saves a lot of computational time.
- Secondly, SGI is great for higher order dimensional problems. Since we are fitting 3 inputs to 4 outputs, SGI can be a great choice.

Now, we need to bound our inputs in a finite range. The chosen range for our inputs is as follows:

- $65 \leq$ Inner Diameter (ID) in mm $\leq 90$.
- $124 \leq$ Outer Diameter (OD) in mm $\leq 150$.
- $5 \leq$ Thickness (t) in mm $\leq 27.5$.

The inputs are continuous variables, this means that within the given range, any value of the variable can be chosen. A discrete variable would mean the value of the variable would be a step addition of $\delta v$ to the original variable $v$.

Table of Outline A2: Design Points of Design of Experiments

| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| 1 | Name | P1 - rotor_thickness (mm) | P2 - rotor_OD (mm) | P3 - rotor_ID (mm) | P4 - Equivalent Stress Maximum (Pa) | P7 - Solid Volume (m^3) | P8 - Total Deformation Reported Frequency (Hz) | P9 - Temperature Maximum (C) |
| 2 | 1 DP 4 | 16.25 | 137 | 77.5 | 1.268E+07 | 0.00087156 | 1638.5 | 365.34 |
| 3 | 2 DP 12 | 5 | 137 | 77.5 | 1.1636E+07 | 0.00042049 | 1101.1 | 873.74 |
| 4 | 3 DP 12 | 27.5 | 137 | 77.5 | 1.2091E+07 | 0.0013226 | 1841.3 | 305.97 |
| 5 | 4 DP 12 | 16.25 | 124 | 77.5 | 1.2432E+07 | 0.00069834 | 1901.3 | 367.55 |
| 6 | 5 DP 12 | 16.25 | 150 | 77.5 | 1.3412E+07 | 0.001062 | 1334 | 364.64 |
| 7 | 6 DP 12 | 16.25 | 137 | 65 | 1.1618E+07 | 0.00092077 | 1493.7 | 362.88 |
| 8 | 7 DP 12 | 16.25 | 137 | 90 | 2.2808E+07 | 0.0008113 | 1460.8 | 366.47 |

Figure 12: Initialized Design Points.

## 7.2 Response Surface

Based on the design points in DOE, one can reconstruct a response surface of inputs to outputs. However, selection of additional points along with DOE design points is necessary to be able to fully reconstruct a 3D surface. These additional points are called refinement points. The response surface type chosen for this problem is Sparse Grid with a maximum of 20 refinement points. Additionally, 5 verification points are also included to validate the integrity of the model.

### 7.2.1 Min-Max Search

The Min-Max Search gives a clear understanding about what the maximum and minimum of each output is based on the initial selected points and refinement points. Thus, localizing the optimum solution becomes easier. For this problem, we can visualize the maximum and minimum of each output variation in the figures below.

| Output Parameter Maximums | | | | | | | |
|---|---|---|---|---|---|---|---|
| P4 - Equivalent Stress Maximum | 27.5 | 150 | 90 | **3.0193E+07** | 0.0015107 | 1470.6 | 304.22 |
| P7 - Solid Volume | 27.5 | 150 | 65 | 1.2278E+07 | **0.0017571** | 1666.6 | 303.92 |
| P8 - Total Deformation Reported Frequency | 27.5 | 124 | 65 | 1.2802E+07 | 0.0011417 | **2247.3** | 307.82 |
| P9 - Temperature Maximum | 5 | 124 | 71.25 | 1.1583E+07 | 0.0003617 | 1492.7 | **902.1** |

Figure 13: Maximum of Outputs

| Output Parameter Minimums | | | | | | | |
|---|---|---|---|---|---|---|---|
| P4 - Equivalent Stress Maximum | 5 | 136.97 | 83.775 | **1.0177E+07** | 0.00042862 | 1247.4 | 870.73 |
| P7 - Solid Volume | 5 | 124 | 65 | 1.247E+07 | **0.00035344** | 1375.2 | 898.81 |
| P8 - Total Deformation Reported Frequency | 5 | 150 | 65 | 1.3378E+07 | 0.00046535 | **528.69** | 870.92 |
| P9 - Temperature Maximum | 27.5 | 150 | 65 | 1.2278E+07 | 0.0017571 | 1666.6 | **303.92** |

Figure 14: Minimums of Outputs

Thus, looking at the above values, we know that the maximums and the minimums of each output is achieved by different variations of input. Thus, it may not be possible to generate one optimum solution where all the requirements are satisfied. Thus, we would end up with a trade-off between our goals, where some objectives may be well satisfied compared to others.

#### 7.2.2 Goodness of Fit

Goodness of Fit (GOF) is a metric that allows us to validate how well our prediction model performed to fit outputs vs inputs. The higher the percentage of fit, the better is the model at predicting new points.

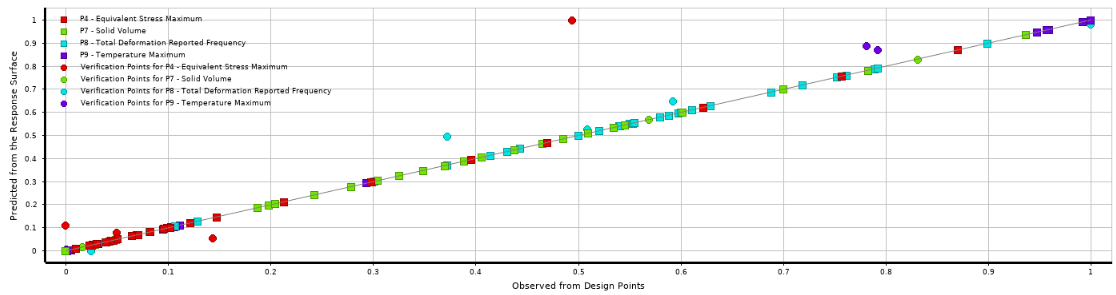


Figure 15: Goodness of Fit

#### 7.2.3 Response Surface

The response surface gives a clear picture of variation of any two input parameters (X and Y axis) and any one output parameter (Z axis). Some of the best response surfaces are shown below.

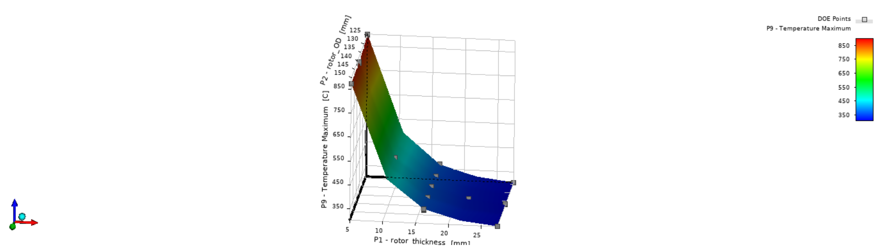


Figure 16: Thickness vs OD vs Temperature

From Fig, 16 we can see that increasing thickness can reduce Maximum Disc Temperature.

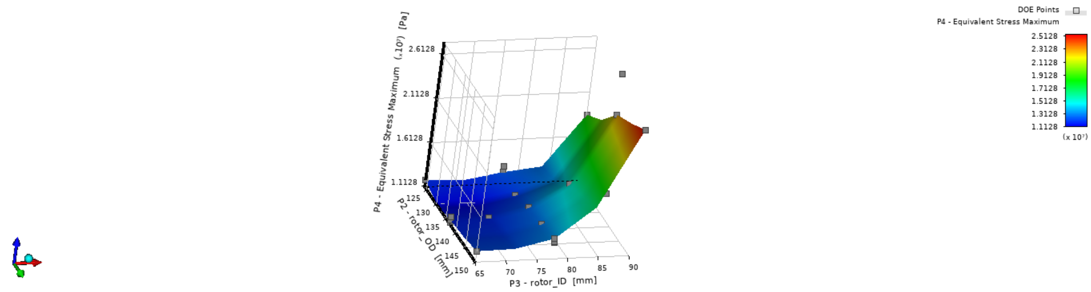


Figure 17: ID vs OD vs Stress

From Fig. 17 we can see that decreasing ID can decrease maximum equivalent stress in the disc.

#### 7.2.4 Local Sensitivity

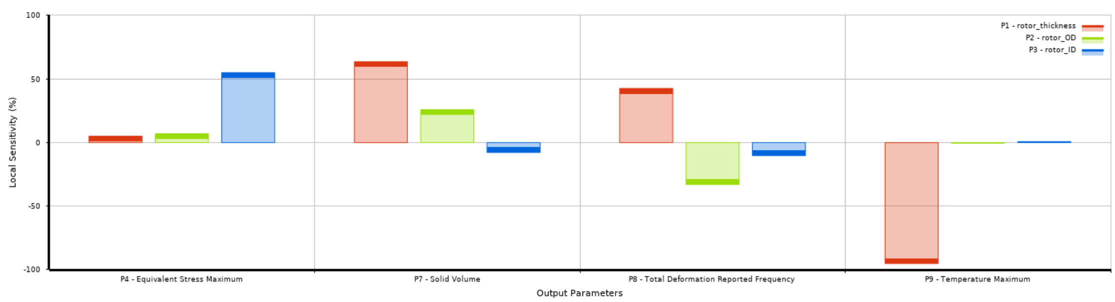


Figure 18: Local Sensitivity Analysis

From Fig. 18 we can see that change in ID has the highest effect on Stress i.e. increasing ID increases stress. Similarly, change in thickness has the highest effect on volume i.e. increase in thickness increases volume. Similarly, thickness has highest effect on Maximum Temperature i.e. decreasing thickness increases maximum temperature. Thus, local sensitivity analysis gives us a very good understanding of how each parameter affects each outcome.

# 8 Optimization

Once we derive the Response Surface, the final goal in this project is to optimize it and find combination of inputs that satisfy objectives of outputs. Reiterating the objectives, we need to:

- Minimize maximum equivalent (Von - Misses) Stress.

- Minimize brake disc volume.
- Maximize first natural frequency of brake disc.
- Minimize maximum temperature in the brake disc.

## 8.1 Optimization Algorithm

Since, there are multiple objectives to satisfy in this problem, MOGA is chosen as the algorithm. MOGA stands for multi-objective genetic algorithm and is used when the objectives are non-linear and multiple. This problem is highly suitable for MOGA. The initial samples chosen are 100 and samples per iteration is also chosen as 100. Convergence for all objectives and inputs was achieved after 700 iterations and can be visualized below:

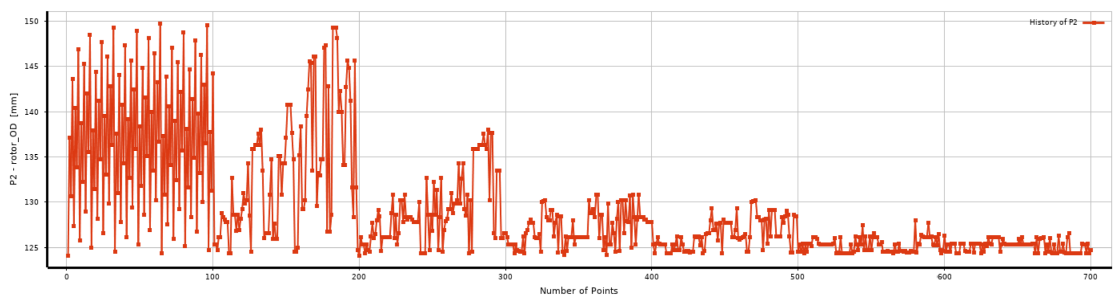


Figure 19: Convergence of Outer Diameter

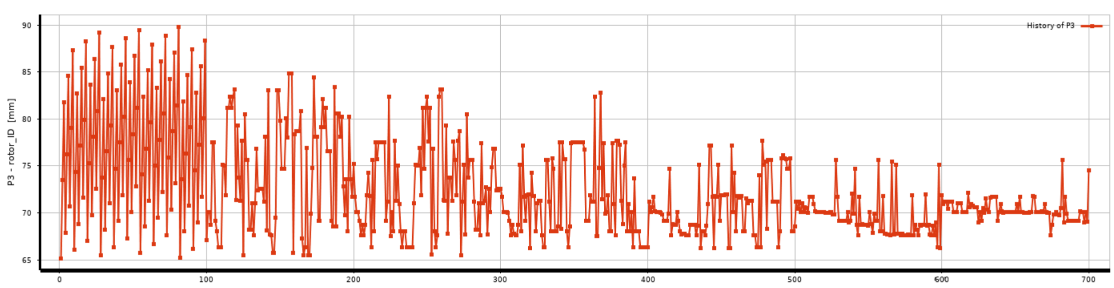


Figure 20: Convergence of Inner Diamter

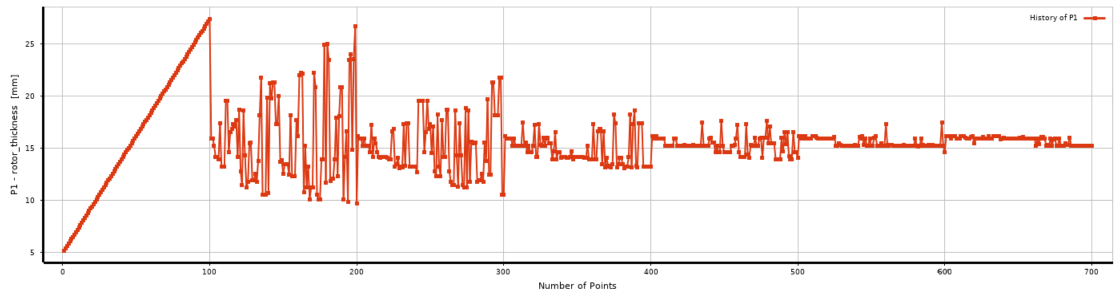


Figure 21: Convergence of Thickness

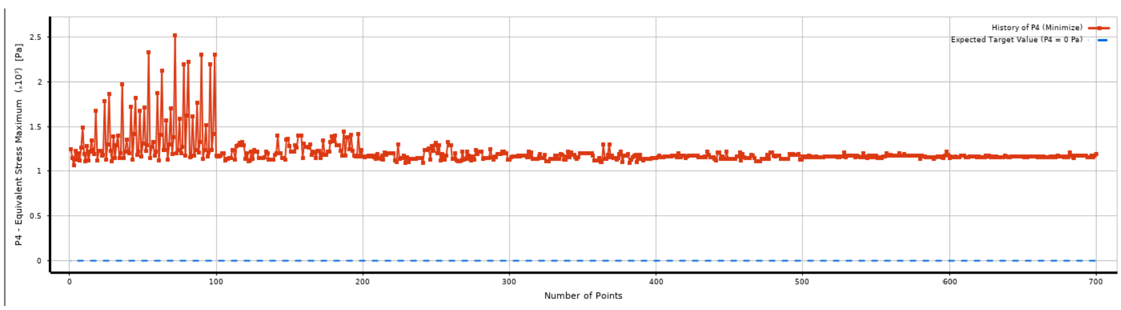


Figure 22: Convergence of Equivalent Stress (Minimize)

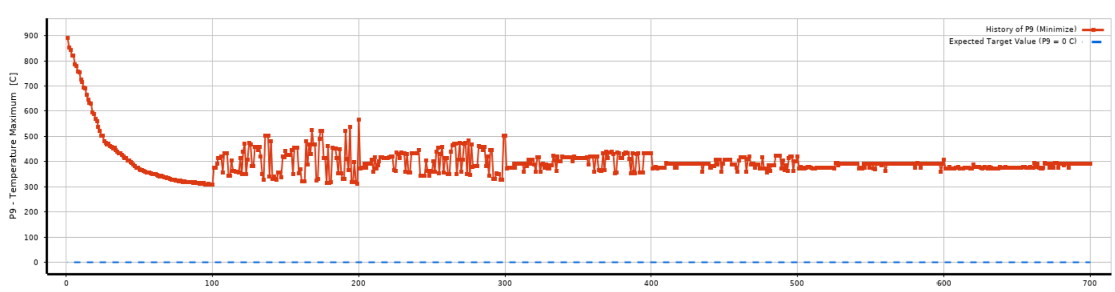


Figure 23: Convergence of Temperature (Minimize)

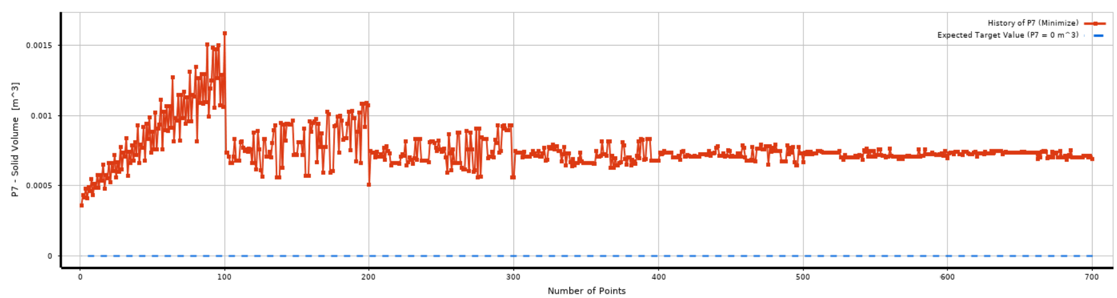


Figure 24: Convergence of Volume (Minimize)

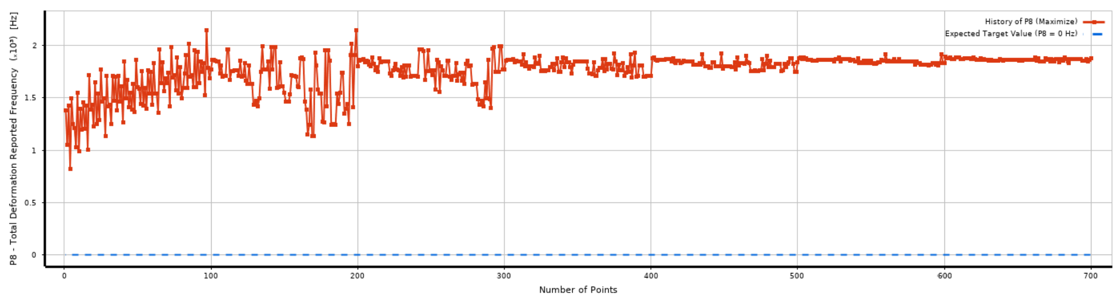


Figure 25: Convergence of Frequency of Deformation (Maximize)

Thus, MOGA seems to be an appropriate choice for this problem.

## 8.2 Trade-off Analysis

The trade-off can be visualized through a series of graphs that show certain trends. These trends show where the feasible points lie when various parameters are changed such that the objectives are satisfied.

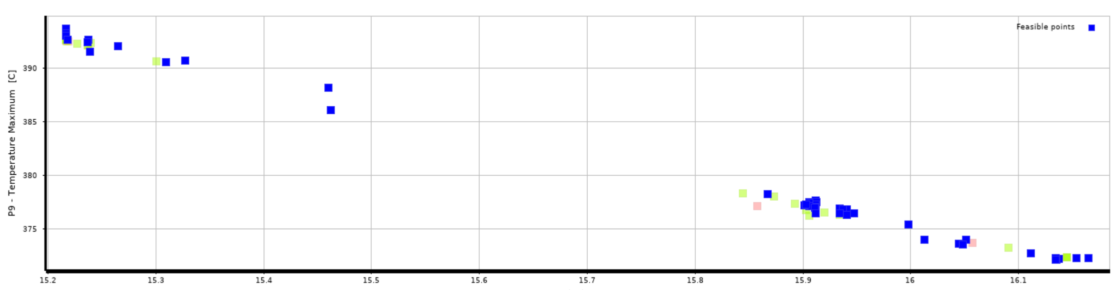


Figure 26: Trade-off Thickness vs Temperature

We see from Fig. ?? that increasing thickness reduces maximum temperature. This was also verified by the response surface graph. Another example can be used as Trade-off between OD and Volume. Increasing OD increases volume.

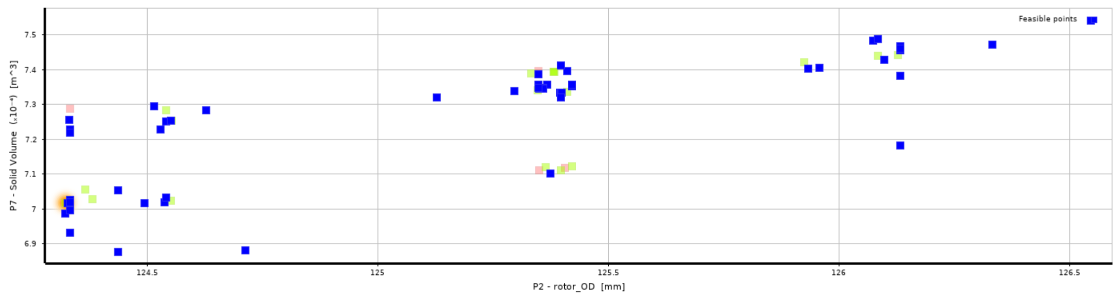


Figure 27: Trade-off Volume vs OD

## 8.3 Final Candidate Points

Following the steps of Optimization, we finally are able to find points that satisfy most of the objectives. For this problem, the optimized points are found to be the following.

| | A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Reference | Name | P1 - rotor_thickness (mm) | P2 - rotor_OD (mm) | P3 - rotor_ID (mm) | P4 - Equivalent Stress Maximum (Pa) | | P7 - Solid Volume (m^3) | | P8 - Total Deformation Reported Frequency (Hz) | | P9 - Temperature Maximum (C) | |
| 2 | | | | | | Parameter Value | Variation from Reference | Parameter Value | Variation from Reference | Parameter Value | Variation from Reference | Parameter Value | Variation from Reference |
| 3 | | Candidate Point 1 | 16.165 | 124.51 | 70.906 | 1.1676E+07 | -7% | 0.00072951 | -27% | 1889.9 | -8% | 372.26 | 18% |
| 4 | | Candidate Point 1 (verified) DP 12 | | | | 1.2426E+07 | -1% | 0.00072941 | -27% | 1963.4 | -5% | 364.34 | 15% |
| 5 | | Candidate Point 2 | 15.913 | 124.53 | 70.456 | 1.1675E+07 | -7% | 0.00072302 | -27% | 1882.7 | -8% | 377.67 | 20% |
| 6 | | Candidate Point 2 (verified) DP 12 | | | | 1.3769E+07 | 10% | 0.00072298 | -27% | 1950.6 | -5% | 367.08 | 16% |
| 7 | | Candidate Point 3 | 16.091 | 125.41 | 72.104 | 1.1681E+07 | -7% | 0.00073387 | -26% | 1872.7 | -9% | 373.29 | 18% |
| 8 | | Candidate Point 3 (verified) DP 12 | | | | 1.2103E+07 | -4% | 0.00073366 | -26% | 1936.7 | -6% | 367.16 | 16% |
| 9 | | Reference Canditate | 25 | 125 | 75 | 1.2562E+07 | 0% | 0.00099626 | 0% | 2056.6 | 0% | 315.55 | 0% |
| 10 | | Reference Canditate (verified) DP | | | | 1.4154E+07 | 13% | 0.00099667 | 0% | 2081.2 | 1% | 311.51 | -1% |
| * | | *New Custom Candidate Point* | *16.25* | *137* | *77.5* | | | | | | | | |

Figure 28: Optimized Candidate Points. Variation from Initial input parameter choice is also highlighted.

We can see that Candidate 1 has 7% less maximum Equivalent Stress, 27% less volume, 8% decrease in maximum frequency and 18% increase in maximum disc temperature. Thus, we can see that the optimization can optimize two parameters and sacrifice two others to yield a solution. In reality this is true because we cannot always find feasible points that can satisfy all criteria.

| ID (mm) | OD (mm) | t (mm) |
| --- | --- | --- |
| Initial | | |
| 75 | 125 | 25 |
| Optimum | | |
| 70.91 | 124.51 | 16.17 |

We thus see that for the optimum design, we reduced ID and thickness significantly. OD did not undergo significant changes.