Project 2: Design Optimization of Brake Disc Geometry

For completion of

MAE 598: Design Optimization

By

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Abstract

The main objective of the project was to optimize the disc brake geometry of a vehicle using Ansys. Throughout the project, we utilized different solvers and optimizers of Ansys in order to reach the final results. The main goal was to minimize the volume of the brake disc assembly by maximizing the frequency of the brake disc while minimizing the stress and heat flux from the brake disc. This project allowed us to get hands-on experience in solving industry level problem using available solvers.

Problem Statement

Main objective of the provided optimization problem is to minimize the volume of the provided brake disc geometry under some constraints. These physical constraints are:

- Maximum Stress that can be applied on the brake disc.
- Maximum Temperature that the brake disc can reach through the application of the brakes.
- Physical constraints on the brake disc geometry to avoid extremely thin or small brake disc.

The parameters of the disc brake that were changed for setting up different geometries are: Inner diameter of the disc, outer diameter of the disc and the thickness of the disc.

Constraints

To formulate the mathematical model, it is important to first understand the physical constraints of the model.

- **Maximum Stress:** Since the brake pads will press against the walls of the brake disc, it will experience both normal stress and shear stress. However, since the shear strength is usually lower than the compressive strength, the constraint applied on the maximum stress is based on the shear strength. Maximum Stress should therefore be less than 15 MPa.
- **Maximum Temperature:** The melting temperature of the gray cast iron is ~1000 C, so by factoring in the factor of safety, I have set the maximum temperature that can be reached should be less than 400 C.
- **Minimum Volume:** Physically the volume of the disc brake cannot be negative, the last constraint is that the volume should be greater than 0.
- **Objective:** The objective of the problem is to minimize the volume of the disc brake, minimize the stress, temperature reached and maximize the lowest non-rigid body frequency mode.

Problem Setup

This section discusses the problem setup in Ansys. Since the optimization concerns the maximum stress on the disc, maximum temperature reached by the disc, and the modal frequency of the disc brakes, the Ansys setup includes Structural Analysis, Modal Analysis and Transient Thermal Analysis.

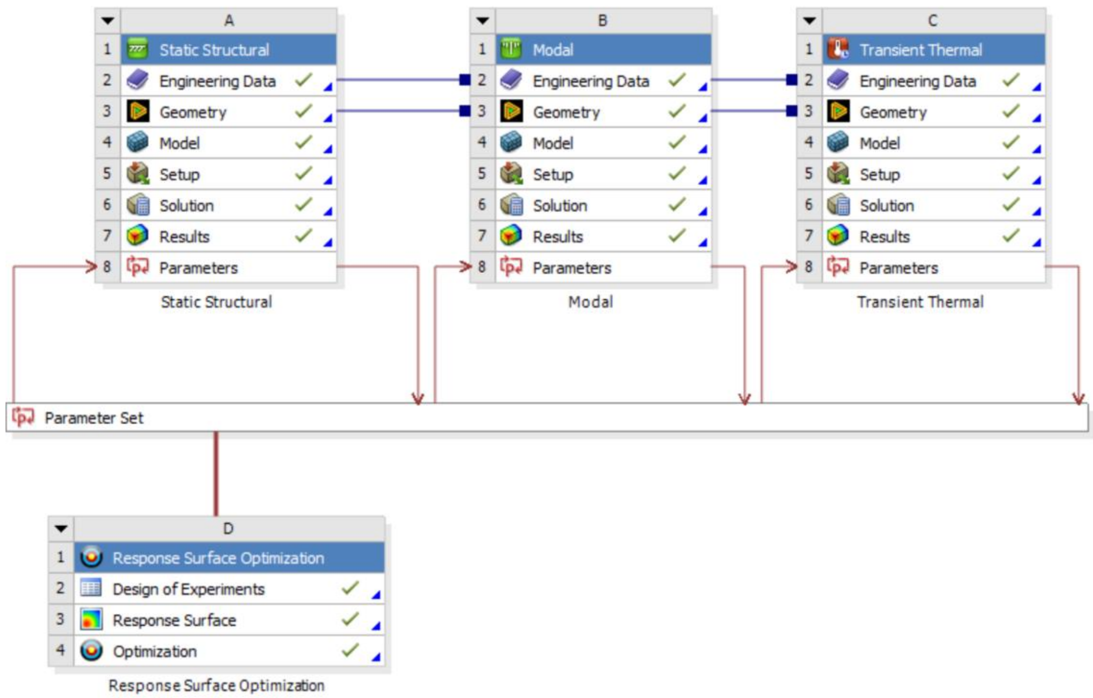
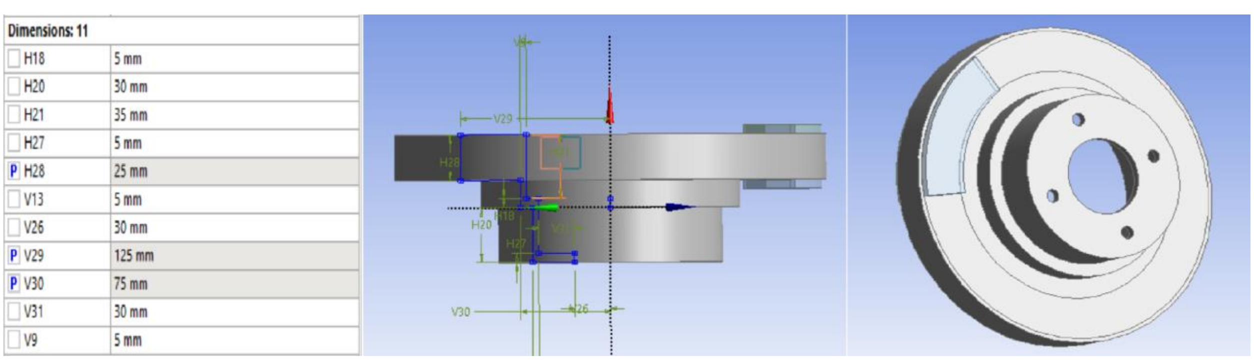


Fig 1: Ansys Problem Setup

The **design parameters** for the brake disc problem chosen based on the objective of minimizing the volume are: Outer diameter of the disc, Inner diameter of the disc and the thickness of the disc rotor.

Geometry of the Model:

This section discusses the geometry of the brake disc geometry and the parameters of the geometry that being changed throughout the process of generating design optimization points.



Dimensions: 11	
H18	5 mm
H20	30 mm
H21	35 mm
H27	5 mm
P H28	25 mm
V13	5 mm
V26	30 mm
P V29	125 mm
P V30	75 mm
V31	30 mm
V9	5 mm

Fig 2: Geometry and the Parameters of the Geometry

Mesh Setup

The meshing of the brake disc includes a lot of separate sizing for different sections in order to accommodate the size differences of different sections of the geometry.

- **Disc Brake Rotor:**
  Most of the geometry of the brake disc has the body sizing of 10 mm because that is the appropriate size for the geometry. This mesh size is appropriate because most of the geometry of the disc does not come under load and so a big mesh size can help in reducing the computation time.
  The mesh size throughout the thickness of the disc is however applied at 8.5mm to accommodate at least 3 layers of mesh, to capture that part of the rotor correctly.
- **Brake pads:**
  Since the brake pads are applying the load on the disc rotor and they are thin, the sizing applied on the brake pads and the projected area of the brake pads on disc rotor, is 3mm.

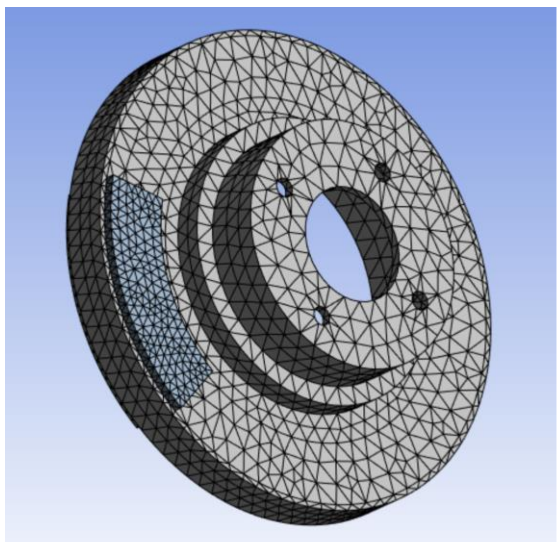


Fig 3: Mesh applied on the brake disc.

Simulation Setups

The simulation setups for static structural analysis, modal analysis and transient thermal analysis are same as those discussed in the tutorial referred here: ANSYS Design Optimization Tutorial. All the steps are listed at the reference and followed the same way. This is true just for the simulation setups and nothing else.

Results

The results for the simulations before and after the optimization step are discussed below:

Static Structural Analysis

The static structural analysis helped analyze the Equivalent Von Mises stress on the brake disc. Before the optimization process took place, the maximum stress experienced by the rotor was 12.38MPa. The stress distribution is shown below:

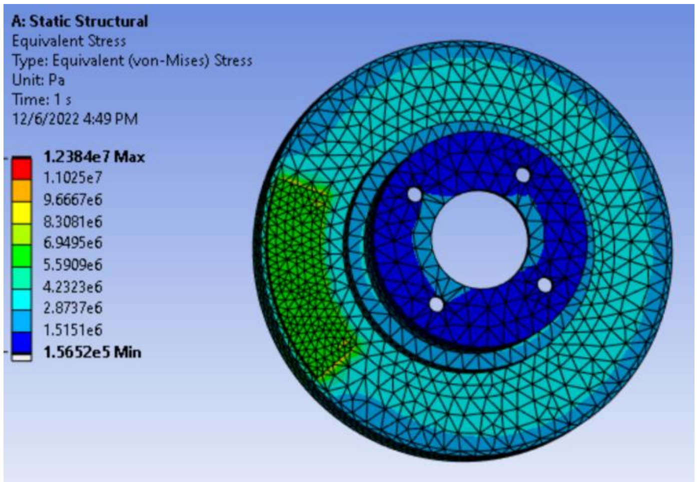


Fig 4: Equivalent Von Mises Stress before Optimization.

After the optimization of the geometry completed, the Maximum Equivalent Von Mises stress of the disc rotor reduced to 12.1 MPa.

Modal Frequency Analysis

Modal Analysis informs about the frequency modes of the brake disc which is important because we need to ensure that the frequency of the brake disc does not match the frequency of the engine. There can be issues of resonance if that's the case. For the modal analysis before optimizing the design, the results showed the lowest non-rigid body frequency of 1592.9 Hz.

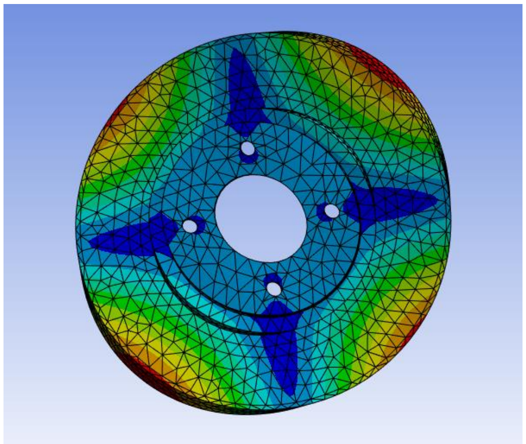


Fig 5: Modal Frequency (1592.9Hz) before Optimization

After the design optimization process ended, the frequency of the lowest mode increased to 1599.2 Hz which is a good compromise because it is still much higher than the frequency of engine and allowing a lower mode of frequency helps in reducing the volume of the disc brake.

Transient Thermal Analysis

Transient thermal response is important because brakes are under a huge thermal load, and so the temperature of the brakes can get high if not designed correctly. This can then lead to problems like brake fade or melting of brakes. Hence it is important to control the temperature of the brakes. In the simulation before the optimization, the maximum temperature reached on the brake disc is about 335.07 C. However, reducing the volume of the brakes lead to an increase in the temperature to 349.47 C. This temperature value if still acceptable because the melting temperature of the gray cast iron is around 1100 C, and even with factor of safety, it is around 500 C, and 349.47 C is significantly lower than that.

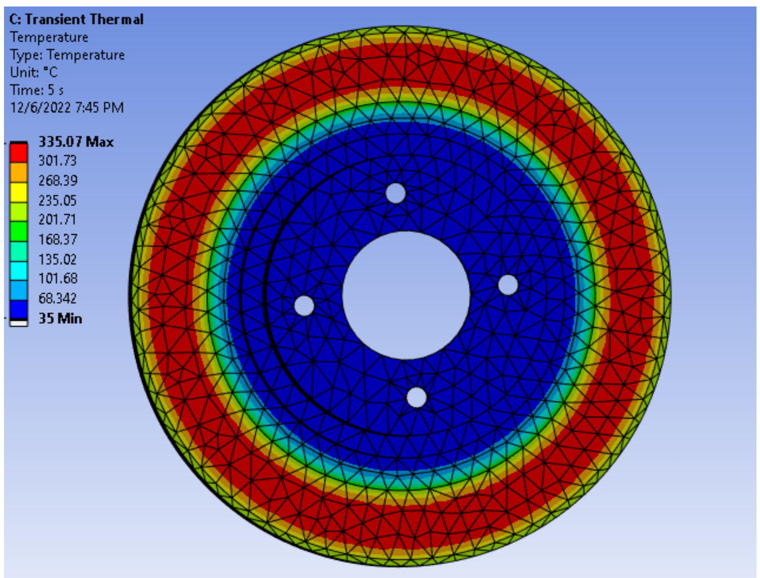


Fig 6: Temperature distribution before Optimization.

Table 1: Results of all the parameters

Parameters	Before Optimization	After Optimization
Equivalent Stress [MPa]	12.38	12.1
Lowest Mode Frequency [Hz]	1592.9	1599.2
Max. Temperature [C]	335.07	349.47
Volume [mm3]	967.91	894.94

Design of Experiments

In this setup, I have used Latin Hypercube Sampling Design method with User defined samples set to 180. The number of samples points was chosen to be 180 because it was the third run after trying 30 and 80 points with the current mesh. The reasoning behind requirement of this high number is that the mesh is a relatively refined mesh, and so whenever the geometry is altered, the mesh changes are drastic which could lead to some unwanted spikes which were causing diversion.

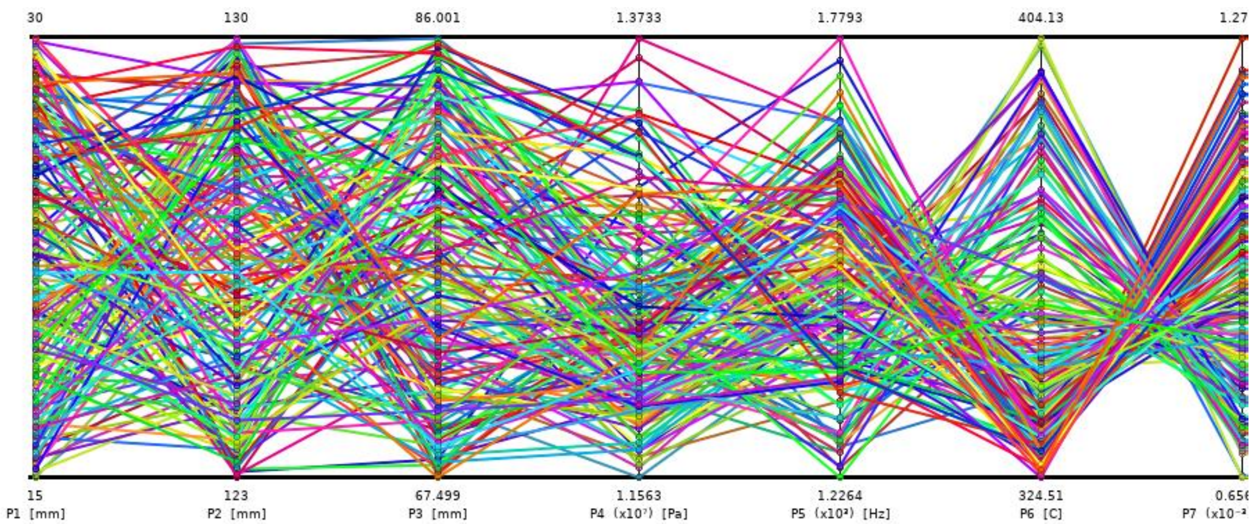


Fig 7: Parameters Parallel Chart.

Response Surface

The response surface used for the analysis was the Standard Response Surface-Full 2nd Order Polynomials.

	A	B	C	D	E	F	G
1		P4 - Equivalent Stress Maximum	P5 - Total Deformation 7 Reported Frequency	P6 - Temperature Maximum	P7 - Solid Volume	P8 - Solid Volume	P9 - Solid Volume
2	Coefficient of Determination (Best Value = 1)						
3	Learning Points	0.84542	0.99727	0.99991	1	1	1
4	Root Mean Square Error (Best Value = 0)						
5	Learning Points	1.8145E+05	6.2202	0.20891	7.3604E-08	7.3604E-08	7.3604E-08
6	Verification Points	2.2327E+05	11.606	0.37882	9.6128E-08	9.6128E-08	9.6128E-08
7	Relative Maximum Absolute Error (Best Value = 0%)						
8	Learning Points	220.67	12.883	2.2988	0.1938	0.1938	0.1938
9	Verification Points	160.52	31.32	6.4191	0.18066	0.18066	0.18066
10	Relative Average Absolute Error (Best Value = 0%)						
11	Learning Points	26.506	4.2281	0.7858	0.038618	0.038618	0.038618
12	Verification Points	33.4	6.6694	1.2145	0.051143	0.051143	0.051143

Fig 8: Goodness of Fit of Response Surface.

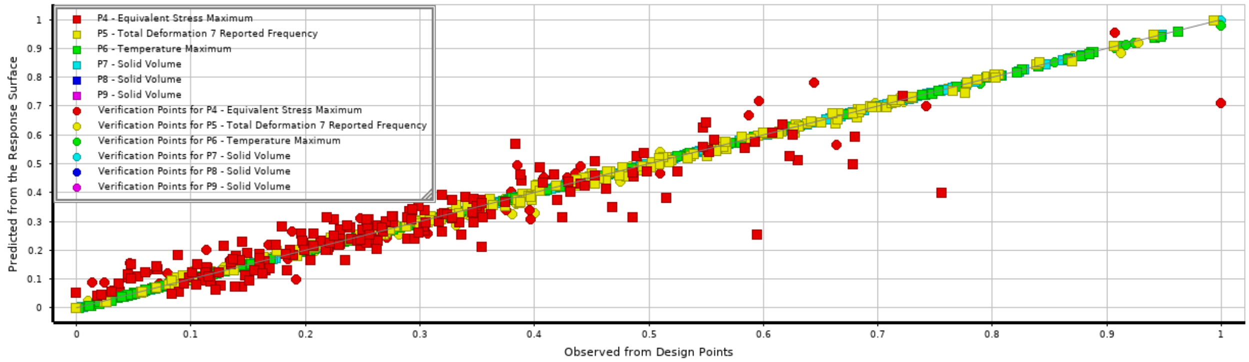


Fig 9: Goodness of Fit of the Design Points.

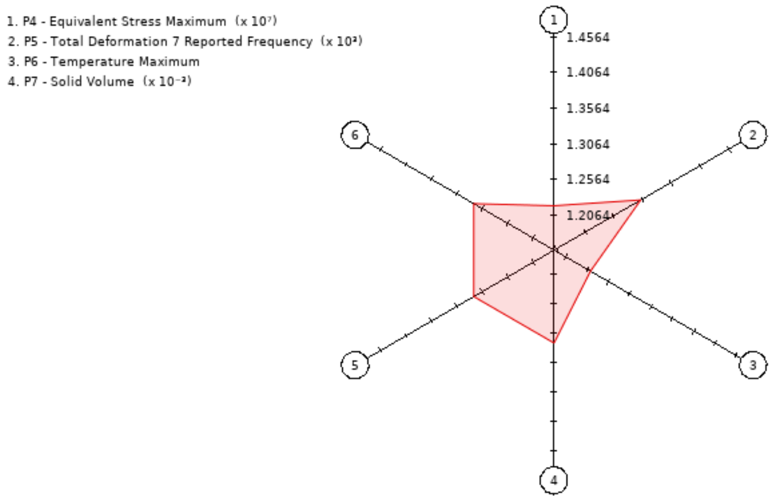


Fig 10: Spyder of Parameters on Response Point.

Optimization Method

The optimization method used for the analysis was Multiobjective Genetic Algorithm. This was chosen because the problem that is being analyzed has multiple objectives: Minimize the volume, stress, maximum temperature, and maximize the lowest non-rigid mode frequency.

The results converged after 8 iterations:

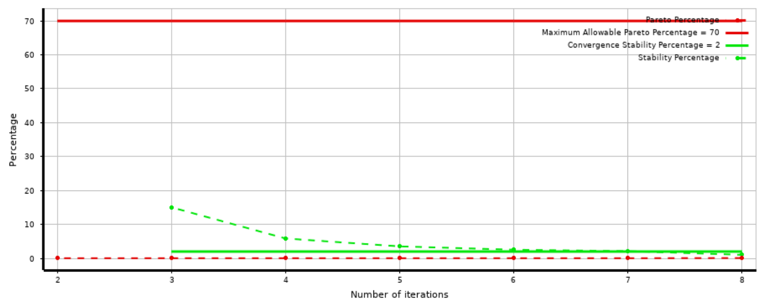


Fig 11: Convergence of the optimization results.

	A	B
1	Property	Value
2	Design Points	
3	Preserve Design Points After DX Run	☐
4	Failed Design Points Management	
5	Number of Retries	0
6	Optimization	
7	Method Selection	Manual
8	Method Name	MOGA
9	Estimated Number of Evaluations	93200
10	Tolerance Settings	☑
11	Verify Candidate Points	☑
12	Number of Initial Samples	5000
13	Number of Samples Per Iteration	1800
14	Maximum Allowable Pareto Percentage	70
15	Convergence Stability Percentage	2
16	Maximum Number of Iterations	50
17	Maximum Number of Candidates	3
18	Optimization Status	
19	Converged	Yes
20	Pareto Percentage	0.11111
21	Stability Percentage	1.044
22	Number of Iterations	8
23	Number of Evaluations	15922
24	Number of Failures	0
25	Size of Generated Sample Set	1800
26	Number of Candidates	3
27	Design Point Report	
28	Report Image	None

Fig 12: Optimization Setup

Name	Parameter	Objective			Constraint			
		Type	Target	Tolerance	Type	Lower Bound	Upper Bound	Tolerance
Minimize P4; P4 <= 1.5E+07 Pa	P4 - Equivalent Stress Maximum	Minimize	1.1E+07		Values <= Upper Bound		1.5E+07	0.001
Minimize P6; P6 <= 400 C	P6 - Temperature Maximum	Minimize	350		Values <= Upper Bound		400	0.001
Maximize P5	P5 - Total Deformation 7 Reported Frequency	Maximize	1600		No Constraint			
Minimize P7; P7 >= 0 m^3	P7 - Solid Volume	Minimize	0		Values >= Lower Bound	0		0.001

Fig 13: Objectives and Constraints of the Optimization problem

Candidate Points	Candidate Point 1	Candidate Point 1 (verified)	Candidate Point 2	Candidate Point 2 (verified)	Candidate Point 3	Candidate Point 3 (verified)
P1 - rotor_thickness (mm)	21.434		21.359		21.459	
P2 - rotor_OD (mm)	124.28		124.34		124.18	
P3 - rotor_ID (mm)	70.58		70.11		71.383	
P4 - Equivalent Stress Maximum (Pa)	★★ 1.2141E+07	★★ 1.201E+07	★★ 1.2138E+07	★★ 1.1892E+07	★★ 1.2144E+07	★★ 1.2109E+07
P5 - Total Deformation 7 Reported Frequency (Hz)	★★★ 1601.9	★★★ 1602	★★★ 1601.7	★★★ 1601	★★★ 1598.3	★★★ 1599.2
P6 - Temperature Maximum (C)	★★★ 349.24	★★★ 349.21	★★★ 349.5	★★★ 349.39	★★★ 349.37	★★★ 349.47
P7 - Solid Volume (m^3)	★ 0.00090089	★ 0.00090097	★ 0.00090221	★ 0.00090227	★ 0.00089494	★ 0.00089504

Fig 14: Optimization Results

Sensitivity Analyses

Sensitivity Analyses helps in understanding how the value of the objectives is affected when the geometric design parameters are slightly changed. It can be seen that increasing the rotor thickness increases stress because the disc brake is able to with stand more load with increasing thickness. Similarly, increase in thickness results in higher frequency because the brake as a whole becomes stiffer and thus vibrates at a high frequency. Similarly other results can be co-related by looking at the sensitivity analyses chart. This helps in changing the the design parameters of the geometry for future use.

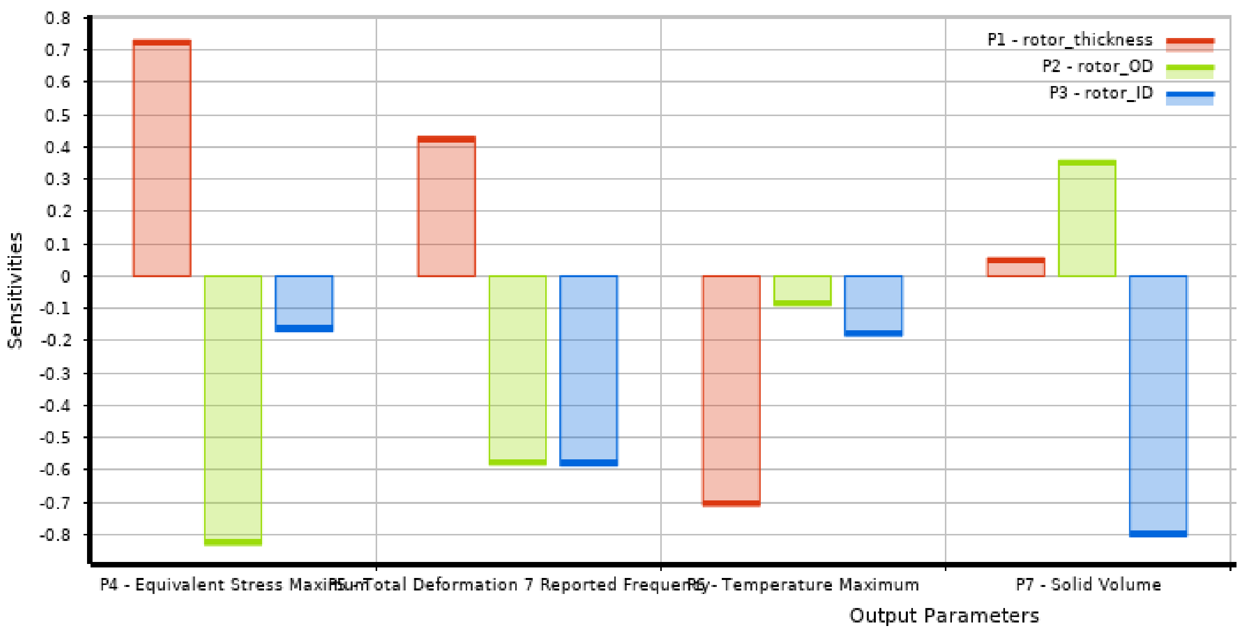


Fig 15: Sensitivity Analysis.