

MAE 598 - Design Optimization
Project 2 - disc design optimization using Ansys Design of
Experiment and Design Optimization Tutorial

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Abstract:

This project conducts structural optimization of the brake disc using ANSYS software. The input variables are disc inner radius, disc outer radius and disc thickness. The main goal of the project is to minimize the volume of the disc, minimize the maximum von-mises stress, minimize the temperature and maximize the first natural frequency of the disc. These will be accomplished by using the optimization algorithms and design of experiments function in the ANSYS.

Introduction:

There are three main aspects that need to be optimized in the design. They are stress analysis, modal analysis and thermal analysis respectively.

Structural Analysis: The brake disc has to sustain the pressure from the hydraulically actuated brake pads during sudden braking conditions. Stresses are induced due to friction between the brake pads and the disc. The disc also experiences centrifugal body forces due to its rotation. Resultant stresses generated due these forces can lead to material failure. Therefore, it is of prime importance to make sure that the stresses in the disc are minimized.

- Modal Analysis: Free modal analysis is performed to ensure that the disc's first natural frequency is higher than the engine firing frequency. This guarantees that the disc does not experience failure due to resonance.

- Thermal Analysis: Braking in a vehicle takes place due to friction between the brake pads and the rotor disc. This leads to heat flux generation in the disc which consequently results in increase in its temperature and thermal stresses. Emergency braking conditions induce high temperatures that damage the contact surfaces. It is therefore essential to minimize the temperature to prevent disc wear and tear.

Problem description and general steps

The disc for optimization was shown in figure 1. It has one pad on each side of the disc. The dimension of the disc is shown in the figure 2, in which inner radius, outer radius and thickness are selected as input parameters. In the design of the experiments, the dimension of these three parameters are changed to find the optimal design. The material for the pad is structural steel and the material for disc is gray cast iron.

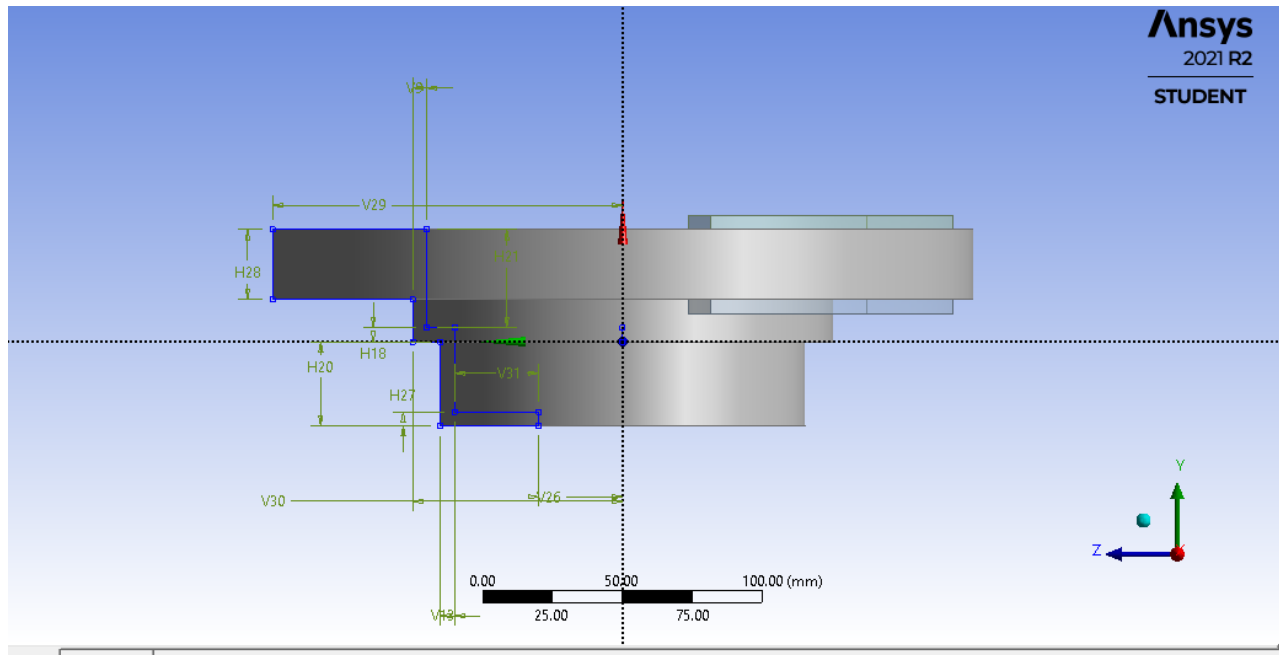


Fig. 1 - Geometry of the model.

Details View	
Details of Sketch1	
Sketch	Sketch1
Sketch Visibility	Show Sketch
Show Constraints?	No
Dimensions: 11	
<input type="checkbox"/> H18	5 mm
<input type="checkbox"/> H20	30 mm
<input type="checkbox"/> H21	35 mm
<input type="checkbox"/> H27	5 mm
<input checked="" type="checkbox"/> H28	25 mm
<input type="checkbox"/> V13	5 mm
<input type="checkbox"/> V26	30 mm
<input checked="" type="checkbox"/> V29	125 mm
<input checked="" type="checkbox"/> V30	75 mm
<input type="checkbox"/> V31	30 mm
<input type="checkbox"/> V9	5 mm

Fig. 2 - Dimensions of model. H28 is thickness, V29 is outer radius, V30 is inner radius. The geometry and the material has been set up, and the three modules are shown below.

Static Analysis:

Mesh is shown in figure 3. The method for mesh is patch conforming method. The mesh for the inner surface of the pads are refined to conform the higher stress at these surfaces.

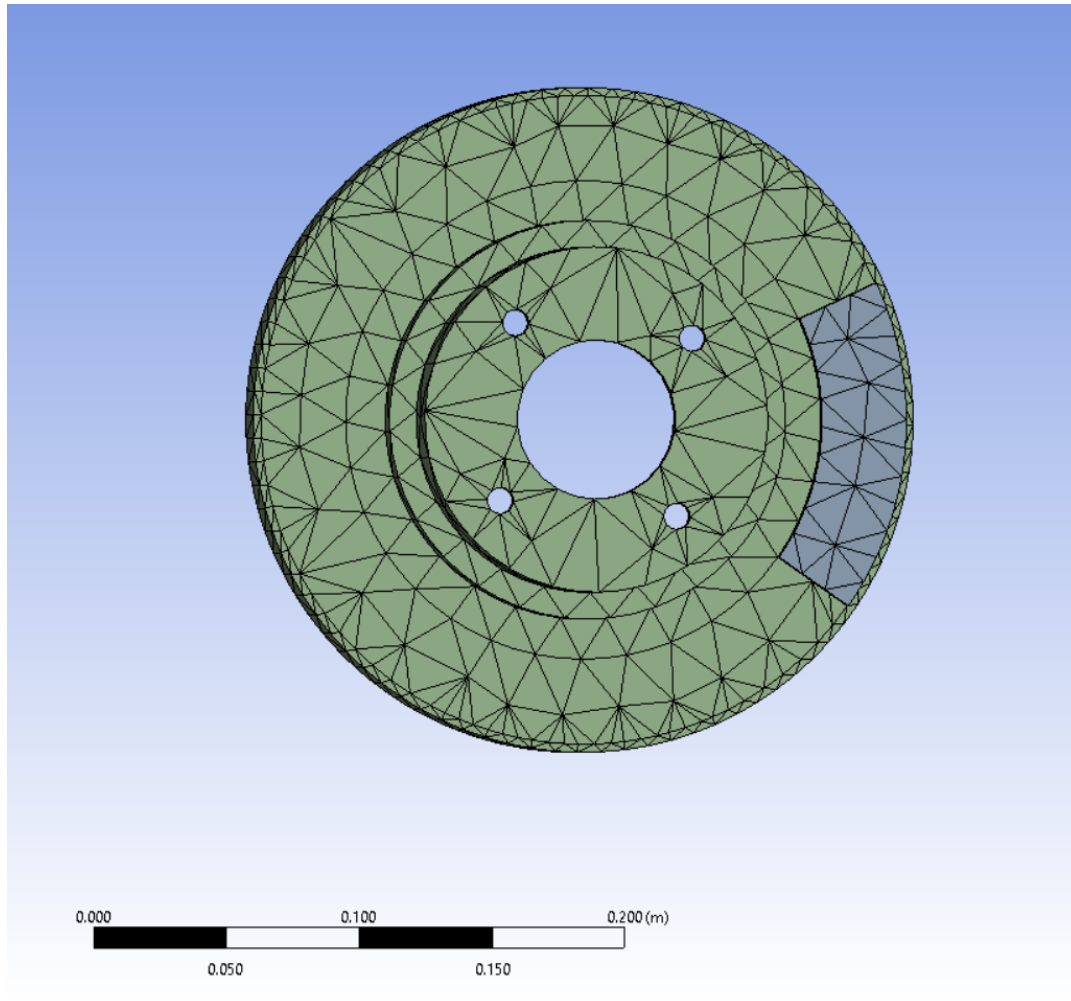


Fig.3 Mesh

There is a contact region between the disc and the pad. The setup is shown in figure 4.

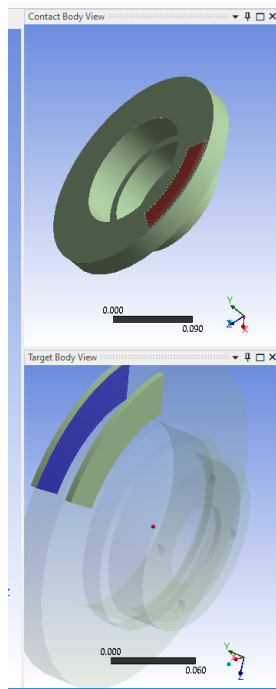


Fig. 4 - Frictional Contact definition

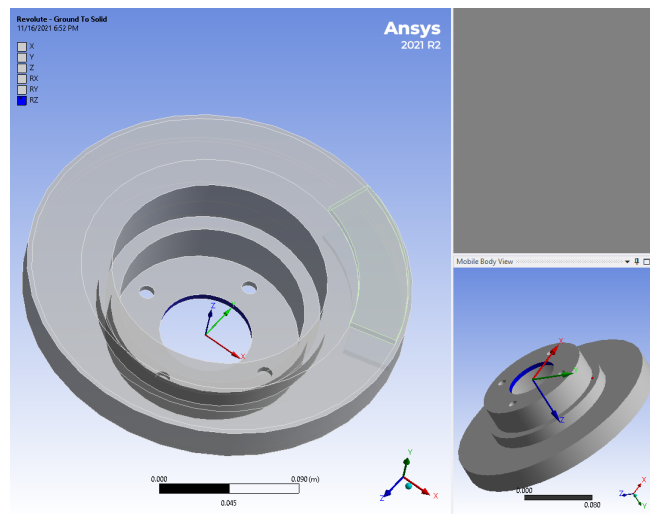


Fig. 5 - Rotational Joint

The rotational joint is used to indicate that the disc can only rotate on a fixed y axis. Next, we define the boundary condition of the problem. The rotational velocity around y axis, with magnitude of 250 rad/s.

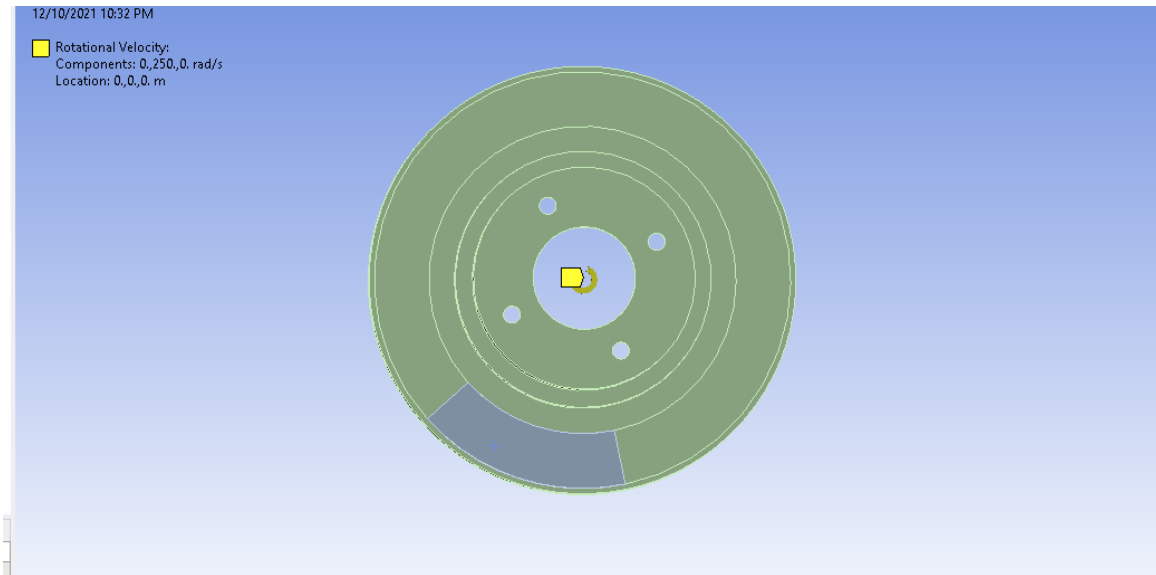


Fig. 6 - Rotational Constraint.

The pressure is applied to the outer surface of the pad.

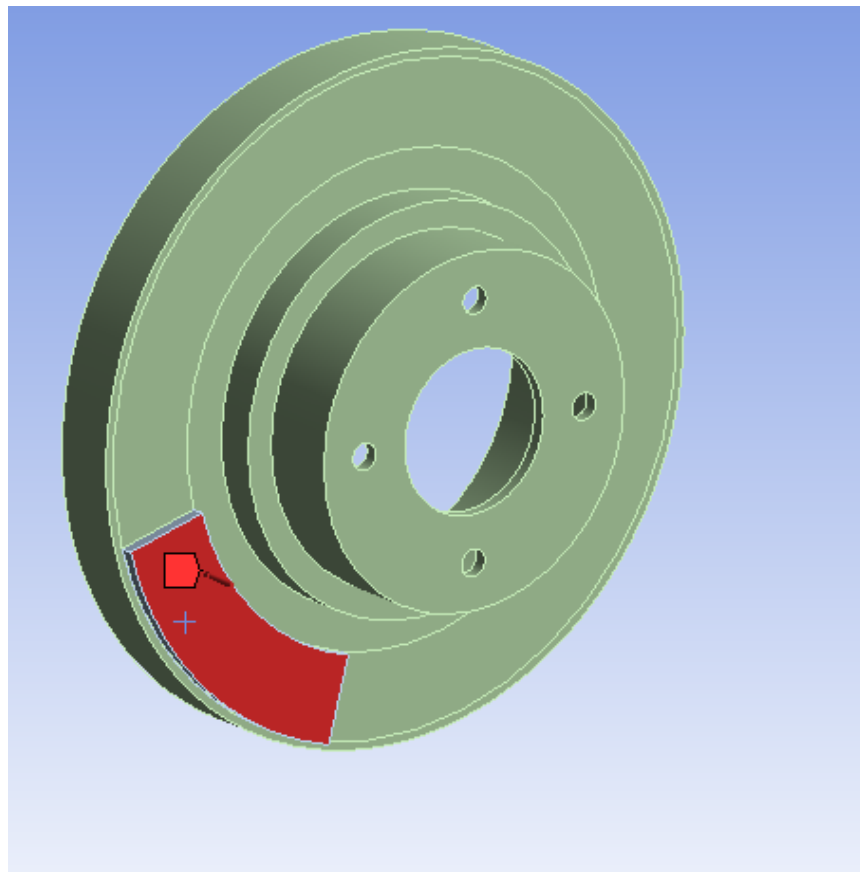


Fig. 7 - Pressure applied by brake pad.

The result of stress analysis is shown below. Von-Mises equivalent stresses are shown. The maximum stress before optimizing the system is 1.325e7 Pascals.

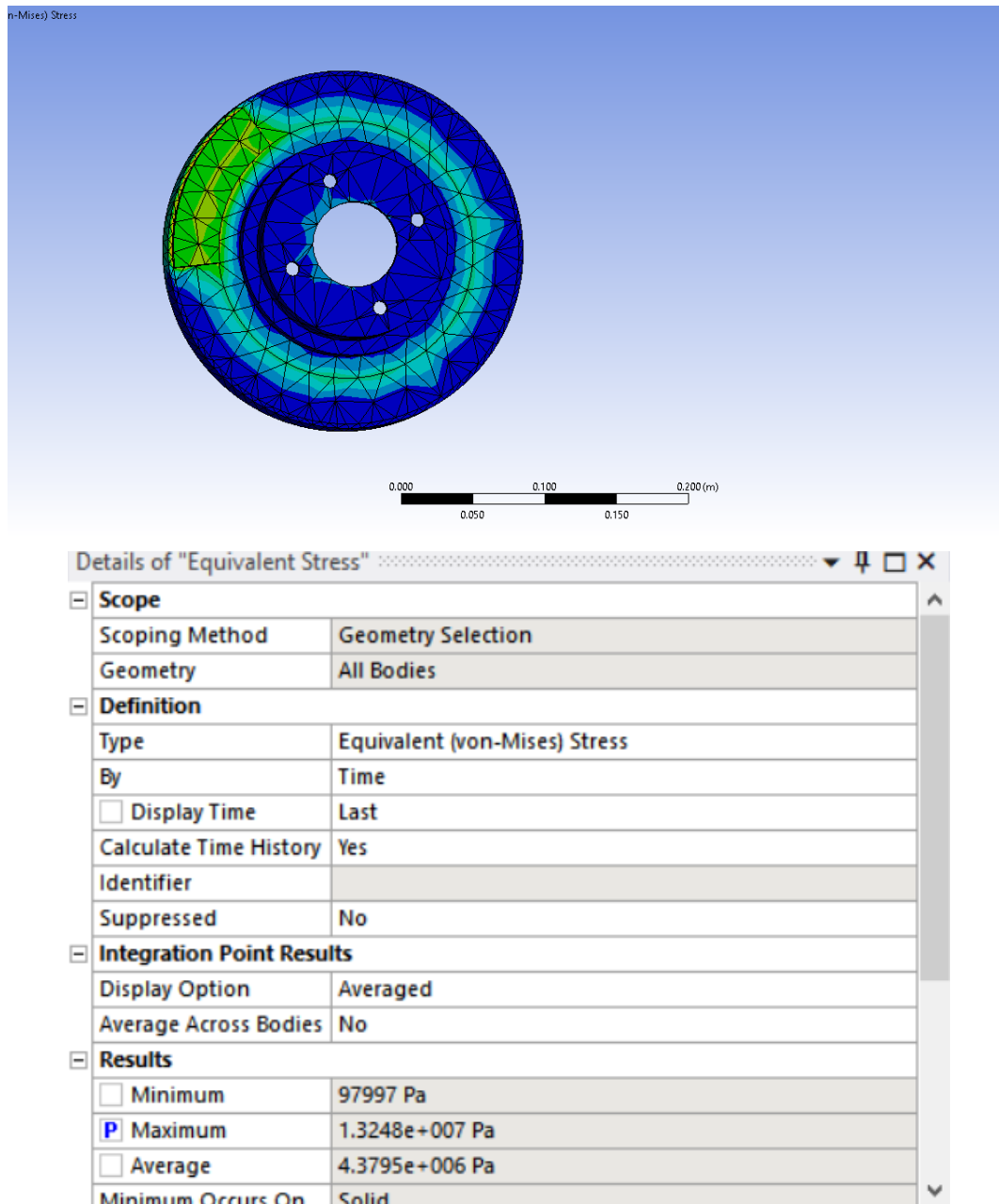


Fig. 8 - Stress contour plot of Brake and maximum stress

Modal Analysis:

The results of modal analysis are shown in the figure 9, 10, 11

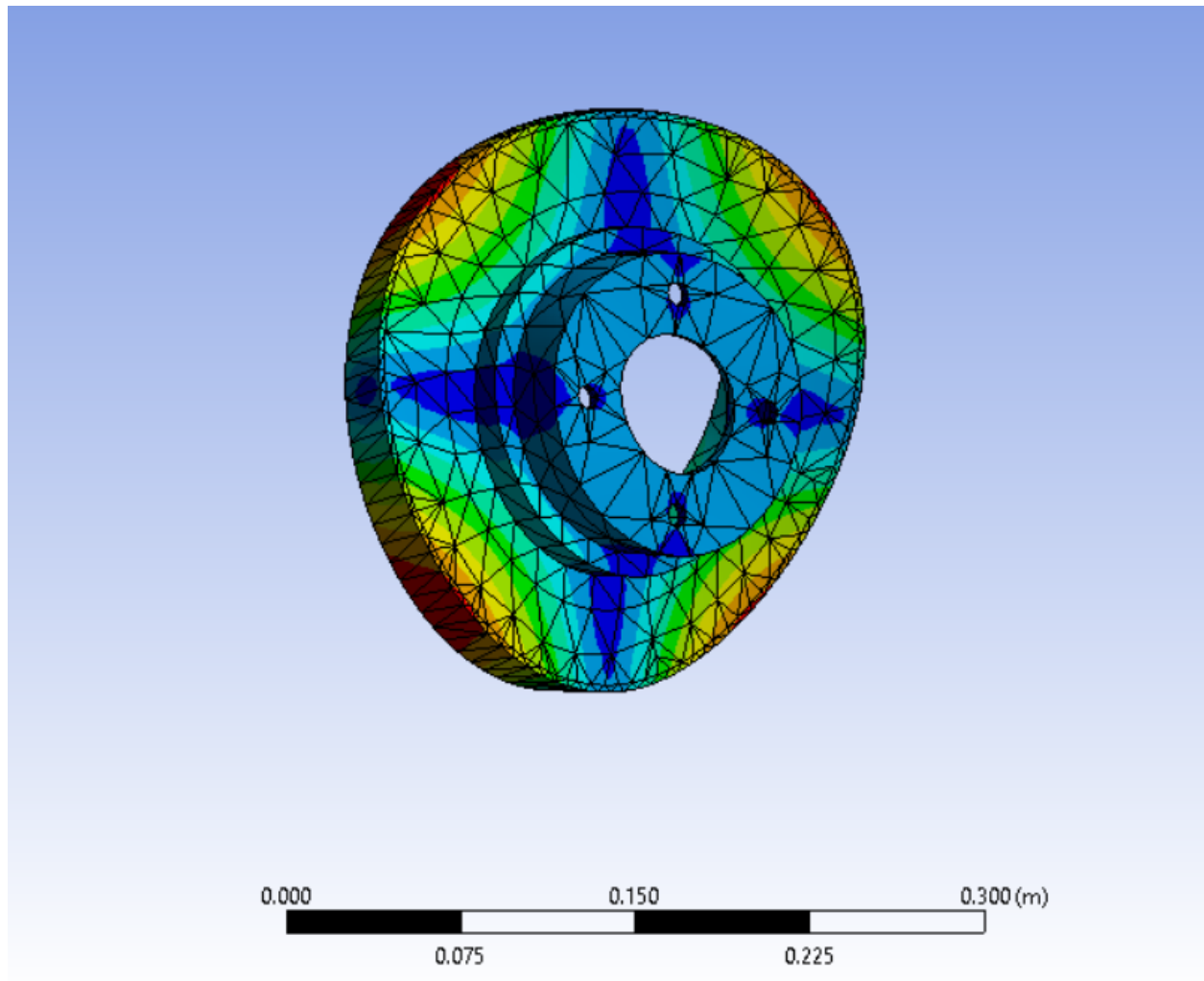


Fig. 9 - Seventh Vibrational mode deformation.

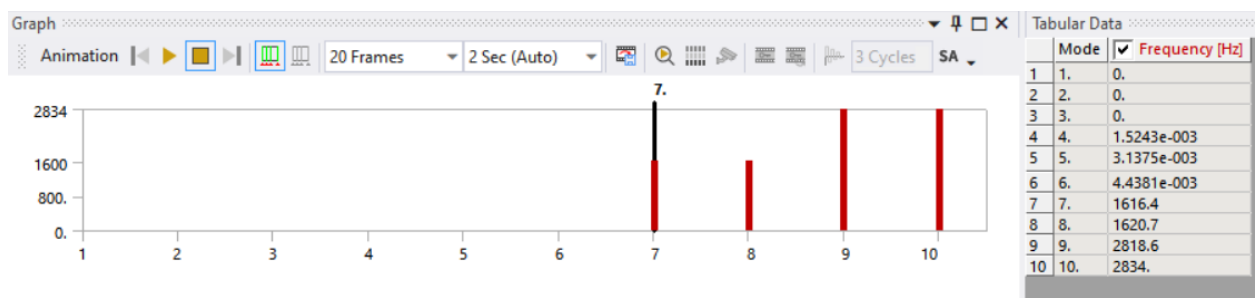


Figure 10 - Vibrational mode values.

Details of "Total Deformation"	
Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Total Deformation
Mode	7.
Identifier	
Suppressed	No
Results	
<input type="checkbox"/> Minimum	3.3091e-003 m
<input type="checkbox"/> Maximum	0.80656 m
<input type="checkbox"/> Average	0.34267 m
Minimum Occurs On	Solid
Maximum Occurs On	Solid
Information	
P Frequency	1616.4 Hz

Figure 11 - Vibrational frequency.

The frequency for disc deformation is 1616.4HZ.

Thermal Analysis:

The setup is the same in the tutorial. The maximum temperature is 341.03 in the setup case.

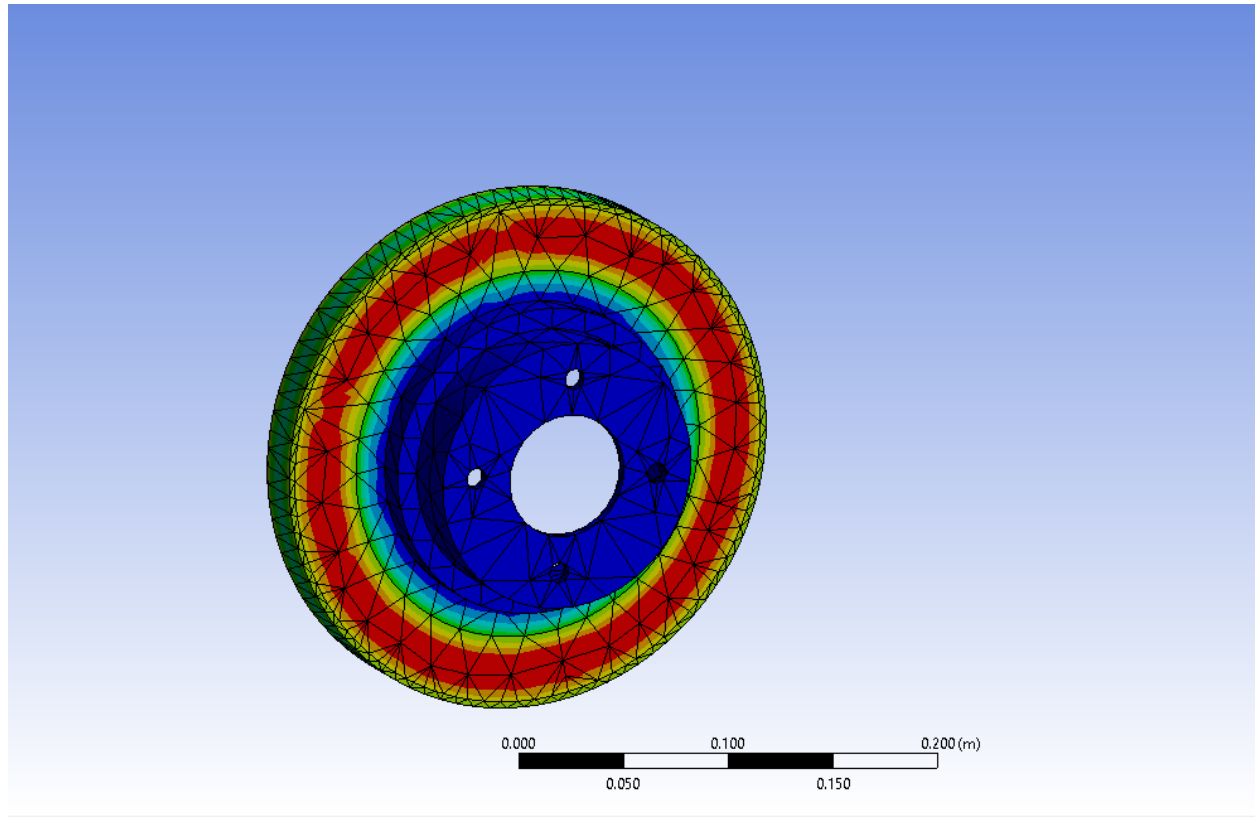


Fig. 12 - Temperature contour plot.

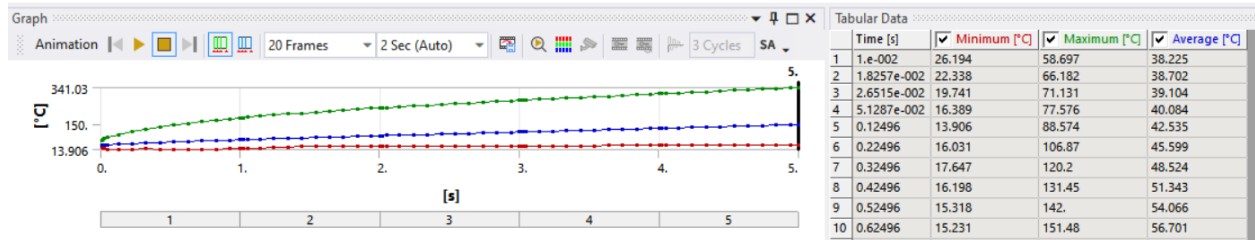


Fig. 13 - Temperature chart.

Design of Experiment:

The Latin Hypercube Sampling Design method is chosen for DOE. The sample type is user-defined samples. The range of the parameter considered in the project is shown in the table 1 below. The disc outer diameter is selected to be larger than the outer diameter of the pad. 15 experimental points are chosen in this analysis. Results of DOE are shown in table 2.

	Disc Thickness (mm)	Disc Outer Diameter (mm)	Disc Inner Diameter (mm)
Lower Bound	22.5	125	67.5
Higher Bound	27.5	137.5	82.5

Table 1 - Lower and Higher Bounds for input parameters

Table of Schematic H2: Design of Experiments (Latin Hypercube Sampling Design : User-Defined Samples : Random Generator Seed = 0 : Number of Samples = 15)							
	A	B	C	D	E	F	G
1	Name	P1 - rotor_thickness (mm)	P2 - rotor_OD (mm)	P3 - rotor_ID (mm)	P4 - Equivalent Stress Maximum (Pa)	P5 - Temperature Maximum (C)	P6 - Total Deformation Reported Frequency (Hz)
2	1 DP 2	25.333	134.58	76	1.1601E+07	340.41	1456
3	2 DP 2	26.333	131.25	77	1.1906E+07	341.93	1504.6
4	3 DP 1	22.667	132.08	70	1.1269E+07	347.85	1491.5
5	4 DP 2	26	125.42	81	1.3379E+07	339.93	1497.7
6	5 DP 1	23	127.08	71	1.1504E+07	346.72	1592.6
7	6 DP 3	27.333	126.25	69	1.1682E+07	335.41	1710.6
8	7 DP 2	25.667	136.25	80	1.1583E+07	339.69	1383.8
9	8 DP 2	27	133.75	79	1.1743E+07	339.66	1449.3
10	9 DP 2	24	127.92	75	1.1533E+07	345.4	1561.6
11	10 DP 1	23.667	132.92	82	1.1749E+07	347.35	1363.9
12	11 DP 2	24.667	129.58	73	1.1738E+07	345.18	1564.8
13	12 DP 1	23.333	135.42	72	1.1708E+07	345.65	1425.2
14	13 DP 2	25	130.42	74	1.1513E+07	343.76	1542.1
15	14 DP 2	26.667	137.08	68	1.178E+07	337.13	1456
16	15 DP 2	24.333	128.75	78	1.1547E+07	344.64	1505.5

Table 2 - DOE Sample and Solutions

The parameters parallel chart is shown below. The input and output parameters are shown in the x axis, and the y axis shows the relative magnitude among different experiment points. A closer and more detailed look at the output value are shown in 15, 16, 17, 18, where the volume, equivalent stress, deformation frequency, maximum temperature are plotted with respect to the design points.

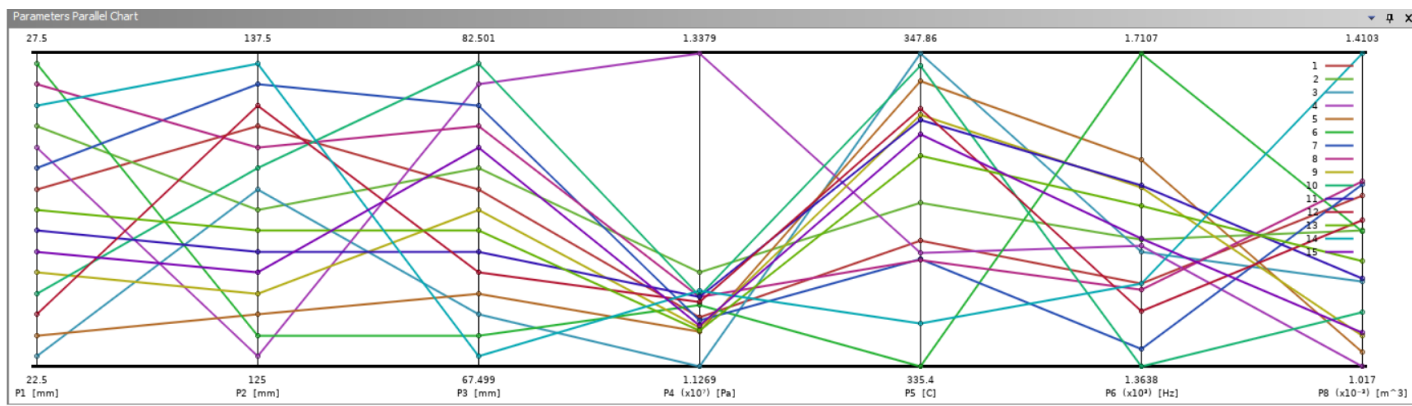


Figure 14 - Parameters Parallel Chart.

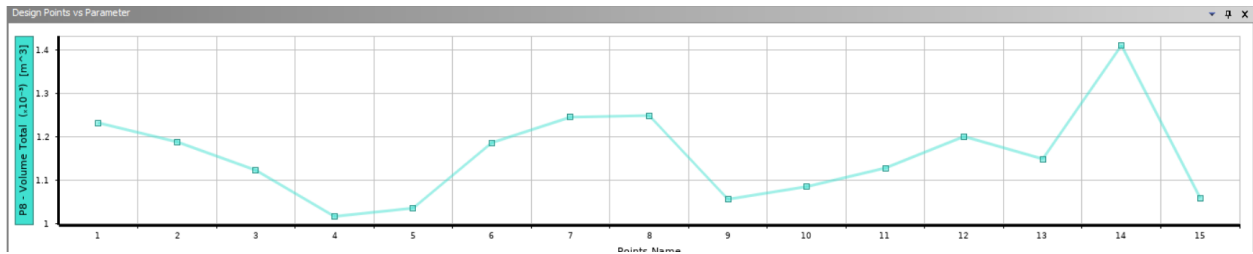


Figure 16 - Design Points vs. Volume

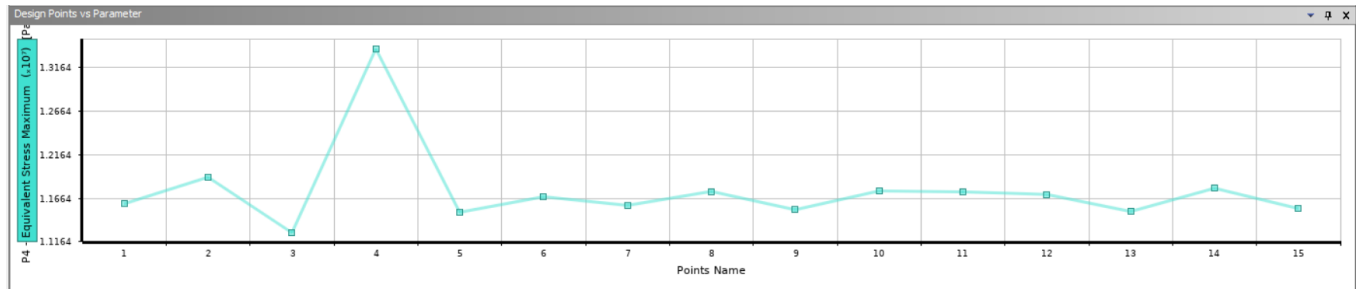


Figure 16 - Design Points vs. Equivalent Stress

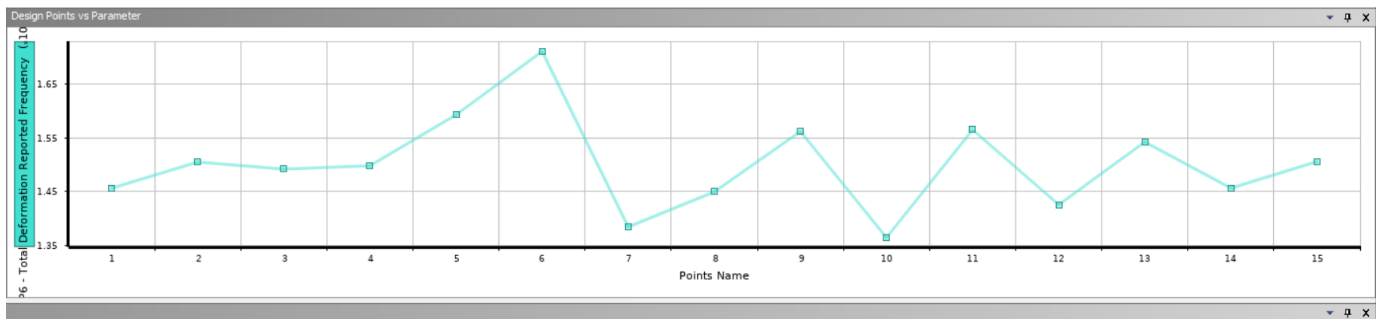


Figure 17 - Design points vs. Deformation Frequency.

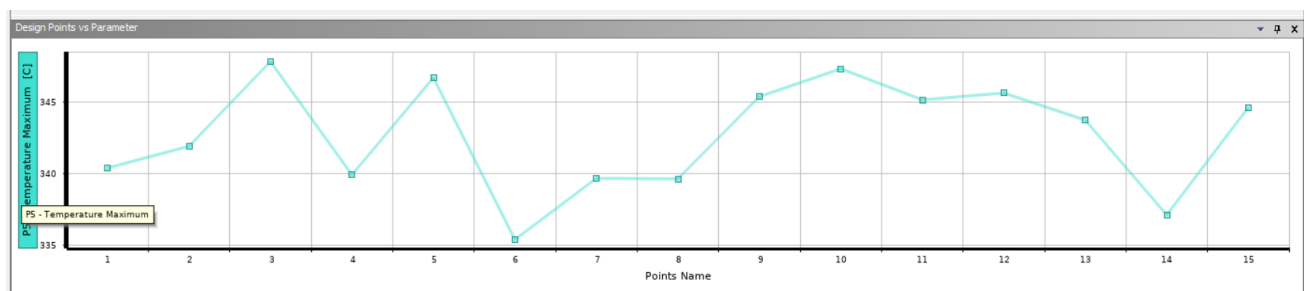


Figure 18 - Design Points vs. Maximum Temperature.

From figures above, based on the optimization criteria set before, 6th points is the best points among them, where it has the smallest stress, maximum frequency and lowest temperature. The values are 1.1504×10^7 pa, 346.72C, 1592.6Hz and 0.00104 m^3 .

Response Surface:

In this project, Kriging is chosen for the response surface. Verification points are 4 points.

A goodness of fit plot is shown below. The circle dot is the training point and the square dot is the verification point. The plot indicates that the model fits very well with the training data(which is the nature of the Kriging method. But the model does not fit the verification data very well. This can be shown in Figures 19 and 20.

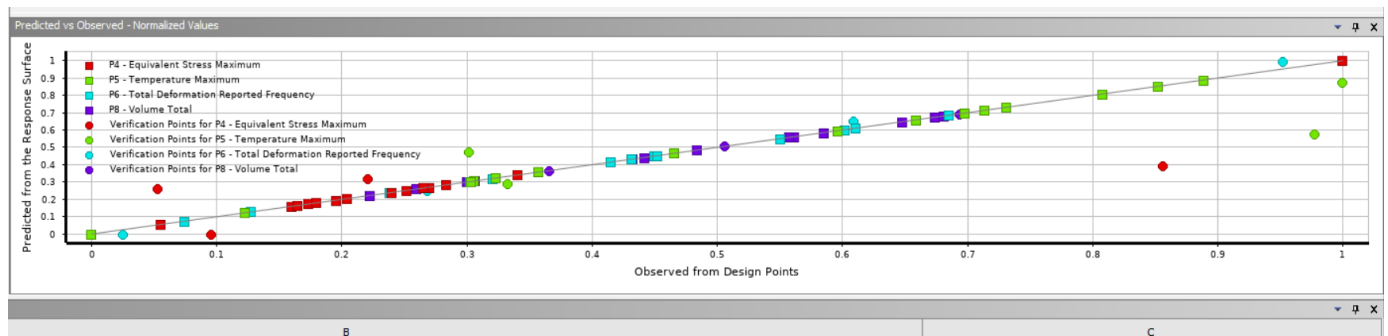


Figure 19 Goodness of fit

Table of Schematic H3: Response Surface					
	A	B	C	D	E
1		P4 - Equivalent Stress Maximum	P5 - Temperature Maximum	P6 - Total Deformation Reported Frequency	P8 - Volume Total
2	Coefficient of Determination (Best Value = 1)				
3	Learning Points	☆☆ 1	☆☆ 1	☆☆ 1	☆☆ 1
4	Root Mean Square Error (Best Value = 0)				
5	Learning Points	0.0047951	2.1981E-08	1.2133E-07	8.1092E-16
6	Verification Points	5.8893E+05	3.1915	12.418	2.4339E-07
7	Relative Maximum Absolute Error (Best Value = 0%)				
8	Learning Points	☆☆ 0	☆☆ 0	☆☆ 0	☆☆ 0
9	Verification Points	✖✖ 191.22	✖✖ 136.19	✖✖ 16.268	☆☆ 0.36264
10	Relative Average Absolute Error (Best Value = 0%)				
11	Learning Points	☆☆ 0	☆☆ 0	☆☆ 0	☆☆ 0
12	Verification Points	✖✖ 89.344	✖✖ 62.739	✖ 11.882	☆☆ 0.17284

Figure 20 response surface

The sensitivity of three input variables with respect to four output is shown below.

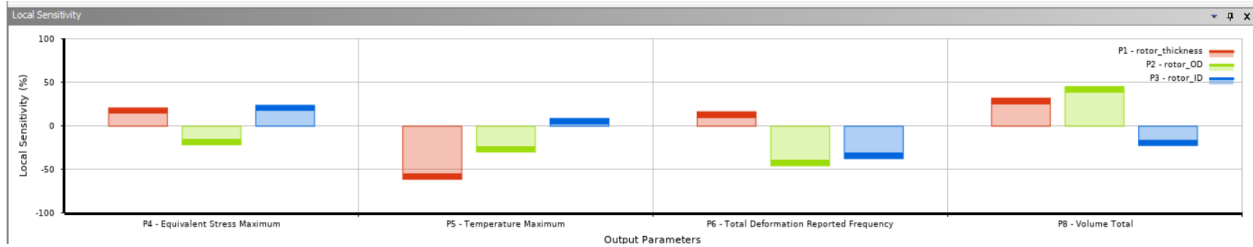


Figure 21. Sensitivity analysis

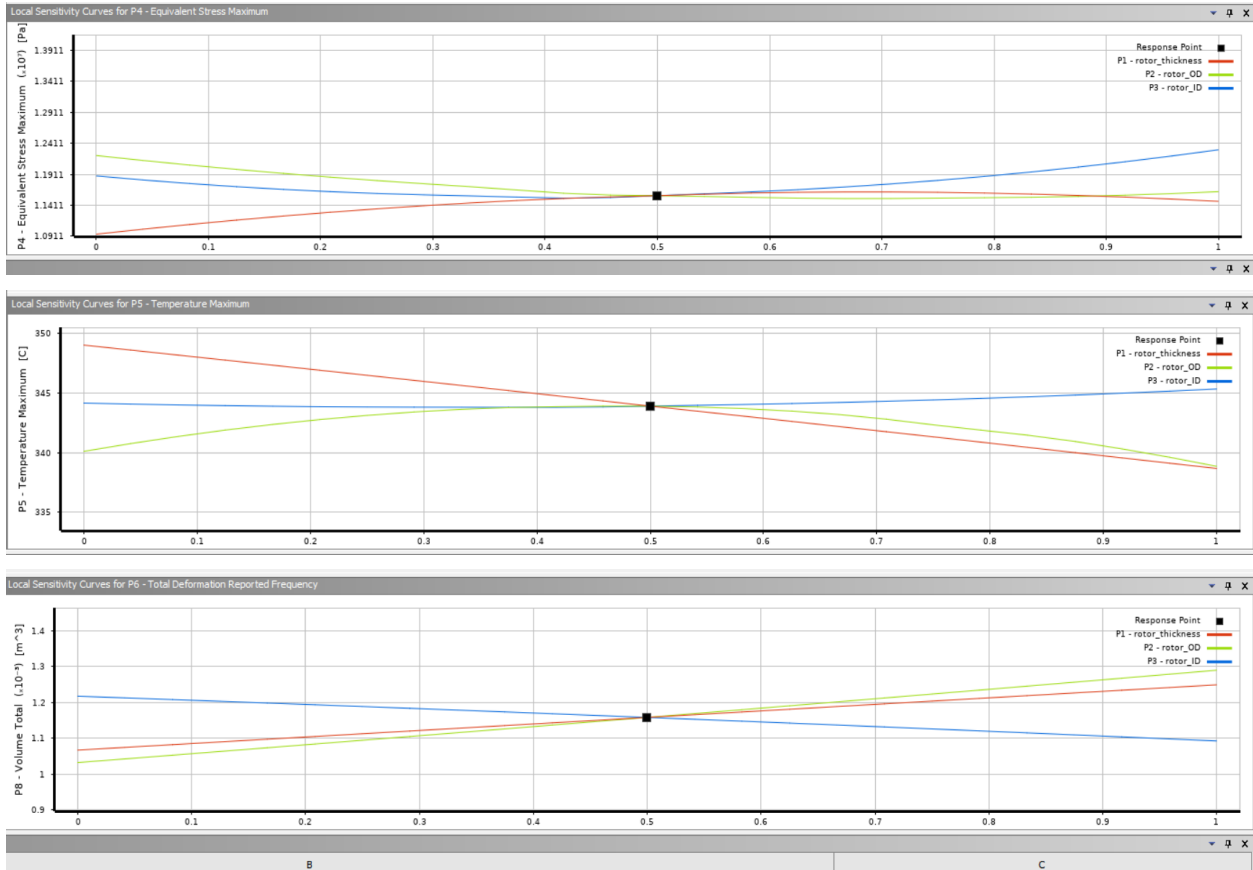


Figure 22. Local sensitivity curves, (a) Equivalent Stress (b) Temperature (c) Volume

Optimization:

We want to minimize the equivalent stress, minimize the temperature and maximize the frequency. The optimization method chosen is MOGA.

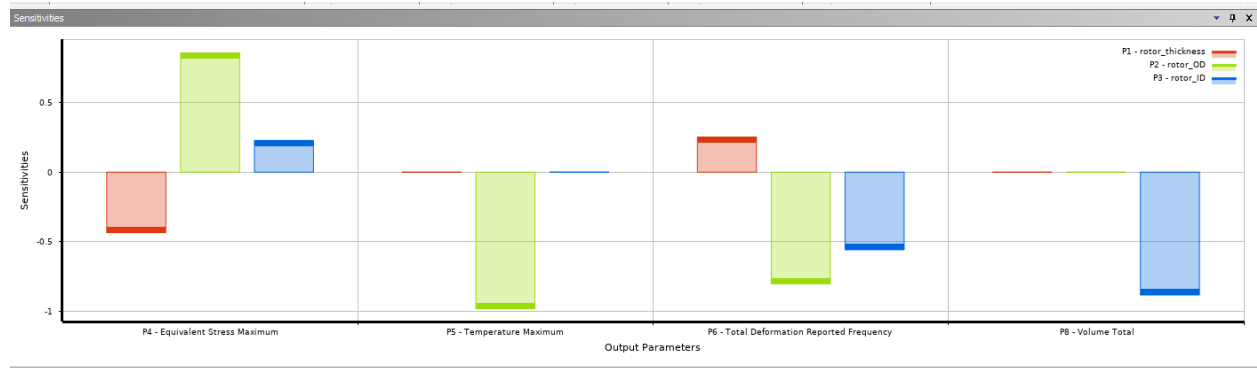


Figure 23. Sensitivity

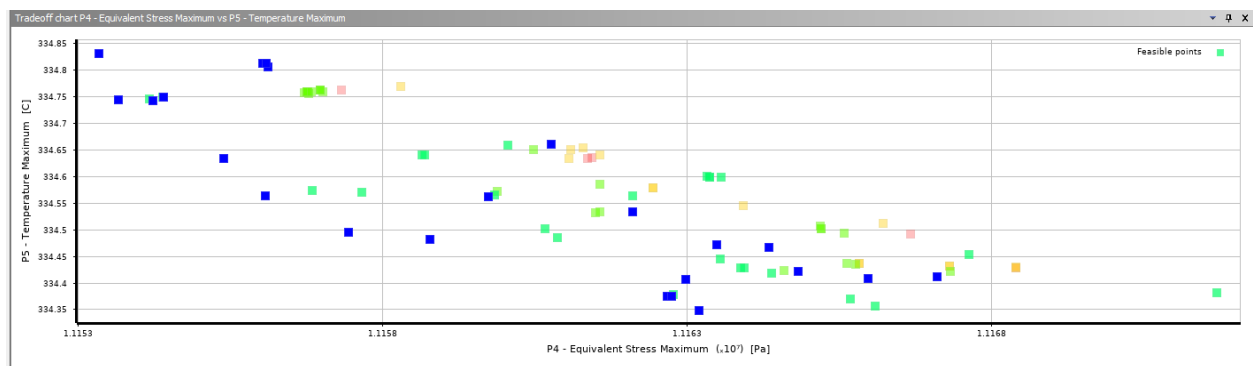


Figure 24. Equivalent Stress Maximum vs Temperature Maximum