MAE 598:
Design Optimization

Project -02

Dr. Max Yi Ren

Name: Gaurav Lavadiya

ASU ID: 1222768924

ABSTRACT

The purpose of the project is to determine the optimum dimensions of the brake disc for a four-wheeler vehicle using ANSYS. These dimensions include the disc inner radius, outer radius and thickness. Structural, modal and thermal load cases for emergency braking conditions are individually considered to determine these dimensions. The optimization objective is to minimize the brake disc volume, whereas the other objectives are to minimize the stress, temperature and maximize the first natural frequency of the disc. These goals are accomplished using response surface optimization in Ansys.

Objective:

- minimize the brake disc volume for emergency braking conditions.
- Minimize the maximum stress in the brake disc.
- Maximize the first natural frequency of the brake disc.
- Minimize the maximum temperature in the brake disc.

Structural Analysis Model:

The brake disc must 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 to these forces can lead to material failure. Therefore, it is of prime importance to make sure that the stresses in the disc are minimized.

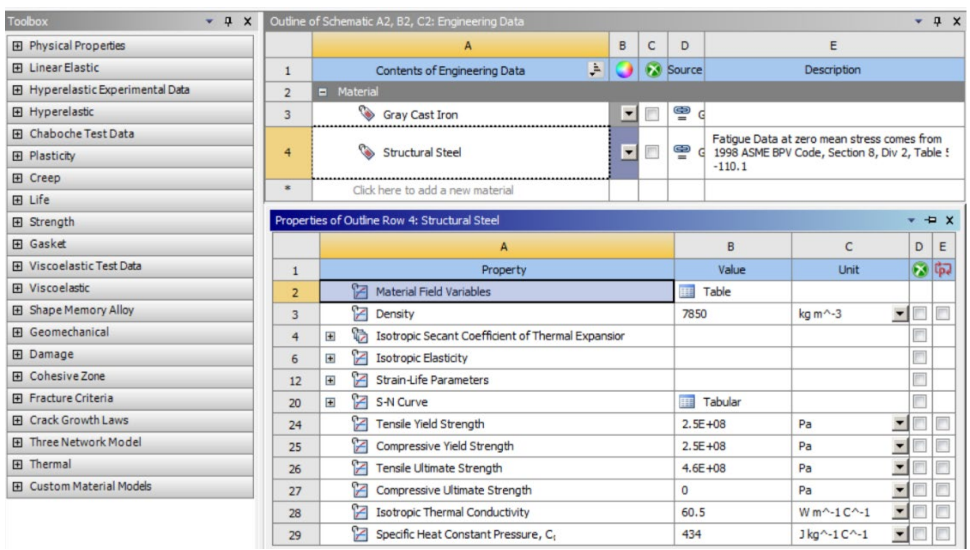

Figure 1 engineering Data

Structural steel and gray cast iron is taken as a material for brake pads and brake disk respectively.

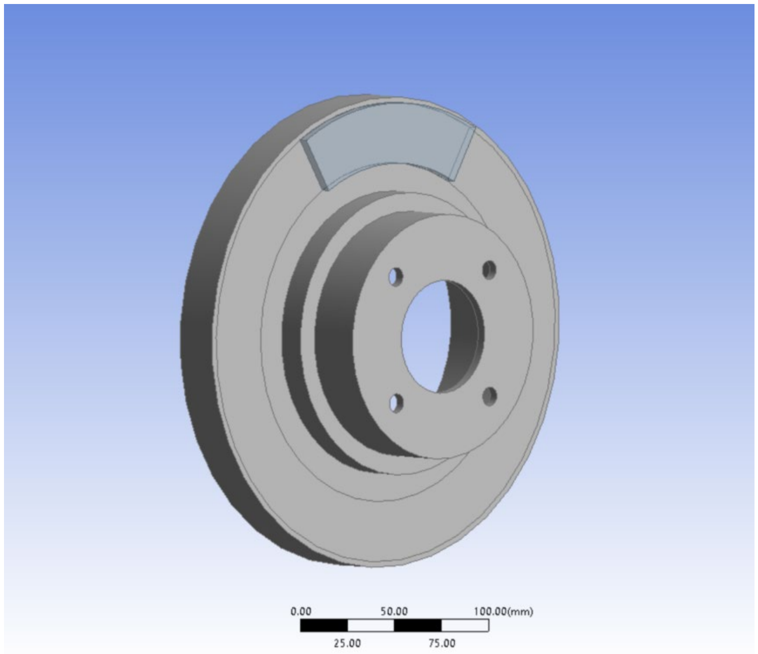

Figure 2 brake geometry

Setup:

Mesh:

A tetrahedron type of mesh has been used for the all the brake bodies. Inner faces of the brake pads and set element size of 3mm because it's the area where generated stress will be highest.

Details of "Patch Conforming Method" - M

Scope	
Scoping Method	Geometry Selection
Geometry	3 Bodies
Definition	
Suppressed	No
Method	Tetrahedrons
Algorithm	Patch Conforming
Element Order	Use Global Setting

Details of "Face Sizing" - Sizing

Scope	
Scoping Method	Geometry Selection
Geometry	2 Faces
Definition	
Suppressed	No
Type	Element Size
Element Size	3.e-003 m
Advanced	
Defeature Size	Default
Influence Volume	No
Behavior	Soft

Figure 3 Mesh setting

Assign Material:

The brake pad is set to structural steel and brake disk is set to gray cast iron.

Boundary conditions:

- Rotational velocity for all bodies is set to 250 rad/s in y-direction.

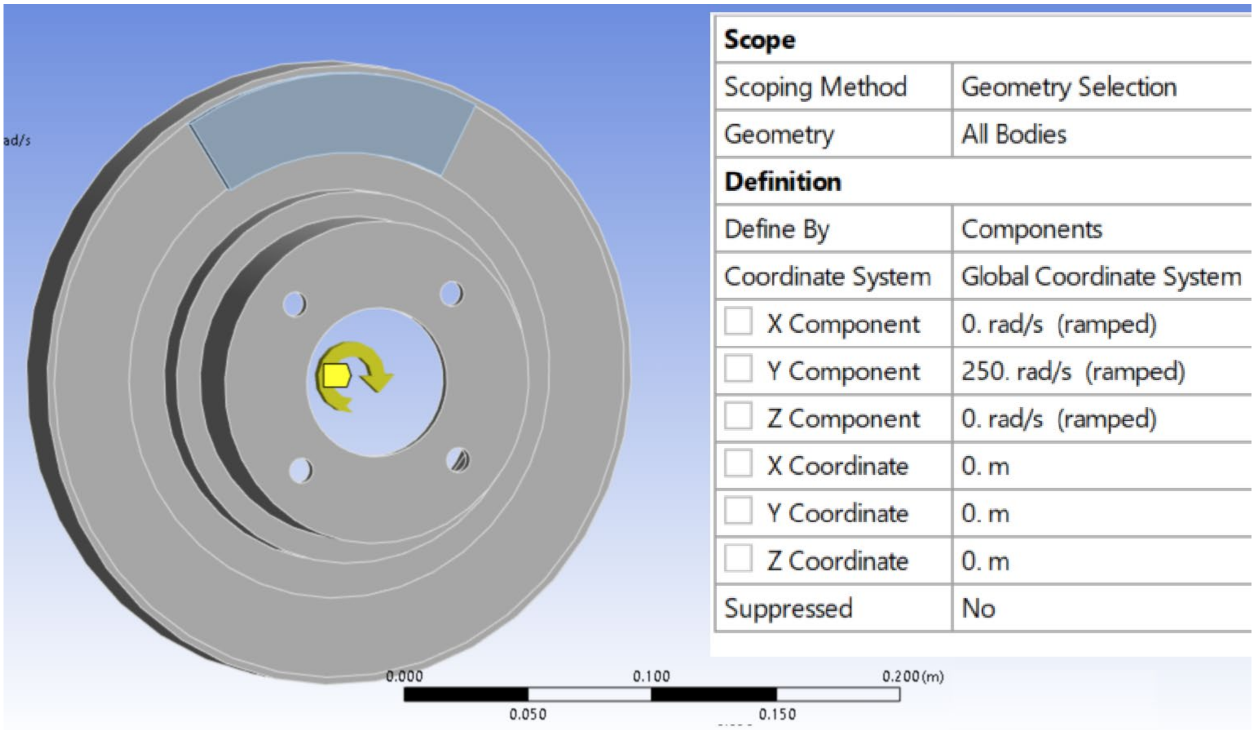

Figure 4 rotational velocity

- add pressure to both outer brake pad surfaces.

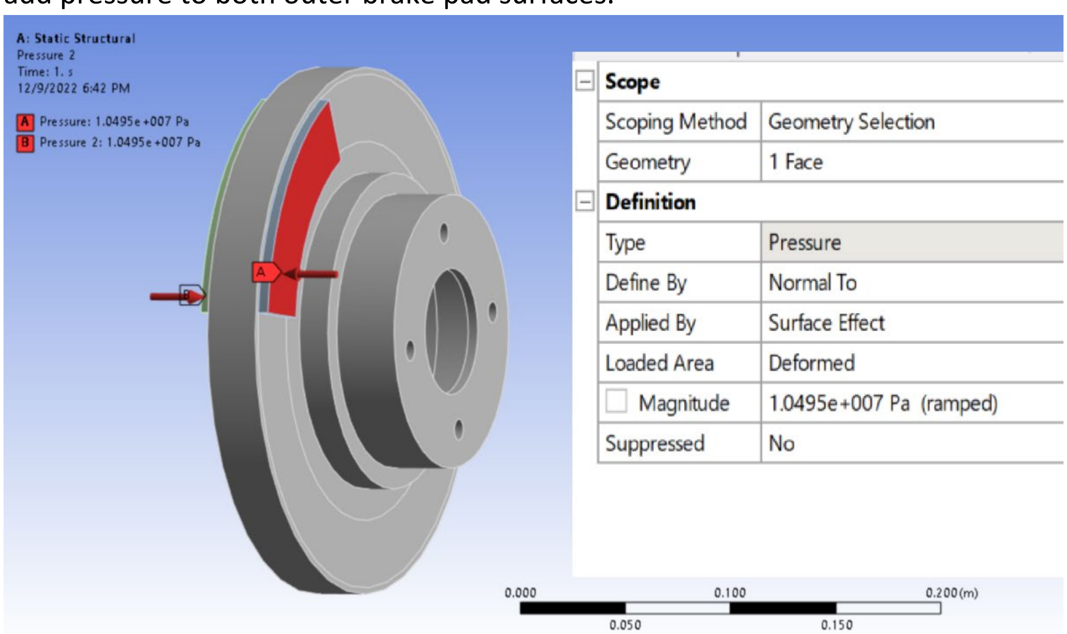

Figure 5 pressure to outer brake pad faces

- Set displacement of the brake pads to zero on x-direction and z -direction.

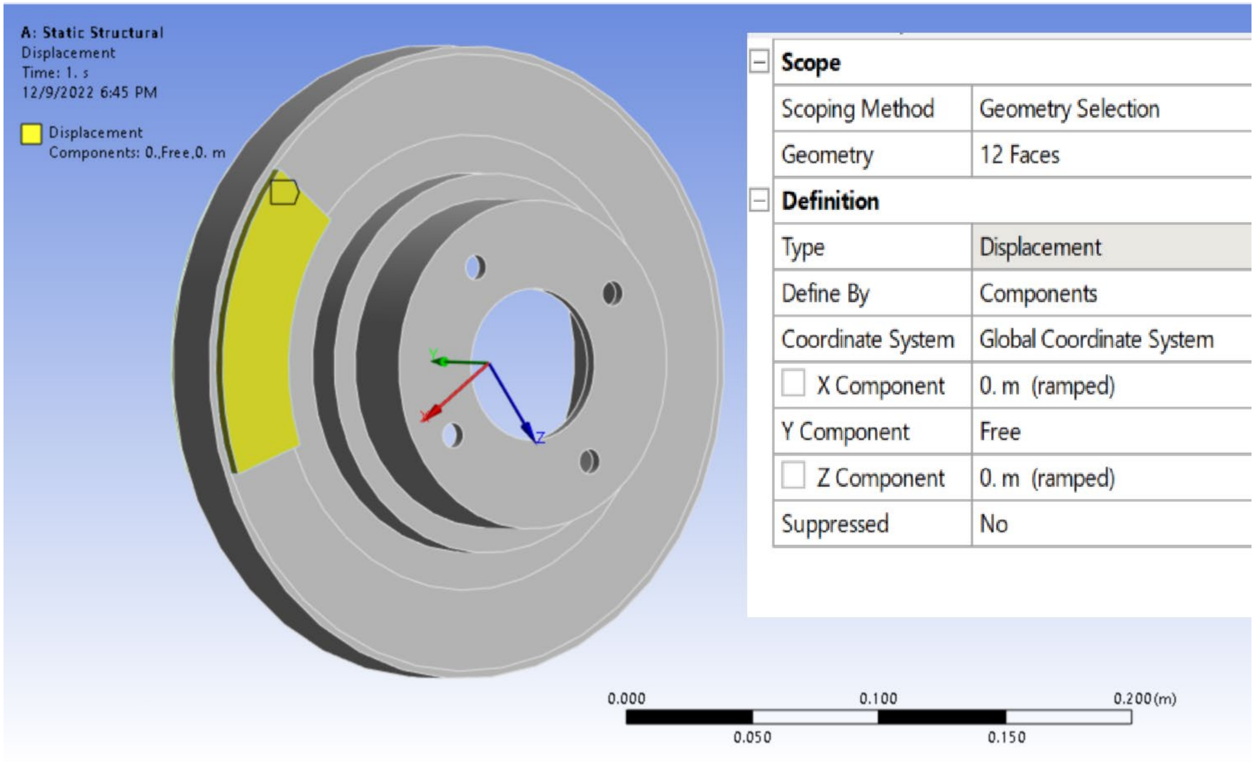

Figure 6 brake pads displacement

Connections:

- Revolute joint at shown surface in fig.7

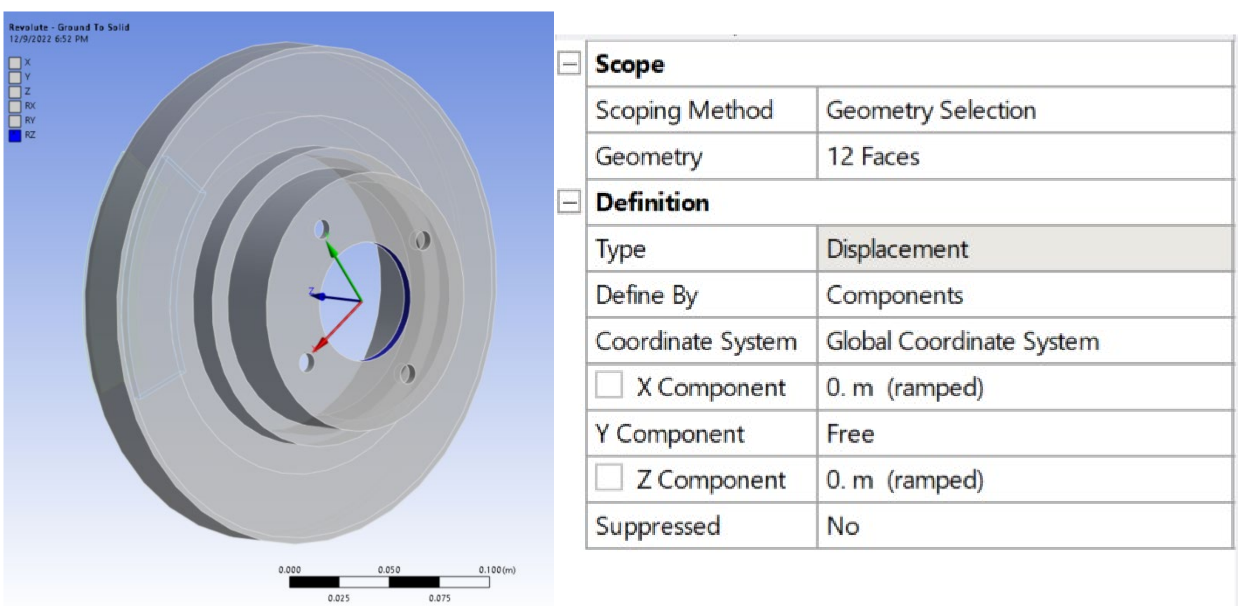

Figure 7 revolute joint setting

- Create fictional contact surfaces between brake disk and brake pads

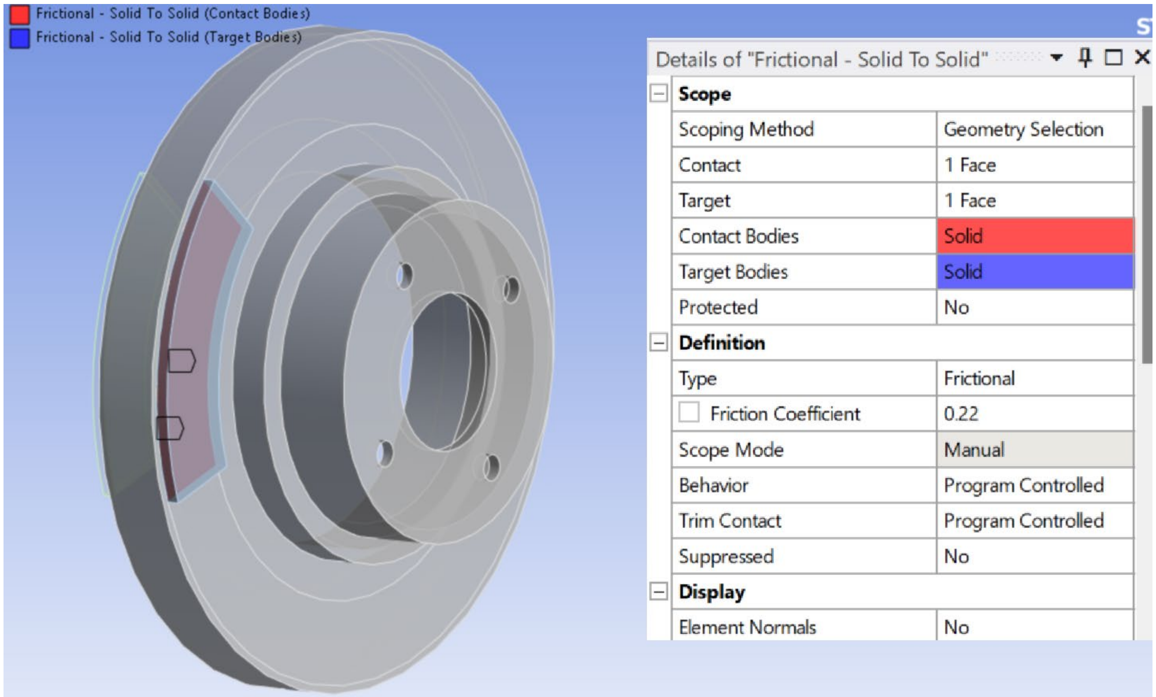

Figure 8 fictional contact

<u>Now, solve for Equivalent (Von -mises) stress and set max stress to parameter.</u>

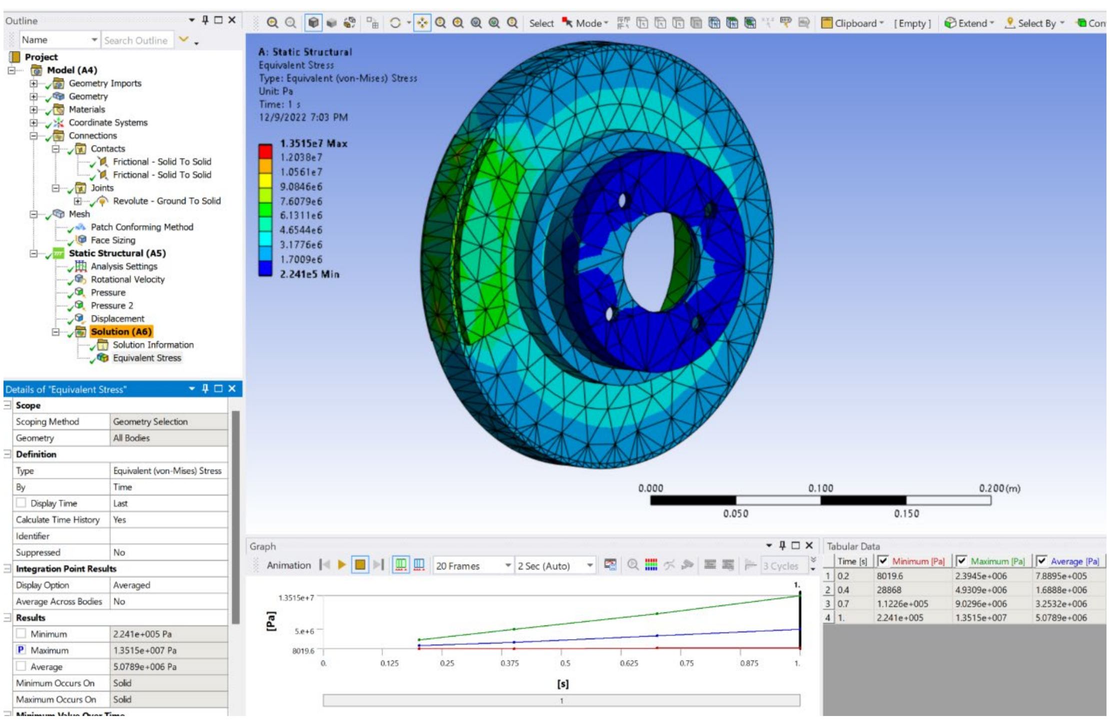

Figure 9 Equivalent stress

Model 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.

Setup:

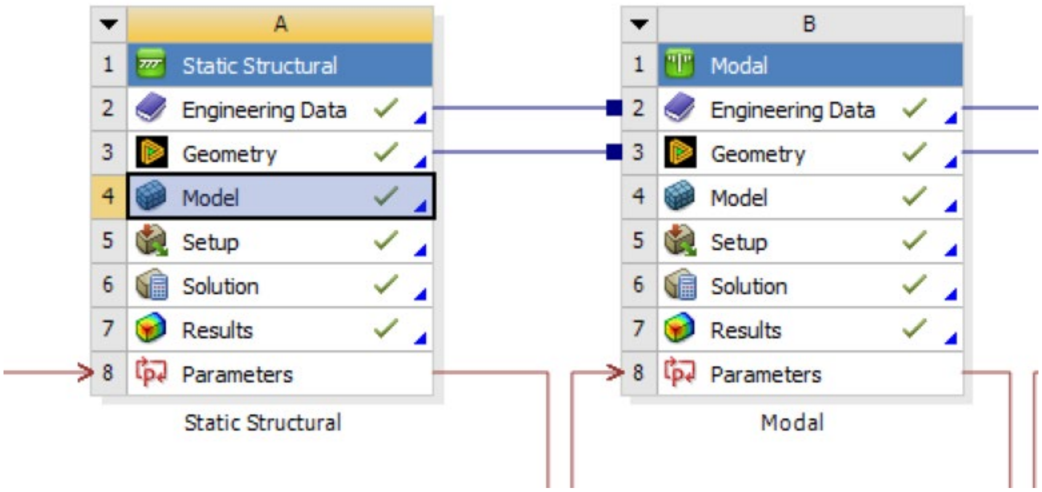

Figure 10 model analysis

- We are going to use the same engineering data and geometry for the model analysis. A tetrahedron type of mesh is used. And the sizing of the mesh is 6mm.
- Suppress the brake pads for this analysis.

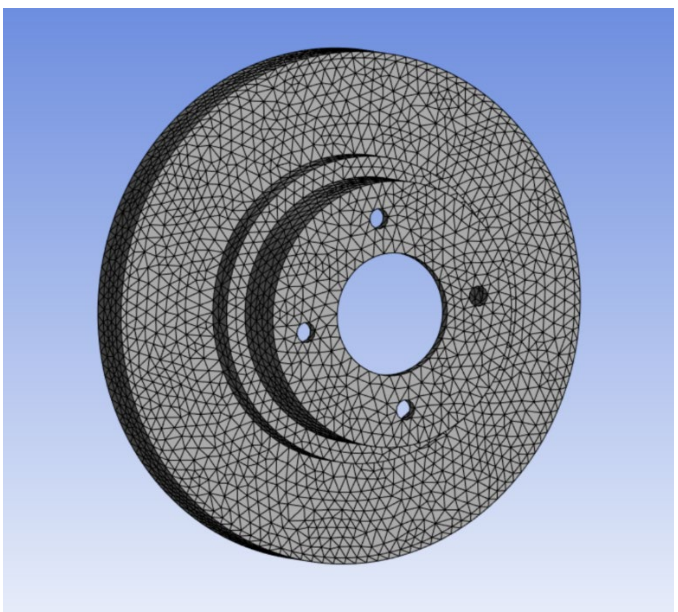

Figure 11 mesh for model analysis

- Click Analysis Settings and enter “Max Modes to Find” as 10 (fig. 12)
- Right click Solution -> Insert -> Deformation -> Total -> Enter the desired mode number. (fig. 13)
- The first 6 modes are the rigid body modes. We do not need those.
- Parametrize the frequency of mode 7 which is the first deformation mode.

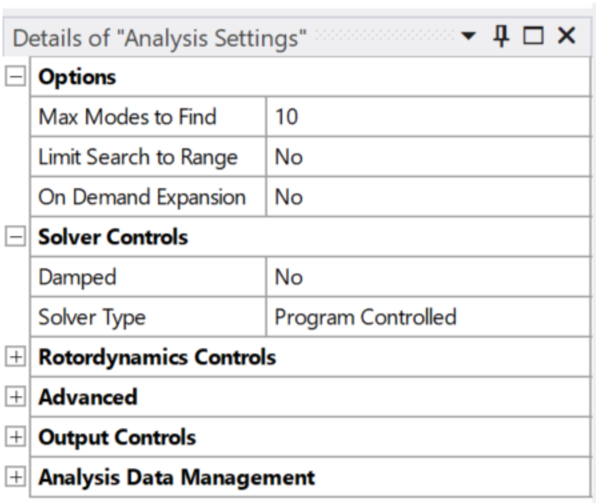

Figure 12 analysis setting

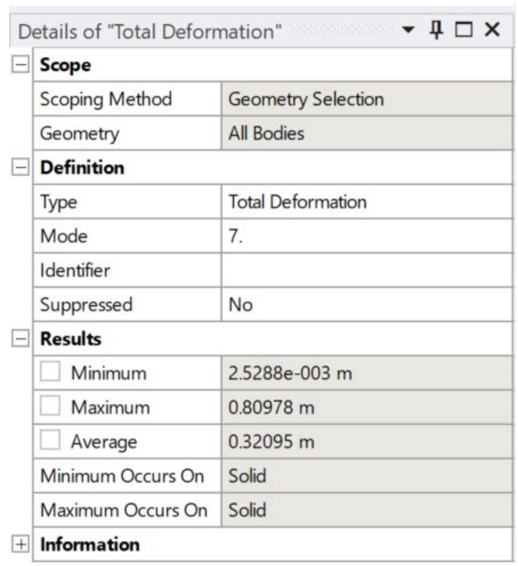

Figure 13 total deformation setting

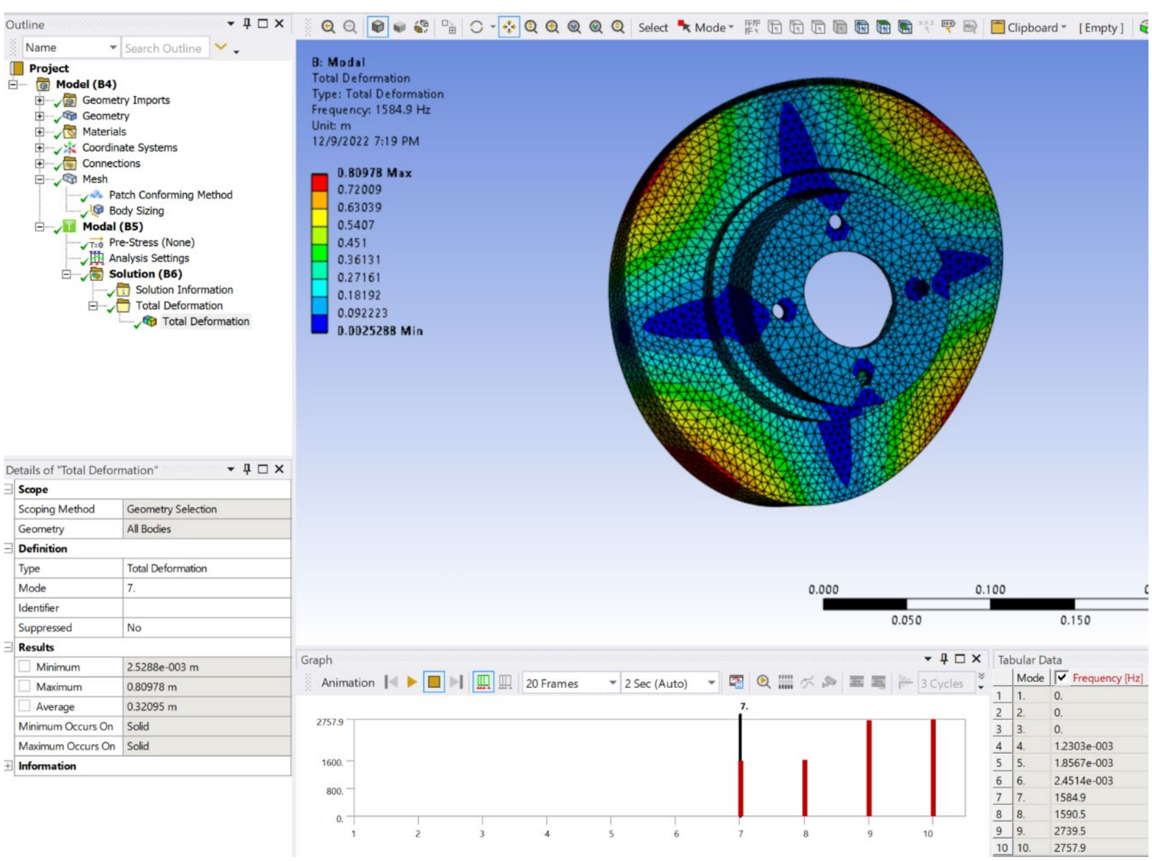

Figure 14 total deformation

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 an 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.

It is assumed that 70% of the braking power is in the front axle of a four-wheeler vehicle. The total heat flux is also multiplied by 0.5 to get the flux generated by a single pad on the disc brake.

$t_e = 5s;\ A_{sp} = 0.021m^2\ ;\ T_{amb} = 35℃$

Calculating the heat flux (q) generated on each face of the disc,

$q = (KE * 0.5 * 0.7)/(te * A_{sp}) = 1.5395e6W/m^2$

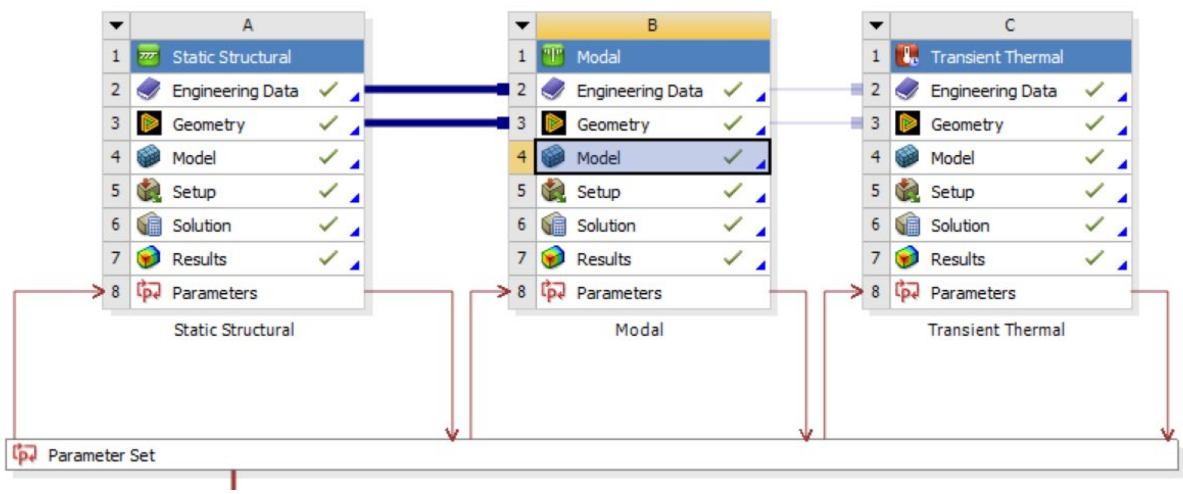

Figure 15 Thermal analysis

Setup:

Boundary conditions:

- Heat flux of 1.5395e6W/m2 is applied on the swept area of both the pads while the direction of heat flow is towards the disc. (fig. 16)
- Convection is applied on all the surfaces with the air film coefficient of 5W/m^2 k which is the default value for standard air. (fig.17)
- Initial temperature is kept at 35℃
- Change analysis settings according to Fig. 18

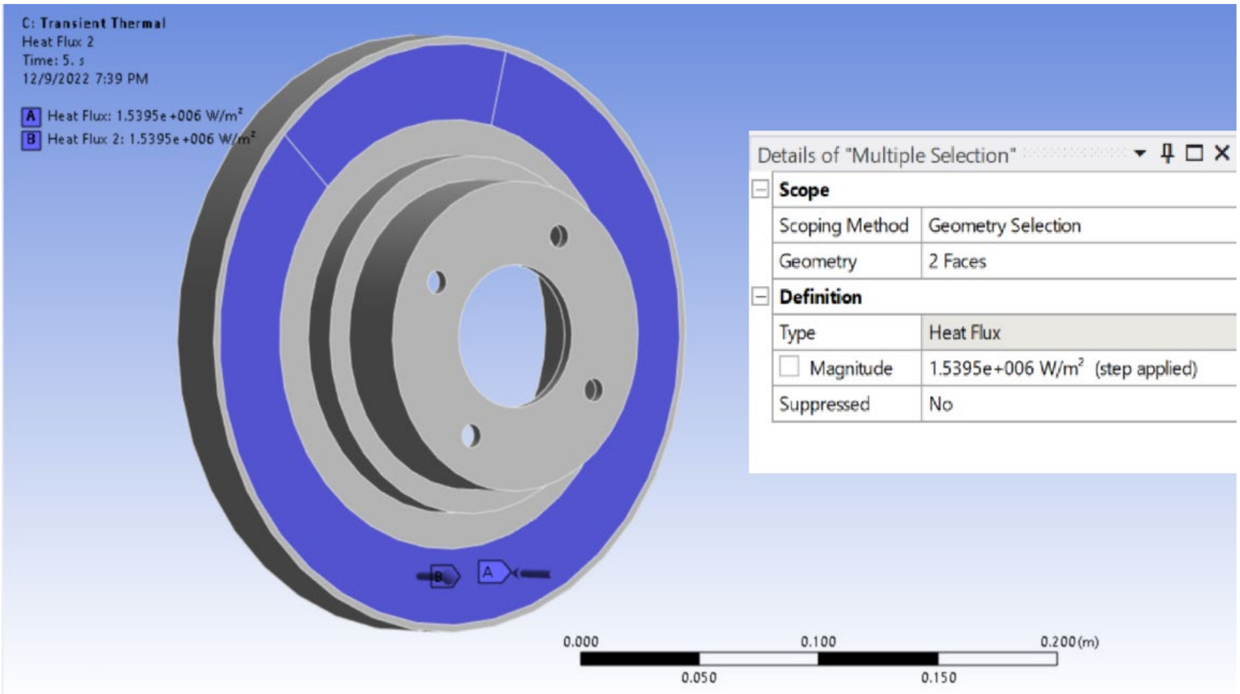

Figure 16 heat flux

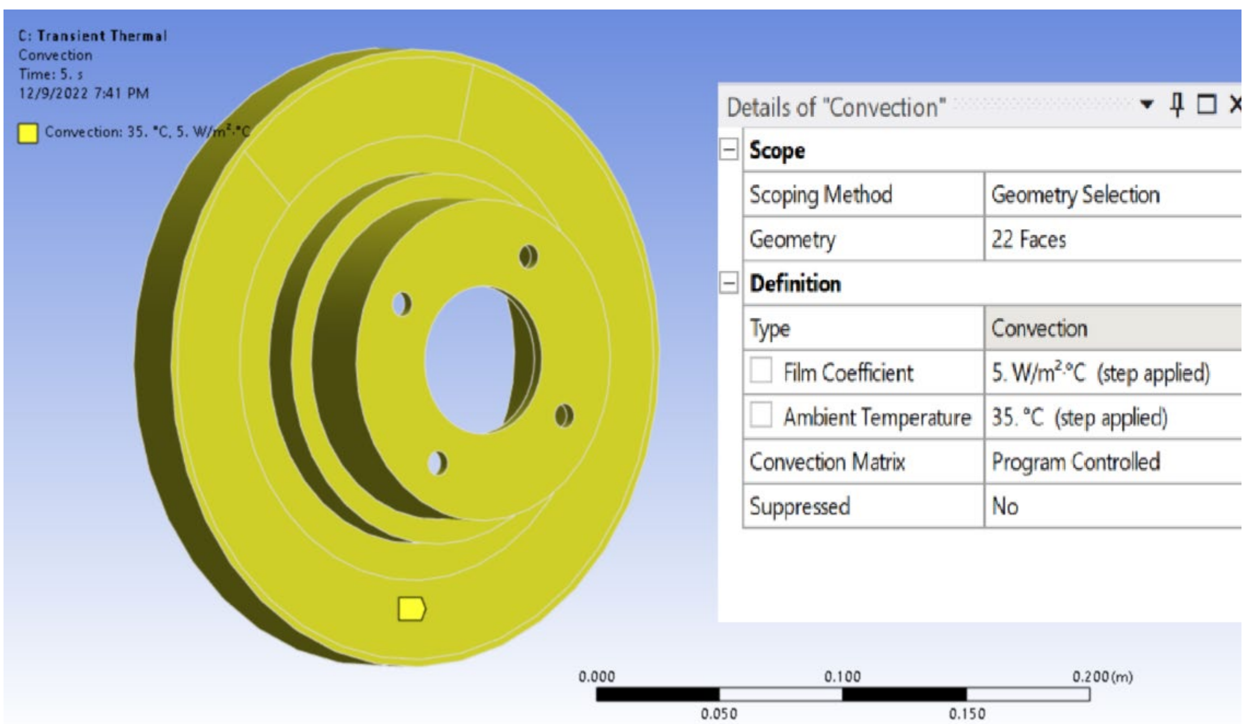

Figure 17 convection

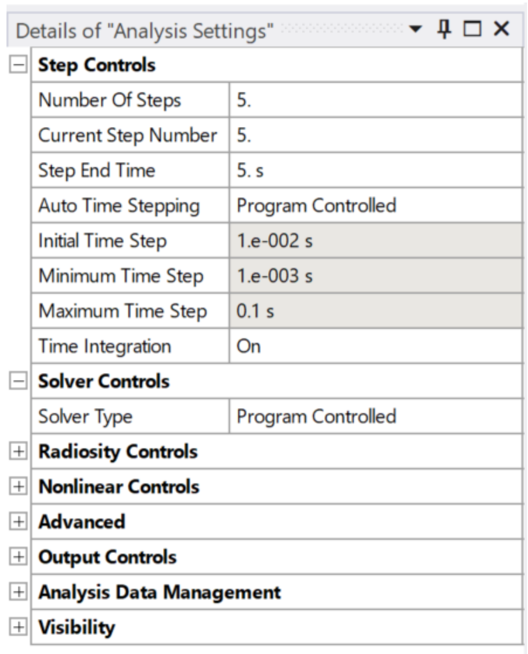

Figure 18 analysis settings

- **Right click Solution -> Insert -> Thermal -> Temperature, parameterize and solve.**

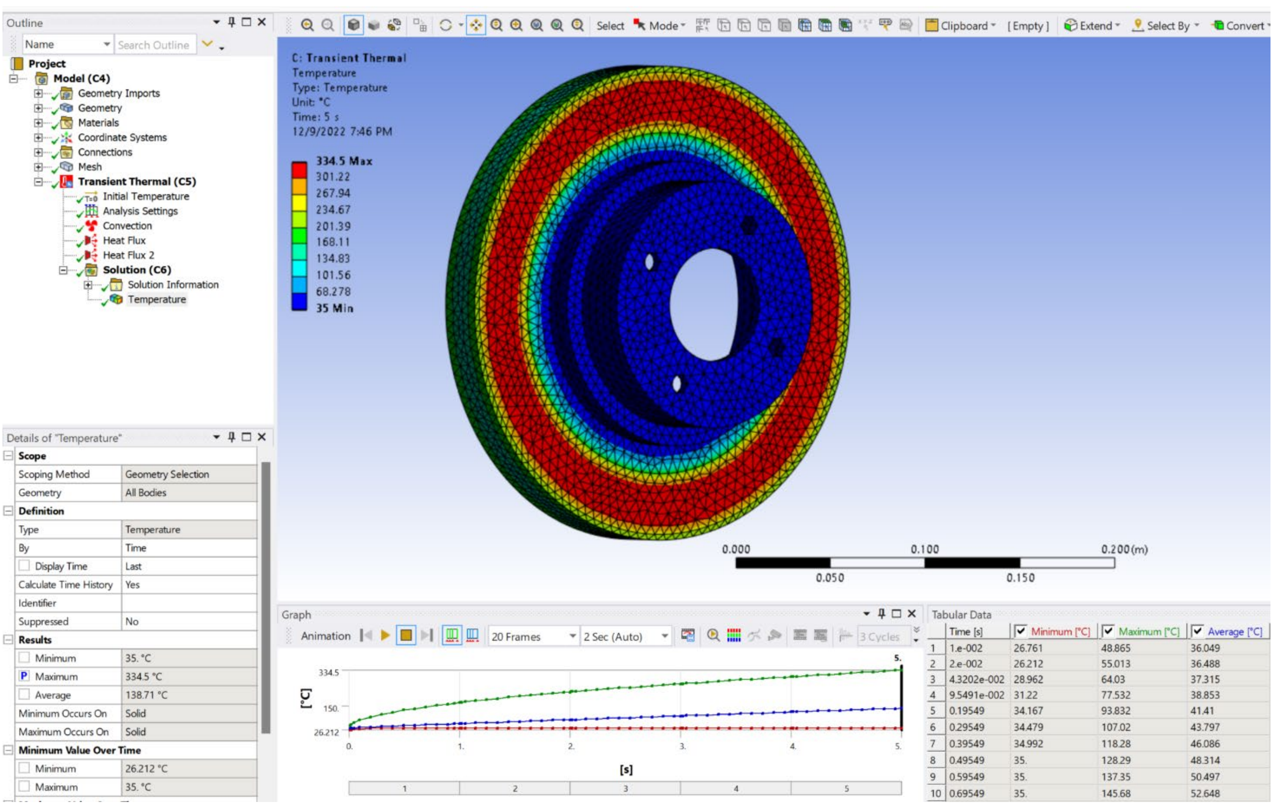

Figure 19 thermal transient analysis

Design of Experiments:

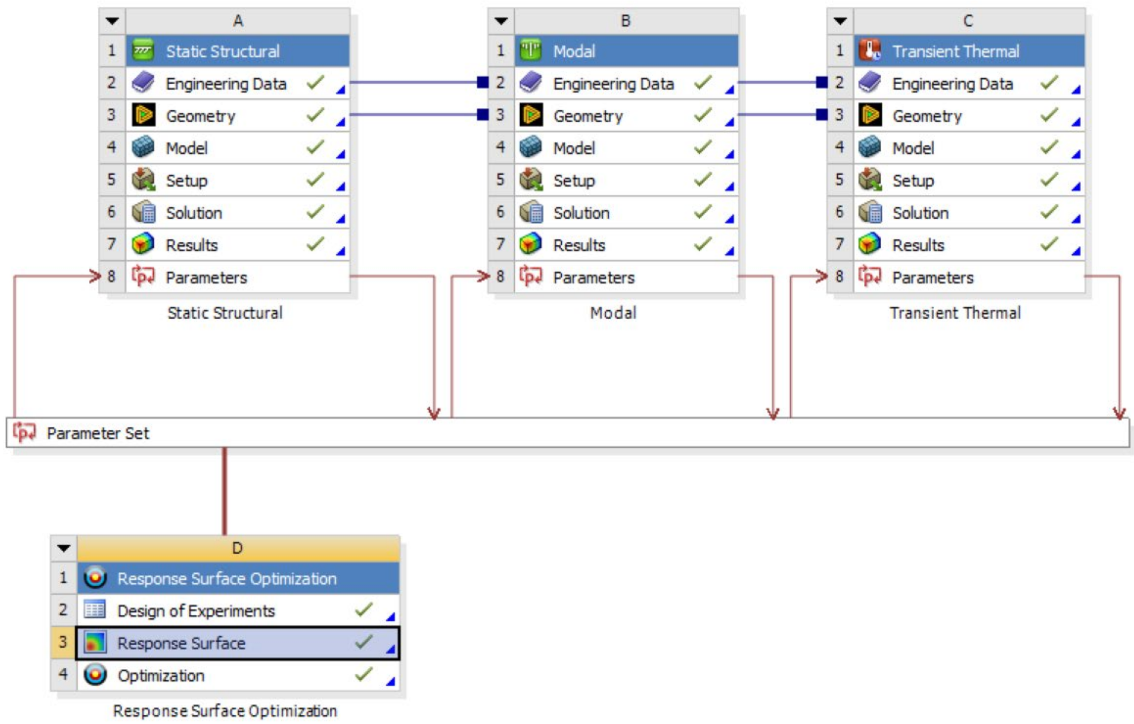

Figure 20 Response surface optimization

- So, the first thing to do is to add the “Response surface Optimization” to the simulation from design exploration.
- Design of experiments has been done using “Latin Hypercube Sampling Design” for sample type user defined sampled is used and I have used 50 sample points which you can find in appendix A.
- It can be seen from the below parallel chart the upper and lower bound of each parameter.

	Lower bound	Upper bound
Rotor Thickness	10mm	20mm
Rotor OD	123mm	130mm
Rotor ID	70mm	85mm

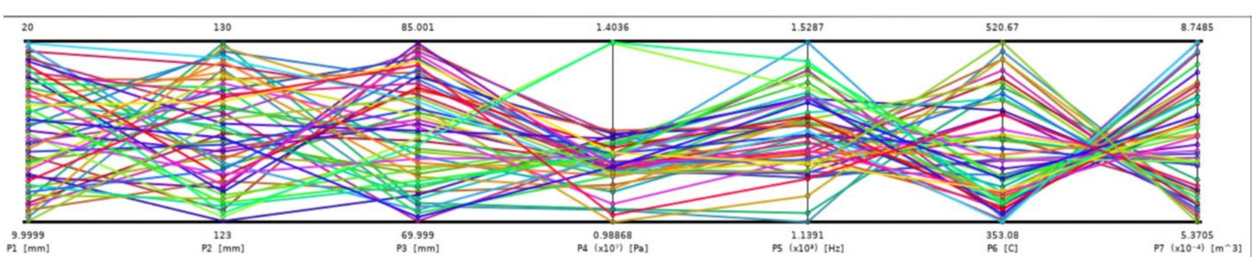

Figure 121 parallel parameter chart

Response surface:

- I have used “standard Response surface – Full 2nd order polynomial” Response surface.
- I have given two verification points.
- Input parameters are rotor thickness, rotor OD, and rotor ID.
- output parameters are equivalent stress maximum, volume, total deformation reported frequency and temperature maximum.

Goodness of fit:

Table of Schematic D3: Response Surface

	A	B	C	D	E
1		P4 - Equivalent Stress Maximum	P5 - Total Deformation Reported Frequency	P6 - Temperature Maximum	P7 - Solid Volume
2	Coefficient of Determination (Best Value...				
3	Learning Points	0.56641	0.99893	0.99994	1
4	Root Mean Square Error (Best Value =...				
5	Learning Points	4.7599E+05	2.753	0.36562	1.188E-07
6	Verification Points	1.4916E+05	14.102	0.97028	2.3156E-07
7	Relative Maximum Absolute Error (Best Value = ...				
8	Learning Points	223.54	10.514	2.3855	0.31043
9	Verification Points	21.063	21.297	2.6631	0.32129
10	Relative Average Absolute Error (Best Value =...				
11	Learning Points	49.424	2.3187	0.6377	0.099074
12	Verification Points	20.824	15.718	1.6817	0.16104

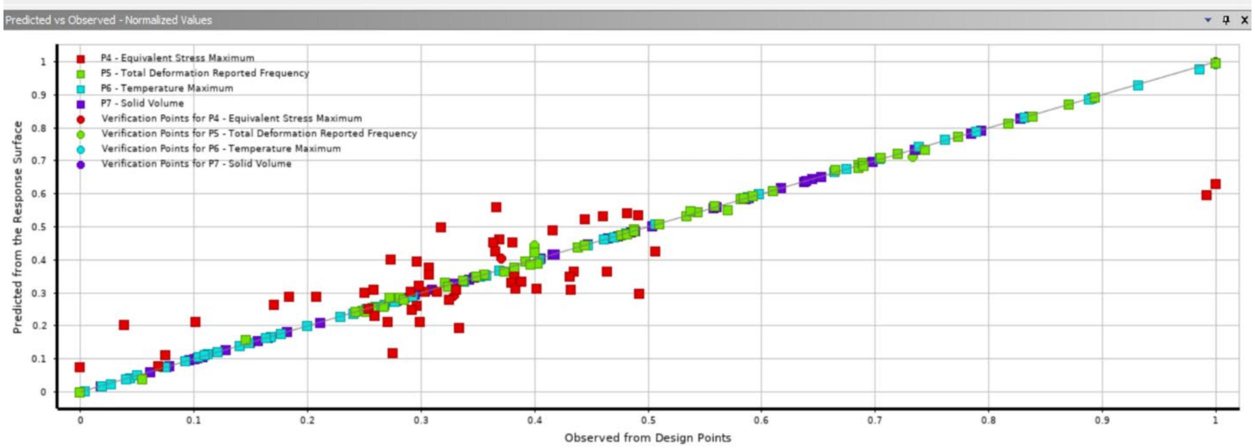

Figure 22 goodness of fit

Sensitivity Analysis:

It can be observed how changing variable of the disc plays a major role in analysis. changing the outer and internal diameter the disc produces the observable change in objective.

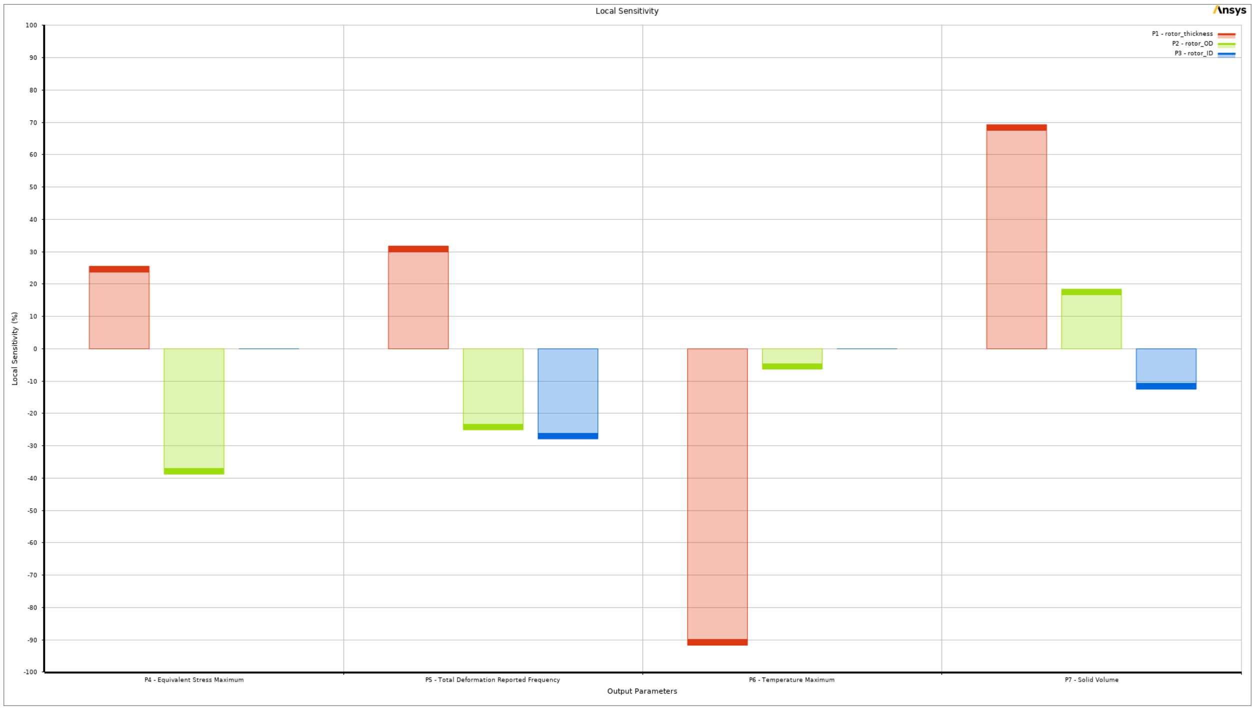

Figure 23 local sensitivity

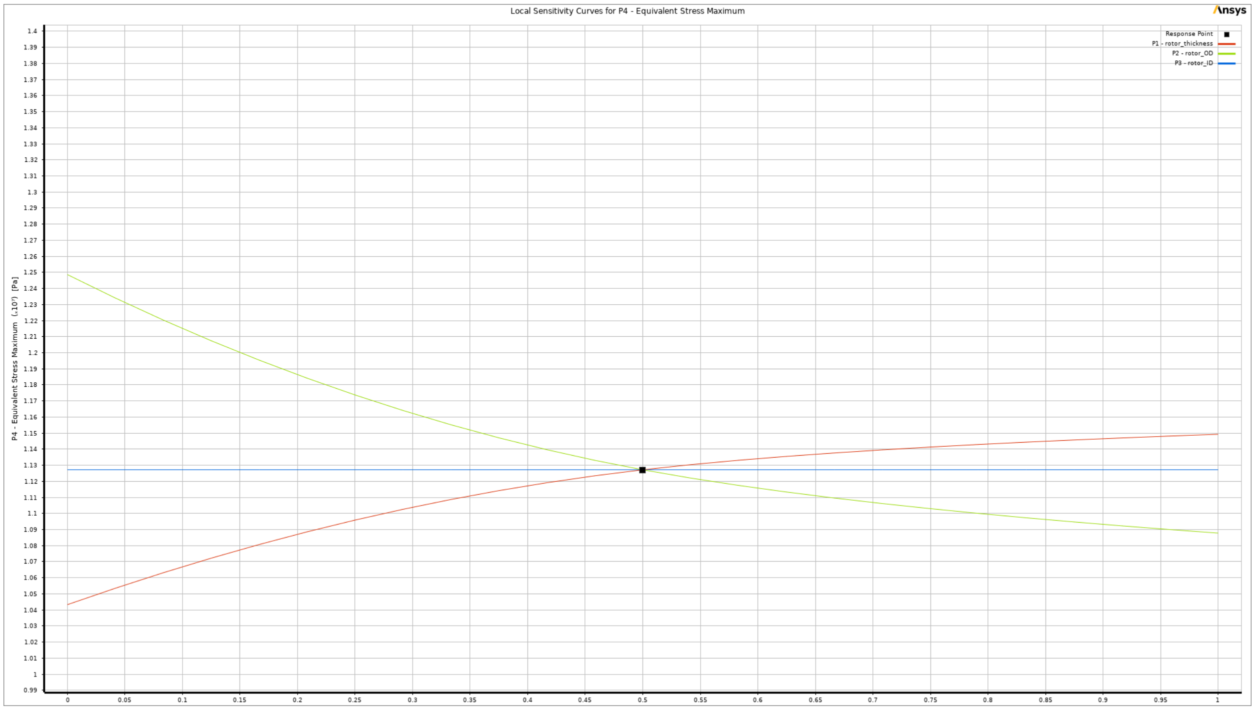

Figure 24 local sensitivity curve

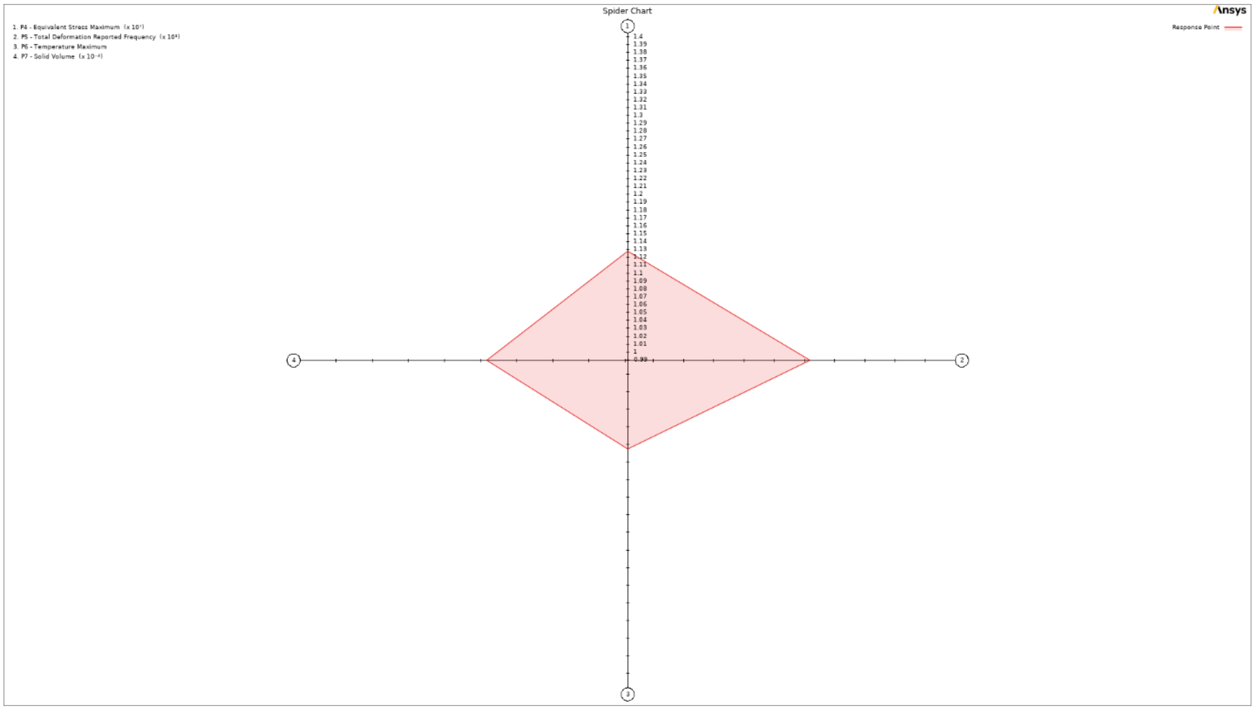

Figure 25 spider

Response surface

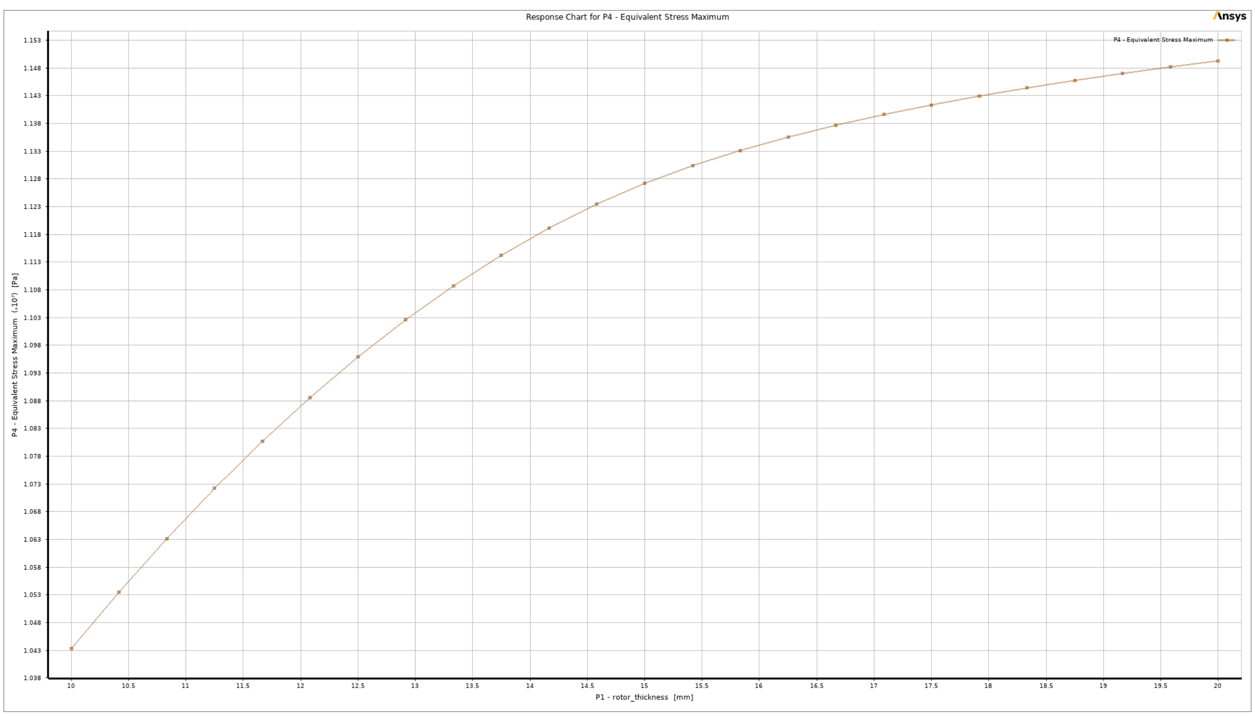

Figure 26 equivalent stress vs rotor thickness

Optimization:

- I have used MOGA for optimization metho
- Estimated number of evaluations. Is 2000.

Objective and constraints:

Table of Schematic D4: Optimization

	A	B	C	D	E	F	G	H	I
1	Name	Parameter	Objective			Constraint			
2			Type	Target	Tolerance	Type	Lower Bound	Upper Bound	Tolerance
3	Minimize P4; P4 <= 1.4E+07 Pa	P4 - Equivalent Stress Maximum	Minimize	0		Values <= Upper Bound		1.4E+07	0.001
4	Minimize P6; P6 <= 400 C	P6 - Temperature Maximum	Minimize	0		Values <= Upper Bound		400	0.001
5	Minimize P7; P7 <= 0.00099967 m^3	P7 - Solid Volume	Minimize	0		Values <= Upper Bound		0.00099967	0.001
6	Maximize P5; P5 >= -1200 Hz	P5 - Total Deformation Reported Frequency	Maximize	0		Values >= Lower Bound	-1200		0.001
*		Select a Parameter							

Figure 27 objective and constraints

Optimization results:

Table of Schematic D4: Optimization

	A	B	C	D	E	F	G
1	Optimization St...						
2	Minimize P4; P4 <= 1.4E+07 Pa	Goal, Minimize P4 (Default importance); Strict Constraint, P4 values less than or equals to 1.4E+07 Pa (Default importanc					
3	Maximize P5; P5 >= -1200 Hz	Goal, Maximize P5 (Default importance); Strict Constraint, P5 values greater than or equals to -1200 Hz (Default importanc					
4	Minimize P6; P6 <= 400 C	Goal, Minimize P6 (Default importance); Strict Constraint, P6 values less than or equals to 400 C (Default importanc					
5	Minimize P7; P7 <= 0.00099967 m^3	Goal, Minimize P7 (Default importance); Strict Constraint, P7 values less than or equals to 0.00099967 m^3 (Default importanc					
6	Optimization Met...						
7	MOGA	The MOGA method (Multi-Objective Genetic Algorithm) is a variant of the popular NSGA-II (Non-dominated Sorted Genetic Algorithm-II) based on controlled elitism concepts supports multiple objectives and constraints and aims at finding the global optimum.					
8	Configuration	Generate 100 samples initially, 100 samples per iteration and find 3 candidates in a maximum of 20 iterations					
9	Status	Converged after 950 evaluations					
10	Candidate Po...						
11		Candidate Point 1	Candidate Point 1 (verified)	Candidate Point 2	Candidate Point 2 (verified)	Candidate Point 3	Candidate Point 3 (verified)
12	P1 - rotor_thickness (mm)	15.182		15.28		15.322	
13	P2 - rotor_OD (mm)	126.54		126.73		126.55	
14	P3 - rotor_ID (mm)	84.705		84.661		84.705	
15	P4 - Equivalent Stress Maximum (Pa)	1.1278E+07	1.1441E+07	1.1252E+07	1.1404E+07	1.1288E+07	1.1391E+07
16	P5 - Total Deformation Reported Frequency (Hz)	[illegible]	1241.7	1238.6	1241.3	1239.9	1242.6
17	P6 - Temperature Maximum (C)	399.8	400.29	398.28	398.74	397.86	398.33
18	P7 - Solid Volume (m^3)	0.00066785	0.00066786	0.00067301	0.000673	0.00067179	0.00067177

Figure 28 optimization results

Convergence criteria:

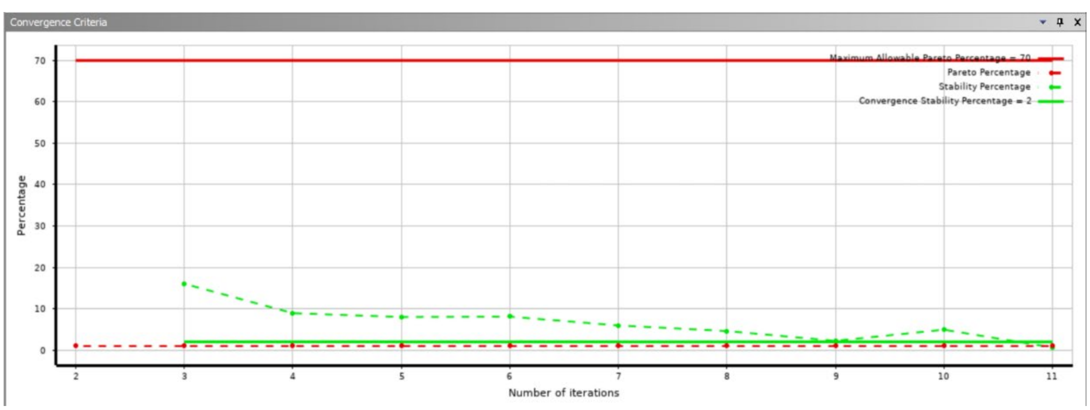

Figure 29 convergence criteria

Candidate points:

Reference	Name	P1 - rotor_thickness (mm)	P2 - rotor_OD (mm)	P3 - rotor_ID (mm)	P4 - Equivalent Stress Maximum (Pa)		P5 - Total Deformation Reported Frequency (Hz)		P6 - Temperature Maximum (C)		P7 - Solid Volume (m^3)	
					Parameter Value	Variation from Reference	Parameter Value	Variation from Reference	Parameter Value	Variation from Reference	Parameter Value	Variation from Reference
	Candidate Point 1	15.182	126.54	84.705	1.1278E+07	-0.09%	1239.3	-0.05%	399.8	0.49%	0.00066785	-0.59%
	Candidate Point 1 (verified)				1.1441E+07	1.35%	1241.7	0.14%	400.29	0.61%	0.00066786	-0.58%
	Candidate Point 2	15.28	126.73	84.661	1.1252E+07	-0.32%	1238.6	-0.11%	398.28	0.11%	0.00067301	0.18%
	Candidate Point 2 (verified)				1.1404E+07	1.02%	1241.3	0.11%	398.74	0.22%	0.000673	0.18%
	Candidate Point 3	15.322	126.55	84.705	1.1288E+07	0.00%	1239.9	0.00%	397.86	0.00%	0.00067179	0.00%
	Candidate Point 3 (verified)				1.1391E+07	0.91%	1242.6	0.21%	398.33	0.12%	0.00067177	0.00%
	New Custom Candidate Point	15	126.5	77.5								

Figure 30 candidate points

- Candidate point 3 is the best of all other candidate points.

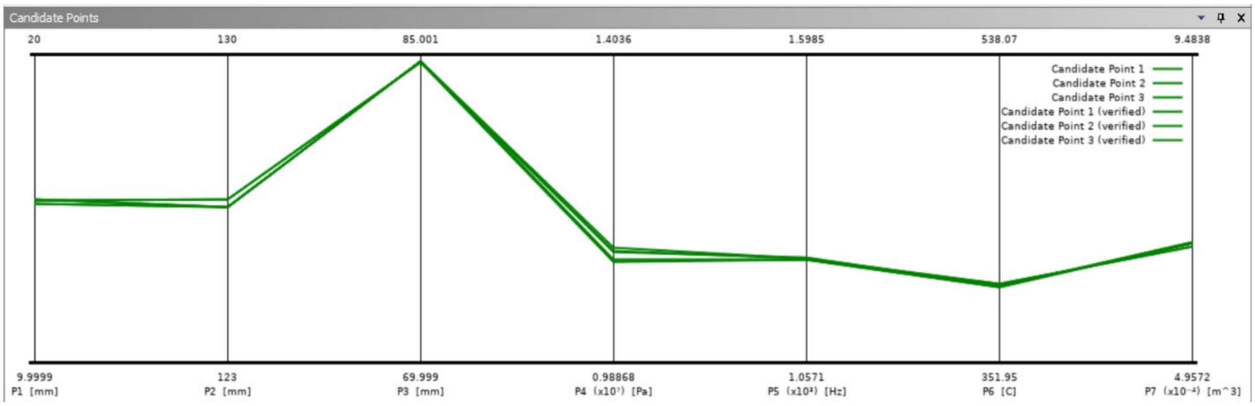

Figure 31 candidate point graph

Sensitivity:

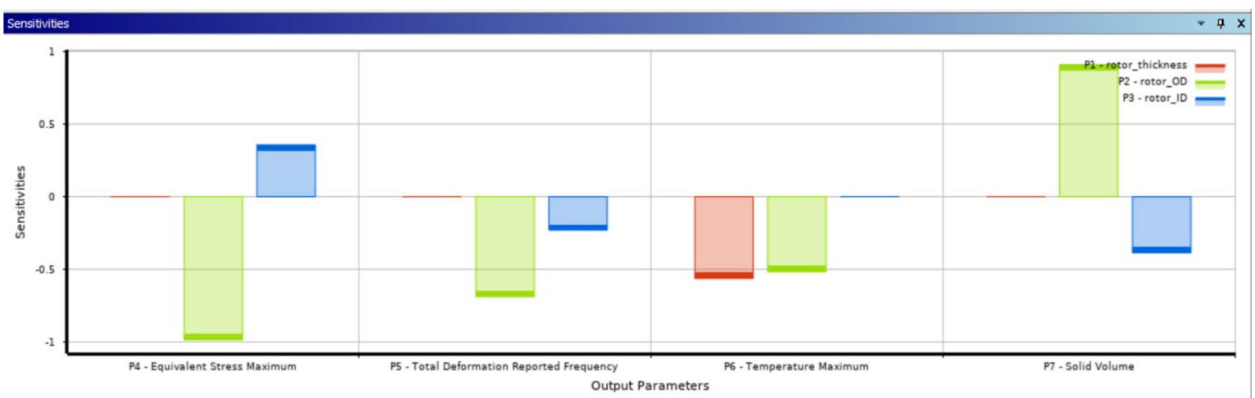

Figure 32 optimization sensitivity

Result and conclusion:

Initial volume of the brake disc: 9.9667e-004 m^2

Optimized volume of the brake disc: 6.7203e-004 m^2

Volume reduction: 33.05%

Initial design:

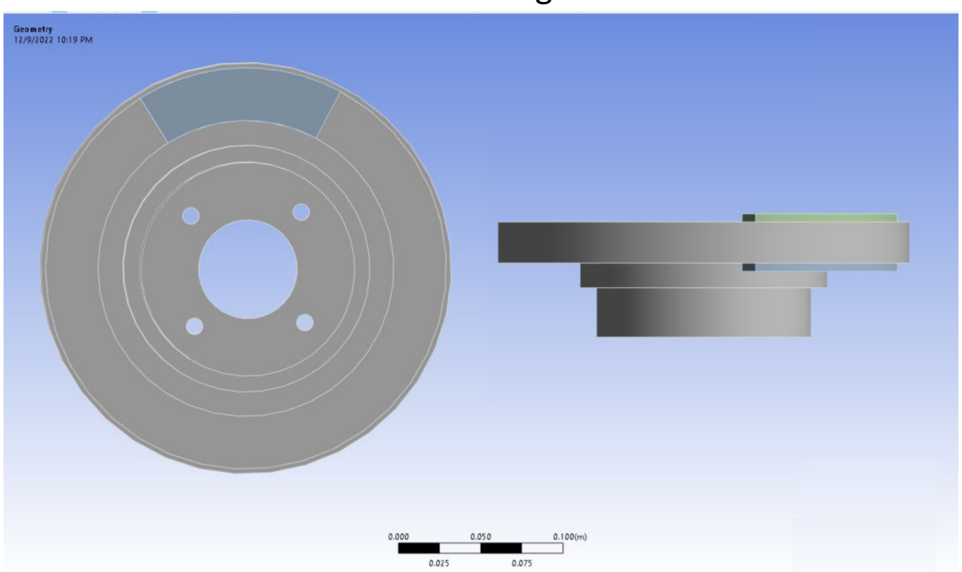

Figure 33 initial design

Final design:

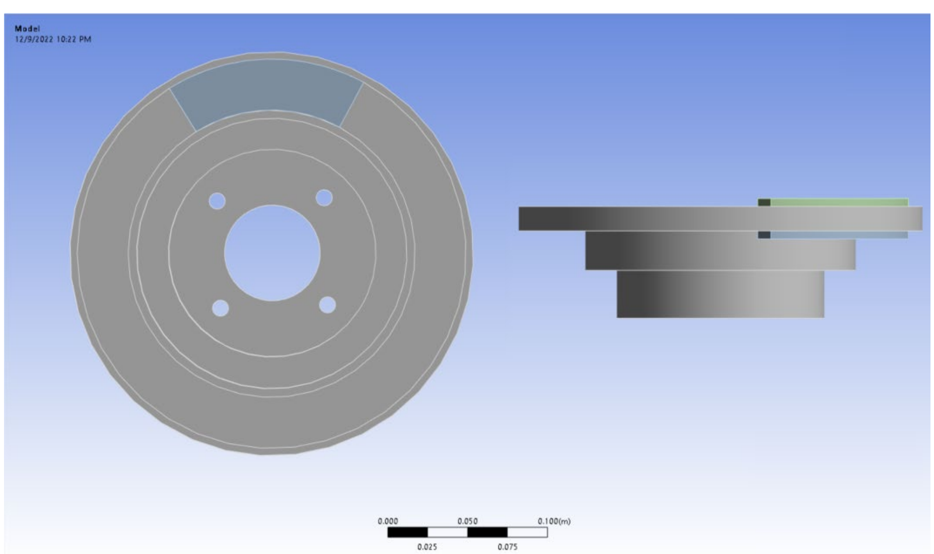

Figure 34 final design

Maximum Equivalent stress for optimized design:

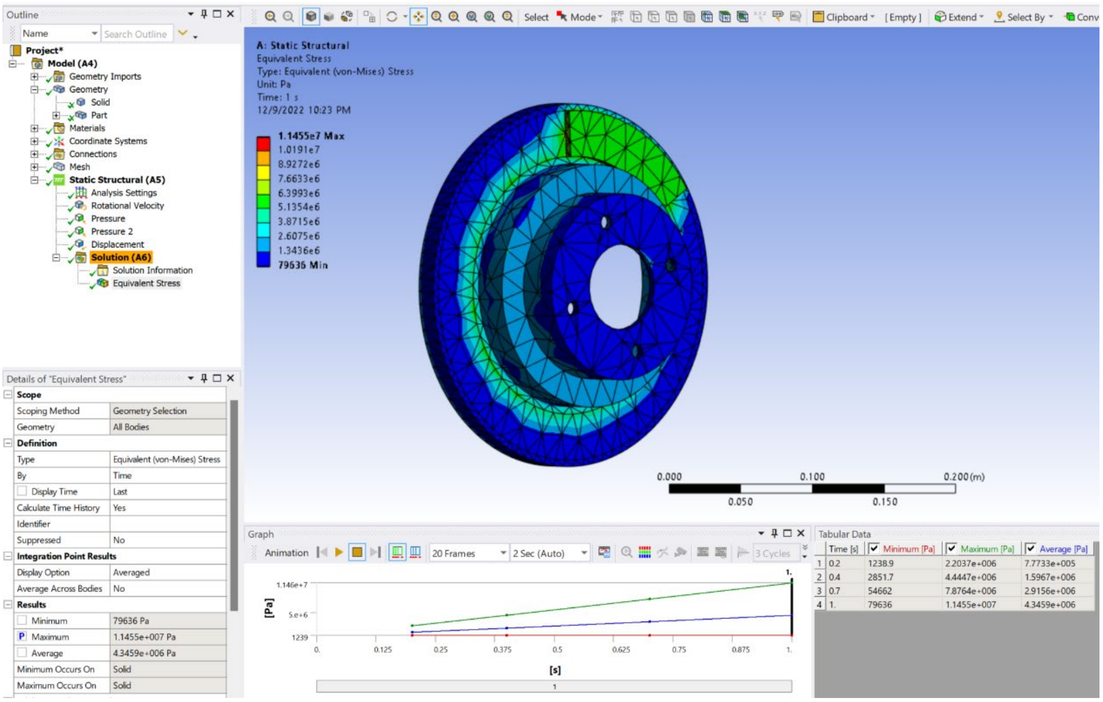

Figure 35 Maximum Equivalent stress for optimized design

Maximum Frequency for optimized design:

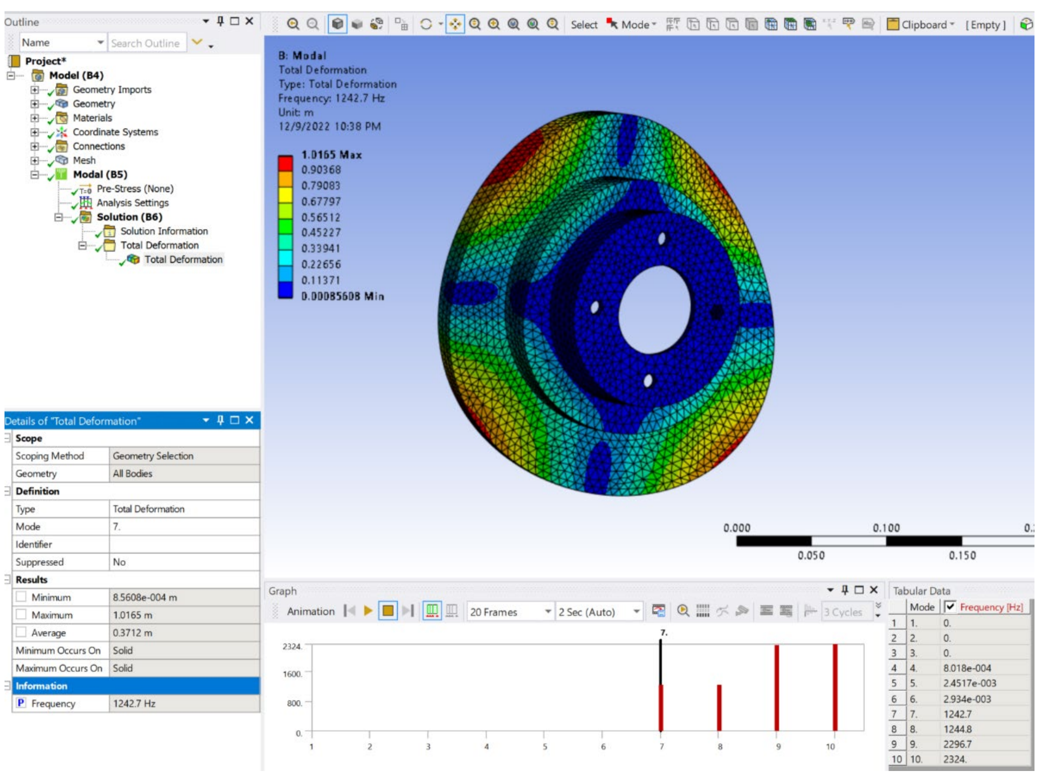

Figure 136 Maximum Frequency for optimized design

Maximum Temperature for optimized design:

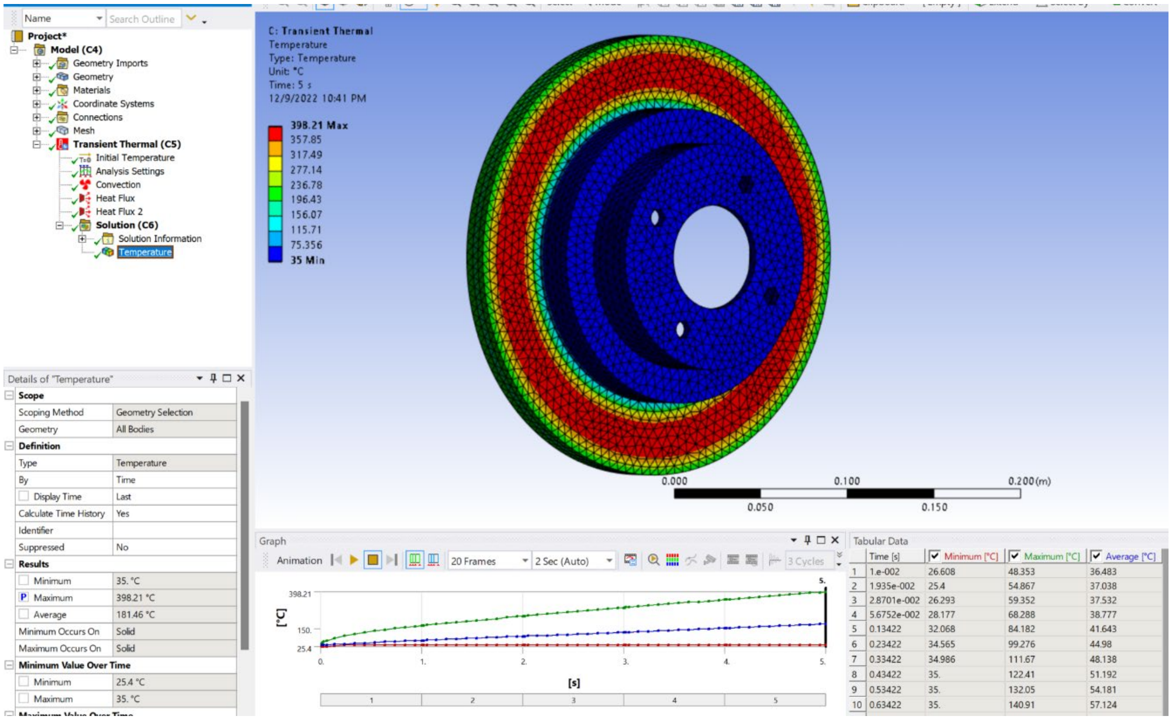

Figure 37 Maximum Temperature for optimized design:

Appendix A.

1	Name	Update Order	P1 - rotor_thickness (mm)	P2 - rotor_OD (mm)	P3 - rotor_ID (mm)	P4 - Equivalent Stress Maximum (Pa)	P5 - Total Deformation Reported Frequency (Hz)	P6 - Temperature Maximu
3	2	3	15.5	127.55	76.15	1.1191E+07	1356.8	395.03
4	3	4	10.3	128.95	71.35	1.0174E+07	1139.1	511.57
5	4	5 3	14.5	127.13	84.25	1.193E+07	1239.5	410.02
6	5	6	10.7	124.61	72.55	1.0749E+07	1295.2	504.59
7	6	7	19.3	125.17	79.15	1.1421E+07	1413.9	359.96
8	7	8	14.3	128.11	83.65	1.1119E+07	1236.2	412.59
9	8	9	19.1	127.27	70.15	1.1473E+07	1466.1	359.26
10	9	10	11.9	125.59	74.65	1.1234E+07	1324.9	465.8
11	10	11	11.3	129.93	71.65	1.0198E+07	1160.4	478.48
12	11	12	12.7	123.07	72.25	1.1888E+07	1406.4	456.58
13	12	13	11.1	126.43	76.75	1.1272E+07	1288.1	487.11
14	13	14	13.5	126.15	74.05	1.1681E+07	1351.1	428.7
15	14	15	16.1	129.51	75.55	1.0598E+07	1329.4	386.58
16	15	16	12.5	124.33	84.85	1.1023E+07	1245.5	454.44
17	16	17	17.9	128.53	82.45	1.1095E+07	1284.7	368.28
18	17	18	17.5	126.57	72.85	1.1692E+07	1440.4	373.1
19	18	19	15.3	129.65	81.85	1.1101E+07	1248.8	396.87
20	19	20	10.9	125.87	78.55	1.1128E+07	1296	494.41
21	20	21	10.5	129.79	79.75	9.8869E+06	1196	504.09
22	21	22	13.3	127.41	77.35	1.0943E+07	1310.1	431.24
23	22	23	18.1	124.19	82.15	1.1928E+07	1347.2	371.56
24	23	24	19.5	129.09	80.65	1.1148E+07	1326.9	355.75
25	24	25	11.5	123.91	75.85	1.1119E+07	1361.5	482.52
26	25	26	16.7	126.71	71.95	1.1678E+07	1419.8	381.13
27	26	27	15.1	125.73	78.25	1.1164E+07	1366	402.49
28	27	28	17.3	125.45	80.95	1.1988E+07	1348.7	376.38
29	28	29	15.9	124.05	74.35	1.1732E+07	1457.6	395.54
30	29	30	19.7	125.31	71.05	1.1397E+07	1528.7	356.99
31	30	31	12.9	128.39	77.95	1.0307E+07	1277.7	438.86
32	31	32	16.9	128.81	73.75	1.065E+07	1370.1	377.81
33	32	33	17.7	128.25	70.75	1.0959E+07	1406.2	370.19
34	33	34	13.9	126.01	79.45	1.1464E+07	1329.2	421.45
35	34	35	18.3	127.97	81.55	1.1125E+07	1312.3	365.09
36	35	36	13.1	128.67	78.85	1.1013E+07	1270.7	434.51
37	36	37	12.1	123.63	73.15	1.1466E+07	1376.9	467.61
38	37	38	18.9	126.85	77.65	1.1814E+07	1407.7	361.02
39	38	39	18.7	124.75	81.25	1.1613E+07	1366.7	365.21
40	39	40	14.9	123.21	77.05	1.4003E+07	1429.1	413.52
41	40	41	19.9	129.37	80.05	1.0928E+07	1337.8	353.08
42	41	42	14.7	124.89	75.25	1.1405E+07	1407.9	410.15
43	42 DP 70	1	14.1	129.23	74.95	1.0965E+07	1291.9	415.48
44	43	43	16.3	123.77	73.45	1.141E+07	1478.3	391.57
45	44	44	11.7	125.03	82.75	1.1262E+07	1275.2	472.56
46	45	45	17.1	124.47	83.95	1.1207E+07	1293.6	380.41
47	46	46	16.5	127.69	83.35	1.1478E+07	1265.6	382.67
48	47	47	18.5	123.35	76.45	1.4036E+07	1487.4	371.08
49	48	48	15.7	126.29	70.45	1.1161E+07	1398.2	393.49
50	49	49	12.3	127.83	83.05	1.0049E+07	1233.8	452.85
51	50	50	10.1	126.99	80.35	1.1031E+07	1250.2	520.67