MAE 598- Design Optimization

Prof. Dr. Yi Yen

Project 1- Design Optimization of a Brake Disc

Mangirish Sanjeev Kulkarni

ASU ID: 1223229852

Problem Definition:

The objective of this project is to create a brake disc that satisfies the following criteria:

• Minimum volume, such as thickness and inner and outer brake disc diameters, to lower the cost of the material needed

• The least amount of maximal stress that might be created without the material failing under braking conditions.

• Highest first natural frequency, to prevent resonance from causing disc failure;

• Lowest possible maximum temperature developed, design optimization strategies to prevent contact surfaces from being harmed by thermal stress (specifically DOE).

All the analysis for this project is carried out on Ansys software, version R18.

Model setup:

A brake disc Part is obtained from Professor Yi Ren's repository. It is then opened in Ansys.

It basically has three modes;

1. Static Structural Analysis

2. Modal Analysis

3. Transient Thermal Analysis

Material Properties:

The model is made comprised of brake pads and a disc brake. The brake disc's material of choice is

Grey Cast Iron and "Structural Steel," respectively, are terms used to describe the brake pad. Mesh size is also maintained.

Here is an overview of how the project schematic looks like-

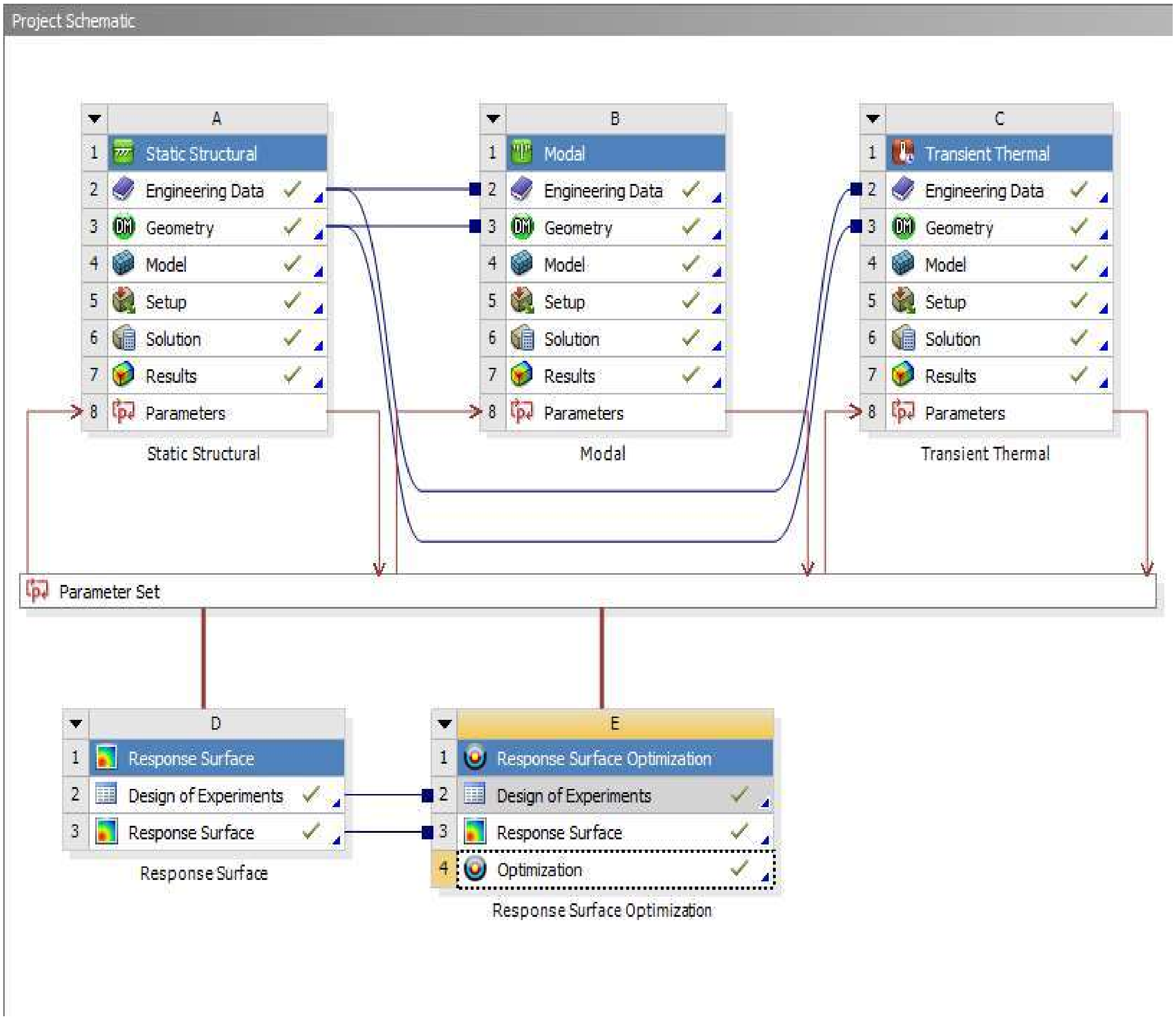


Fig 1: Project Schematic window.

Initial setup

The geometry of the disk brake is imported into the static structural analysis. The body has predefined dimensions which can be changed according to the need. The analysis is carried out in static structural, modal and transient thermal.

Static Structural Setup:

The static structural study helps to understand the stress and strain developed and deformation due to applied loads (such as forces, friction, etc.). Following loads and boundary conditions are applied to simulate braking conditions:

- the rotational velocity of all the bodies is considered as 250 rad/s,
- a revolute joint is added to the inner radius of the brake disc,
- pressure is applied on the brake pads (1.0495 * 10^7 Pa),
- friction is added between the brake pads and disc (frictional coefficient = 0.22)
- the movement of brake pads in other directions except along the y-axis (towards and away from the brake disc) is restricted.

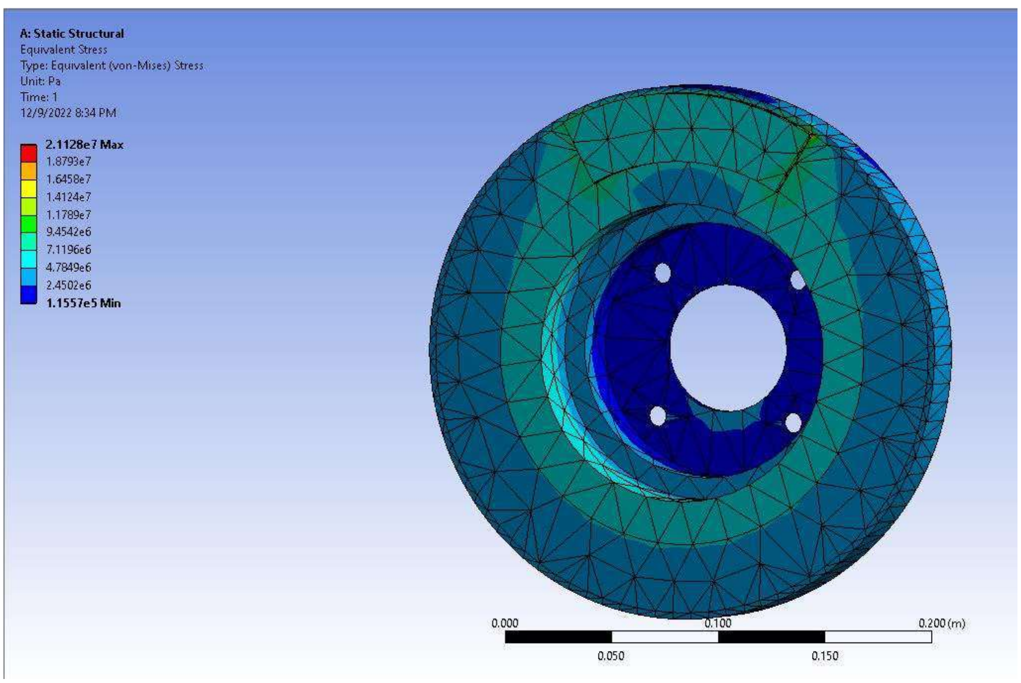


Figure 2. Results of Equivalent von-Mises Stress for Brake Disc

Results	
Minimum	1.1557e+005 Pa
P Maximum	2.1128e+007 Pa
Minimum Occurs On	Solid
Maximum Occurs On	Solid

After solving, a maximum stress value of 21.128 MPa is obtained for the given model. The lowest possible value of stress on the circular contact patch (between disc and brake pad) can be observed to be around 7.1196 MPa.

Modal Setup:

The modal analysis provides the natural frequencies at which the model will resonate. The natural frequency of the brake disc is required, as it may fail if it resonates with the engine firing frequency. Boundary Conditions:

• Brake pad geometry is suppressed

• 10 modes are evaluated for this analysis

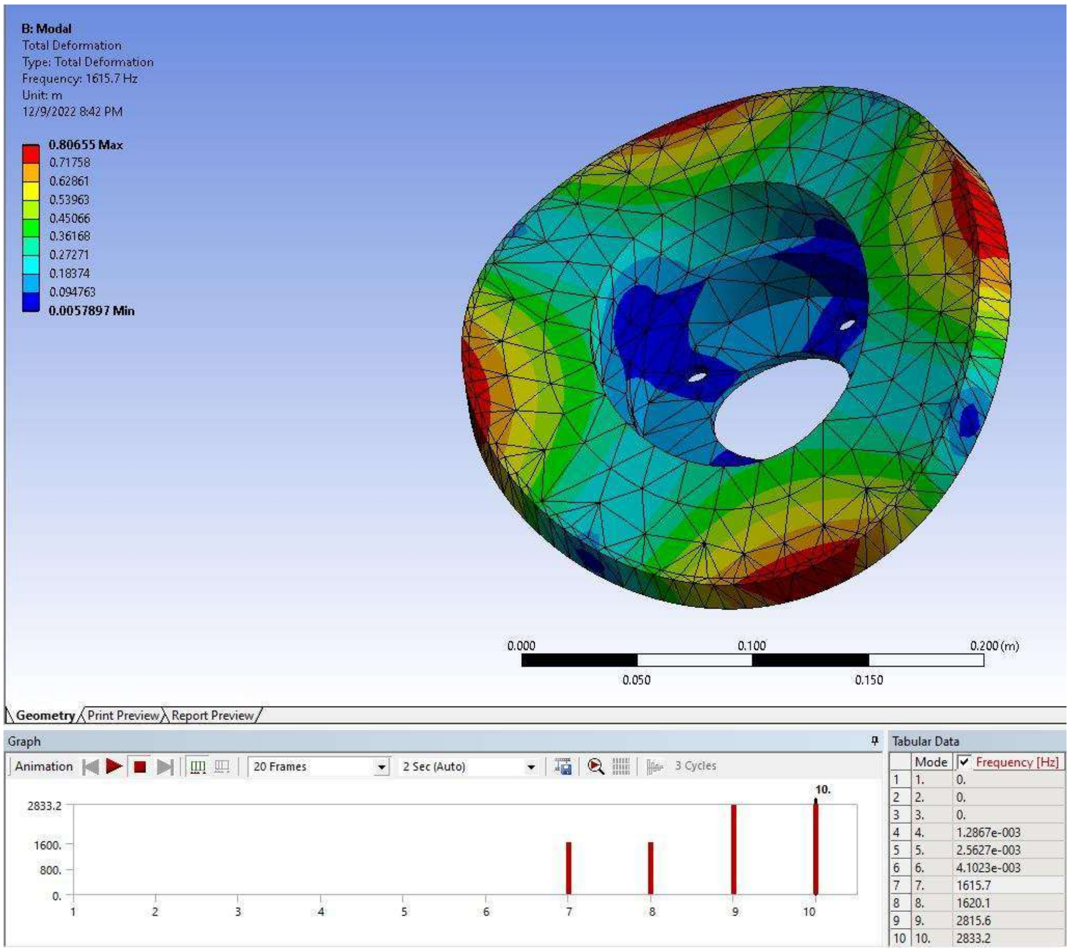


Figure 3. Results of Deformation and Frequency for Brake Disc

Results	
Minimum	5.7897e-003 m
Maximum	0.80655 m
Minimum Occurs On	Solid
Maximum Occurs On	Solid
Information	
P Frequency	1615.7 Hz

The first natural frequency can be observed to be 1615.7Hz for mode 7. The maximum value of deformation evaluated in the analysis is 0.80655m. The deformation is focused primarily at 90degrees from the holes in the back of the disc.

Transient Thermal Setup:

Transient thermal analysis shows how a structure/model behaves under fixed or varying conditions over time. The braking conditions are simulated as follows:

• The initial temperature of the disc is considered 35 degrees Celsius.

• The end time is considered as 5 seconds and 5 steps were taken in between.

• Convection is applied to all the disc faces and the heat transfer coefficient is chosen as 5 W/m^2.C)

• Heat flux is applied to the contact patch of the brake pad and brake disc

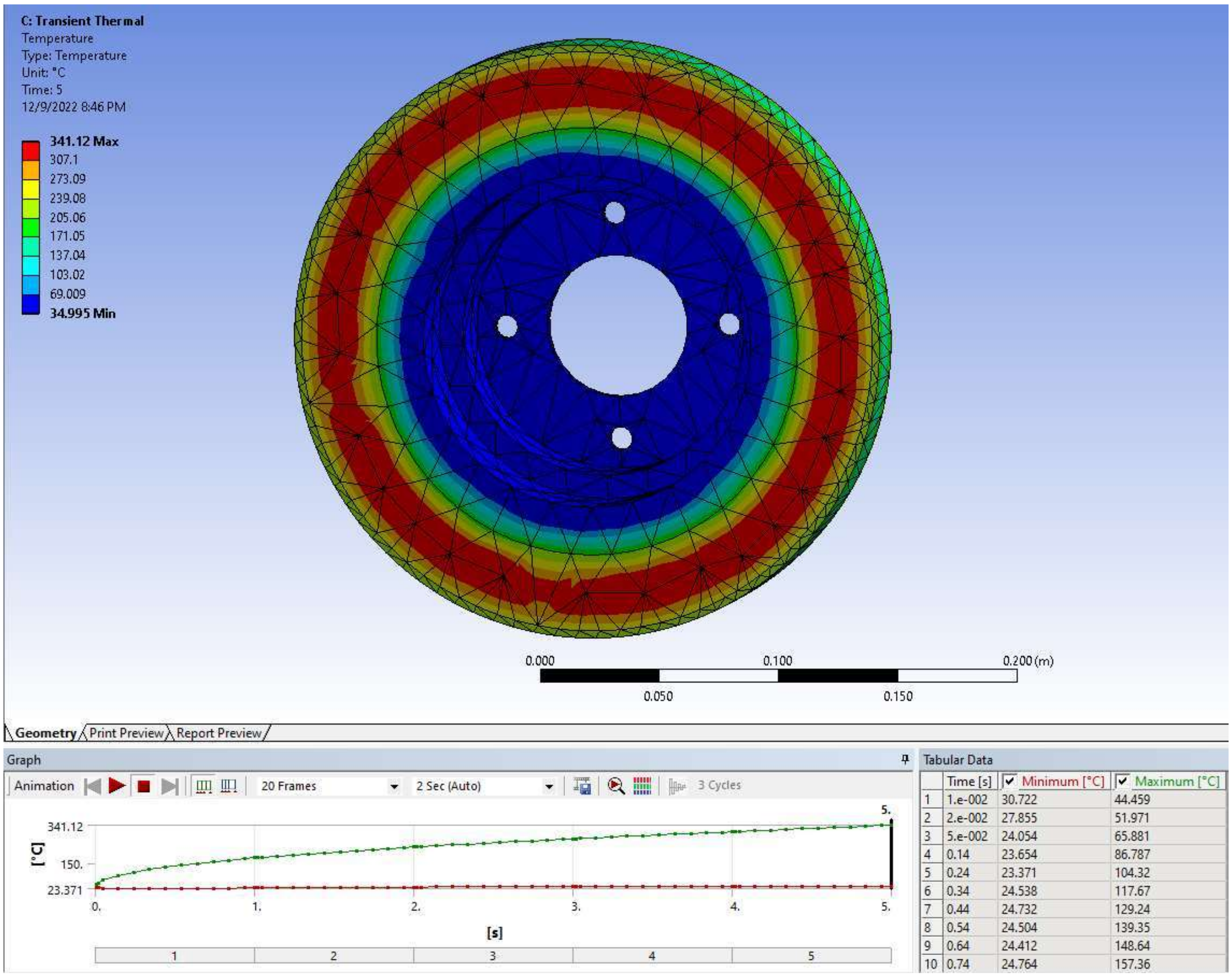


Figure 4. Details and Resulting Model of Temperature

Results	
Minimum	34.995 °C
P Maximum	341.12 °C
Minimum Occurs On	Solid
Maximum Occurs On	Solid

The maximum temperature observed is 341.12 degrees Celsius.

DOE and Optimization

Through an iterative approach, optimization will assist decrease or maximize the target. Determining which design to evaluate from design spaces of various sizes will help with a specific DOE methodology. The objective values of different designs with lesser uncertainties can be predicted statistically from this, and the sensitivity of the variables can be identified.

Design Objectives and Constraints

The maximum equivalent stress, maximum temperature, natural frequency, and disc volume are the four objectives that may be optimized. All four objectives can be optimized at once using a Multi-Objective Genetic Algorithm (MOGA). An alternate strategy is to pick one goal to optimize while placing limits on all other goals. The outcome is a set of solutions known as the Pareto Optimal and a surface that fits through these solutions known as the Pareto Frontier, which can help expose trade-offs between various objectives statistically.

In this report, The DOE method used in this case is '**Latin Hypercube Sampling**', which is a statistical method for generating a near-random sample of parameter values from a multidimensional distribution.

Define Input Parameters

The input parameters are defined in Figure 7 for the model dimensions, where H28 is the rotor thickness, V29 is the rotor outer diameter, and V30 is the rotor inner diameter.

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

Figure 5. Defined Input Parameters

For the response surface, the DOE method chosen was the Latin Hypercube Sampling (LHS) design with 20 samples. The number of samples was later increased to 30 to improve the response surface's fit to the data. The DOE sample ranges for computing the three parameterized inputs are displayed in Table 1. The results of the DOE computations, determined by the input parameter bounds, are displayed in Figure 6.

Table 1. DOE Sample Value Ranges to Compute

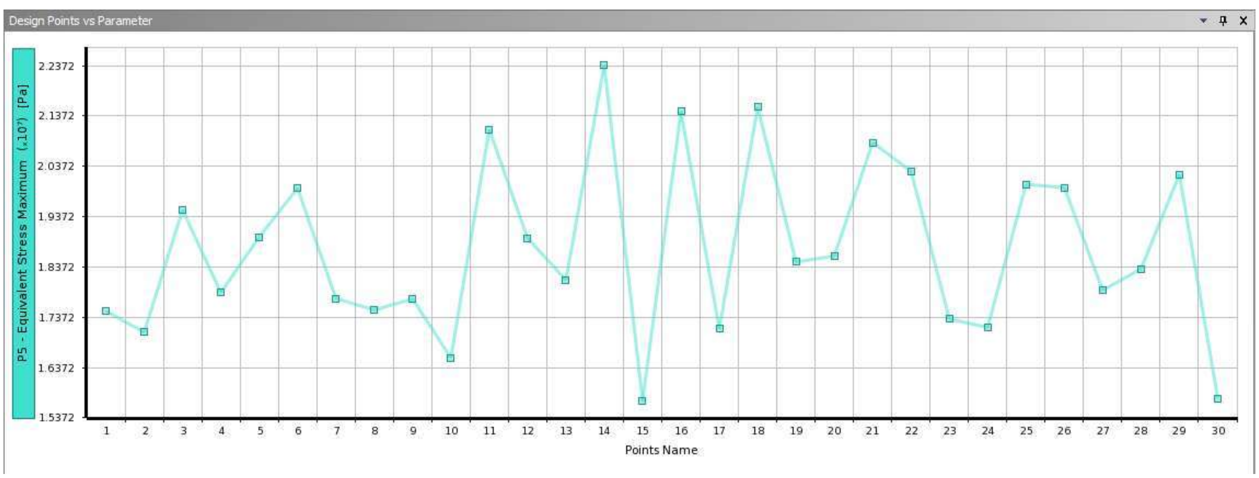
Name	Brake disc thickness	Brake disc inner diameter	Brake disc outer diameter
Lower Bound	22	68	124
Upper bound	28	80	130

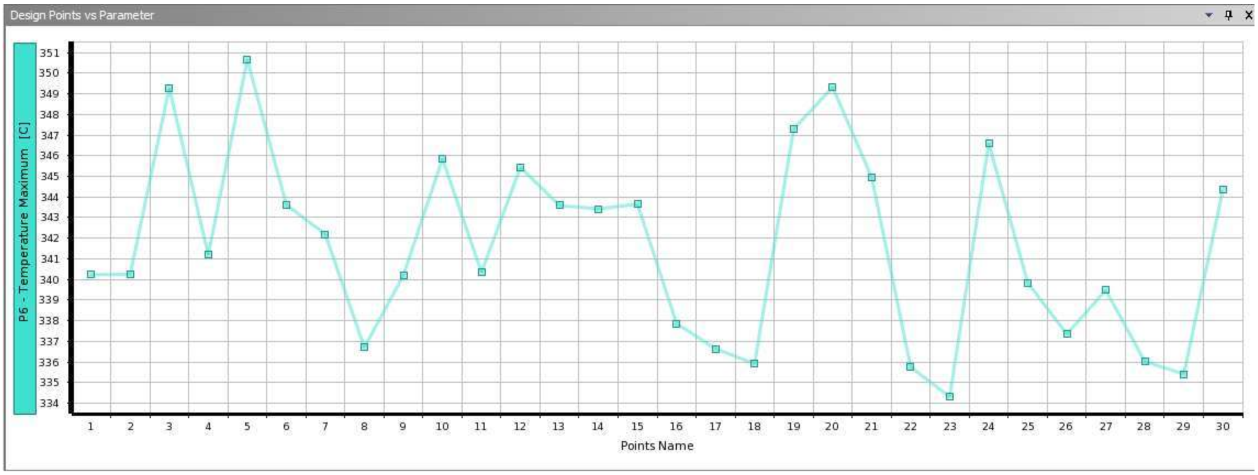
Table of Schematic D2: Design of Experiments (Latin Hypercube Sampling Design : User-Defined Samples : Random Generator Seed = 0 : Number of Samples = 30)

	A	B	C	D	E	F	G
1	Name	P1 - rotor_thickness (mm)	P2 - rotor_OD (mm)	P3 - rotor_ID (mm)	P4 - Total Deformation Reported Frequency (Hz)	P5 - Equivalent Stress Maximum (Pa)	P6 - Temperature Maximum (C)
2	1	24.7	127.2	68.2	1632.8	1.7497E+07	340.24
3	2	25.7	127.73	73.8	1608.6	1.7075E+07	340.24
4	3	22.1	125.07	74.6	1580.6	1.9505E+07	349.3
5	4	25.1	128.8	77.8	1515.7	1.7864E+07	341.19
6	5	22.5	124	71	1652.6	1.8969E+07	350.67
7	6	27.5	122.13	79.8	1593.5	1.9938E+07	343.62
8	7	24.9	129.33	72.6	1575.1	1.7747E+07	342.2
9	8	27.3	129.07	78.6	1531.6	1.7518E+07	336.71
10	9	23.5	125.87	71.4	1625.6	1.7738E+07	340.2
11	10	23.1	129.87	77	1486.6	1.6567E+07	345.85
12	11	23.9	125.6	75.8	1573.3	2.1104E+07	340.35
13	12	22.9	124.53	69.8	1656.3	1.8944E+07	345.43
14	13	24.5	126.13	78.2	1527.2	1.8111E+07	343.59
15	14	26.1	122.4	71.8	1738.6	2.2388E+07	343.42
16	15	23.7	128.53	74.2	1557.9	1.5706E+07	343.65
17	16	26.9	125.33	73.4	1668.3	2.1462E+07	337.87
18	17	26.7	128.27	70.2	1656.9	1.7141E+07	336.64
19	18	25.5	124.8	69.4	1703.9	2.1552E+07	335.92
20	19	22.7	123.73	73	1634.8	1.8471E+07	347.29
21	20	22.3	123.47	77.4	1551.7	1.859E+07	349.32
22	21	24.3	122.67	79.4	1538.2	2.0842E+07	344.96
23	22	27.1	126.67	76.6	1586.7	2.0276E+07	335.75
24	23	27.7	128	72.2	1660.6	1.7337E+07	334.32
25	24	23.3	126.93	75.4	1548.8	1.7172E+07	346.6
26	25	26.3	122.93	79	1581.2	2.0015E+07	339.83
27	26	25.3	124.27	68.6	1715.6	1.9949E+07	337.36
28	27	26.5	127.47	75	1606.7	1.7907E+07	339.48
29	28	25.9	126.4	70.6	1668.4	1.8336E+07	336.03
30	29	27.9	123.2	69	1793.9	2.021E+07	335.42
31	30	24.1	129.6	76.2	1514	1.5761E+07	344.34

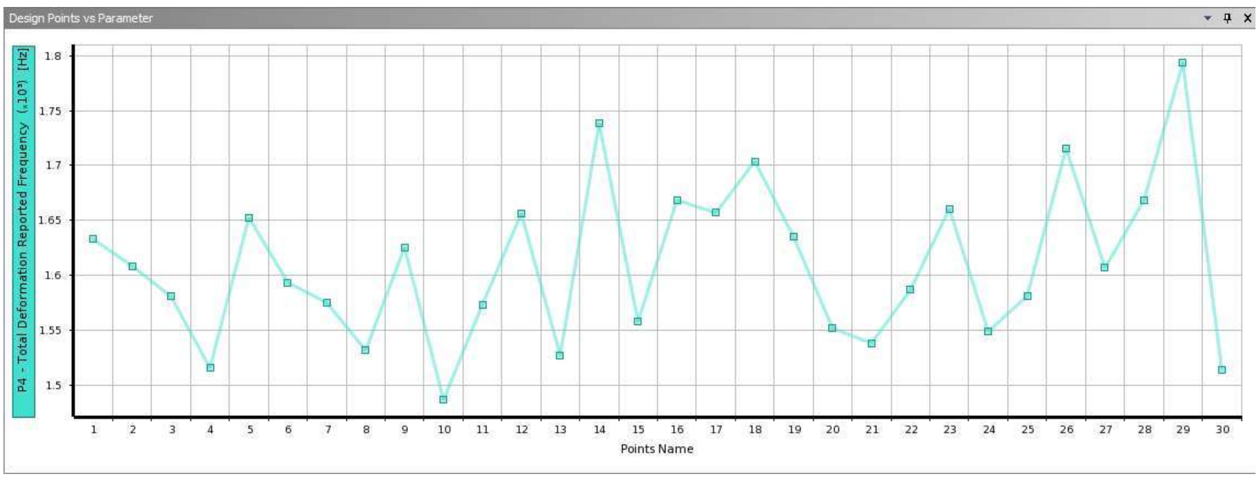
Figure 6. Results of DOE Computations

The above table can be better understood with the help of charts below:





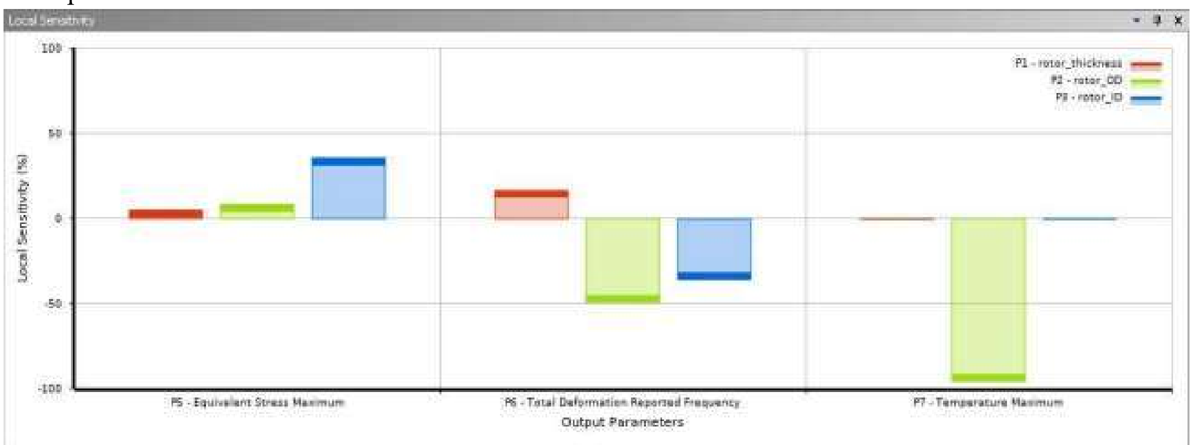
Design Points vs Parameter
P6 - Temperature Maximum [C]
351
350
349
348
347
346
345
344
343
342
341
340
339
338
337
336
335
334
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Points Name



Design Points vs Parameter
P4 - Total Deformation Reported Frequency (x10³) [Hz]
1.8
1.75
1.7
1.65
1.6
1.55
1.5
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Points Name

Response Surface and Sensitivity Analysis:

The link between a number of explanatory variables and one or more response variables is examined using the response surface methodology. Answer surface methodology's fundamental tenet is the utilization of a series of planned trials to produce an ideal response. Observe the local sensitivity in the example below:



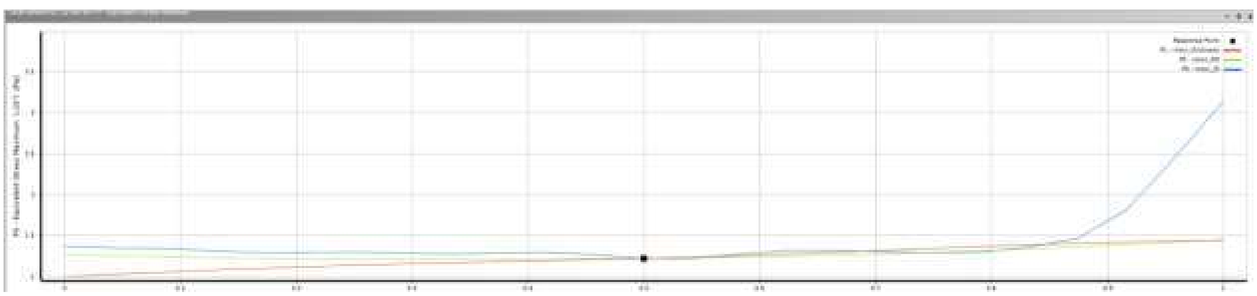


Figure 10. Local Sensitivity Curves for Equivalent Stress

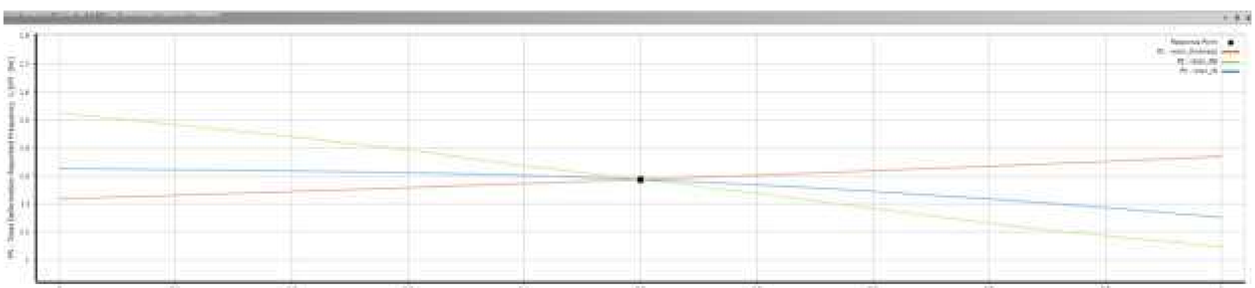


Figure 11. Local Sensitivity Curves for Frequency

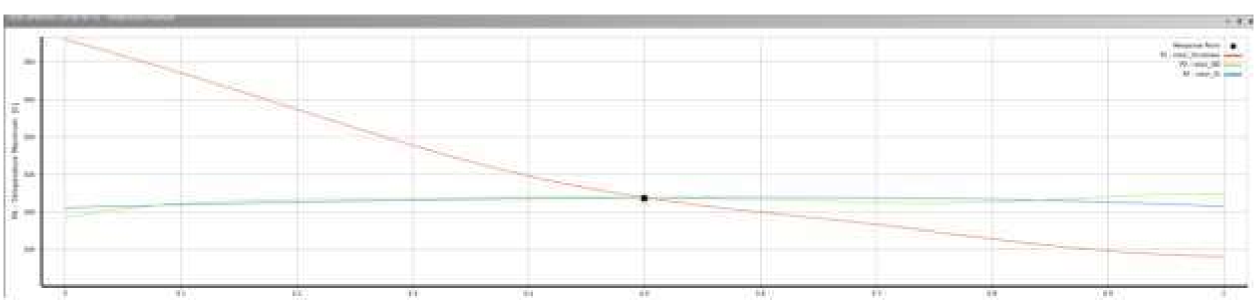


Figure 12. Local Sensitivity Curves for Temperature

The inner diameter's fluctuation has a significant impact on the equivalent stress. The variability of the outer diameter has the greatest impact on the reported first natural frequency, followed by the variability of the inner diameter in a lesser degree and, to a lesser extent, the variability of the thickness of the disc. The variation of the outer diameter, change in thickness, or inner diameter has little to no effect on the temperature evaluated in the transient thermal study.

Genetic Aggregation was the sort of response surface approach applied. This approach makes use of a genetic algorithm to develop a variety of simultaneous solutions. Verification points were then calculated after determining that goodness of fit was satisfactory. A moderately accurate surface model will do for optimization since the objective is to do optimization and a precise response surface is not required. The overall Goodness of Fit plot is shown in Figure 13 after all the adjustments. Figure 14 shows the numerical results after all iterations, which indicate that the verification points were still functioning reasonably well. The resulting point is shown in Figure 15 as well. Figures 16 and 17, respectively, list the points for verification and refining.

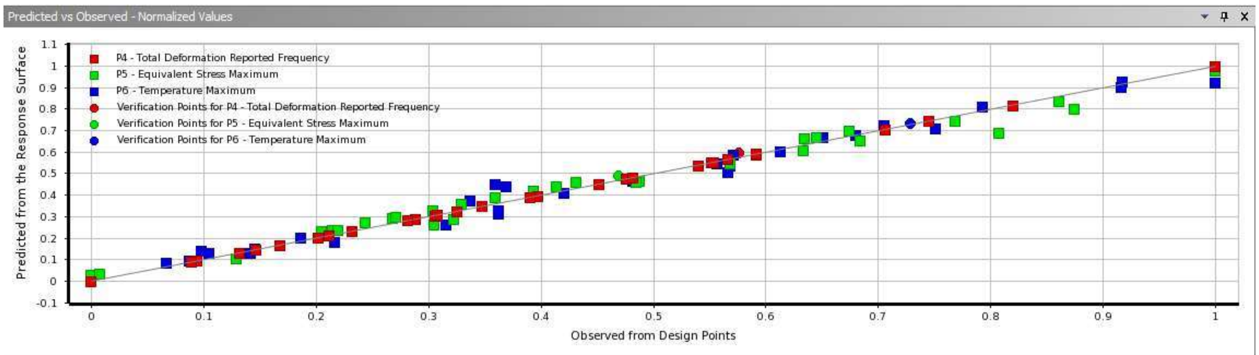


Figure 13. Goodness of Fit for Last Iteration of Verification Points

Table of Schematic E3: Response Surface

	A	B	C	D	E
1		P4 - Equivalent Stress Maximum	P5 - Total Deformation Reported Frequency	P6 - Temperature Maximum	P7 - Solid Volume
2	Coefficent of Determination (Best Value = 1)				
3	Learning Points	0.99855	0.99988	0.99282	1
4	Cross-Validation on Learning Points	0.93451	0.99887	0.94863	1
5	Root Mean Square Error (Best Value = 0)				
6	Learning Points	2.7492E+05	2.2133	0.78296	3.7018E-09
7	Verification Points	6.7298E+05	7.0371	1.0256	3.575E-08
8	Cross-Validation on Learning Points	1.8507E+06	6.7935	2.0936	1.3244E-07
9	Relative Maximum Absolute Error (Best Value = 0%)				
10	Learning Points	11.351	2.5668	22.706	0
11	Verification Points	26.242	7.6033	21.42	0.04508
12	Cross-Validation on Learning Points	64.331	8.081	69.501	0.18638
13	Relative Average Absolute Error (Best Value = 0%)				
14	Learning Points	2.6793	0.81991	6.6609	0
15	Verification Points	5.4344	2.1544	8.6889	0
16	Cross-Validation on Learning Points	19.077	2.7976	16.99	0.027466

Figure 14. Goodness of Fit Results of Response Surface

1	Name	P1 - rotor_thickness (mm)	P2 - rotor_OD (mm)	P3 - rotor_ID (mm)	P4 - Total Deformation Reported Frequency (Hz)	P5 - Equivalent Stress Maximum (Pa)	P6 - Temperature Maximum (C)
2	Response Point	22.5	124	68	1670.4	1.8994E+07	346.37

Figure 15. Response Point

	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)	P5 - Total Deformation Reported Frequency (Hz)	P6 - Temperature Maximum (C)	P7 - Solid Volume (m^3)
2	1	29.925	159.81	89.907	3.9467E+07	1045.7	332.86	0.0019073
3	2	29.898	124.87	70.386	1.4111E+07	1781.8	332.23	0.001199
4	3	23.412	159.37	89.802	3.3561E+07	964.52	344.58	0.0015407
5	4	23.956	125.09	83.671	1.2941E+07	1411.6	344.42	0.0008931
6	5	29.024	124.26	89.74	3.3266E+07	1347.4	331.67	0.00093922
7	6	20.094	158.92	85.303	1.2732E+07	958.91	362.59	0.0013835
8	7	20.302	157.62	70.001	1.2514E+07	991.33	354.39	0.0014664
9	8	24.264	134.22	78.23	1.2768E+07	1419.8	342.71	0.0011293
10	9	28.689	136.68	70.065	1.4228E+07	1520.6	338.23	0.0014359
11	10	25.384	125.52	89.983	3.2701E+07	1277.4	335.05	0.00087738
12	11	26.812	158.73	87.924	2.0646E+07	1023.8	337.96	0.0017295
13	12	20.221	144.81	70.499	1.1837E+07	1194.4	362.38	0.0012124

Figure 16. Refinement Points

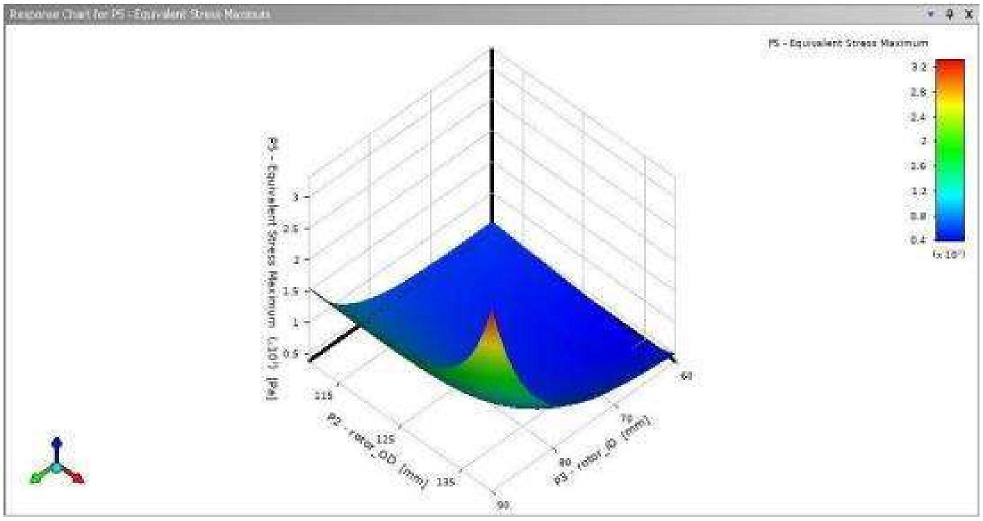
	A	B	C	D	E	F	G	H
1	Name	P1 - rotor_thickness (mm)	P2 - rotor_OD (mm)	P3 - rotor_ID (mm)	P4 - Equivalent Stress Maximum (Pa)	P5 - Total Deformation Reported Frequency (Hz)	P6 - Temperature Maximum (C)	P7 - Solid Volume (m^3)
2	1	29.925	159.81	89.907	3.9467E+07	1045.7	332.86	0.0019073
3	2	29.898	124.87	70.386	1.4111E+07	1781.8	332.23	0.001299
4	3	20.221	144.81	70.499	1.1837E+07	1194.4	362.38	0.0012124
5	4	23.412	159.37	89.802	3.3561E+07	964.52	344.58	0.0015407
6	5	29.024	124.26	89.74	3.3266E+07	1347.4	331.87	0.00093922
7	6	29.939	159.74	89.921	1.7528E+07	1115.8	333.31	0.0020165
8	7	23.956	125.09	83.671	1.2941E+07	1411.6	344.42	0.0008931
9	8	20.443	142.68	78.878	1.2072E+07	1225.9	360.42	0.0011528
10	9	20.07	127.08	84.454	1.2559E+07	1332	361.83	0.00081387
11	10	20.302	157.62	70.001	1.2514E+07	991.33	354.39	0.0014664
12	11	20.094	158.92	85.303	1.2732E+07	958.91	362.59	0.0013835
13	12	28.689	136.68	70.065	1.4228E+07	1520.6	338.23	0.0014359
14	13	24.264	134.22	78.23	1.2768E+07	1419.8	342.71	0.0011293
15	14	25.384	125.52	89.983	3.2701E+07	1277.4	335.05	0.00087738
16	15	26.901	126.9	73.362	1.3647E+07	1637	336.39	0.0011117
17	16	26.812	158.73	87.924	2.0646E+07	1023.8	337.96	0.0017295
18	17	24.865	150.78	70.114	1.3632E+07	1192.9	340.65	0.0015867
19	18	26.184	144.87	76.132	1.3884E+07	1290.7	338.11	0.0014647

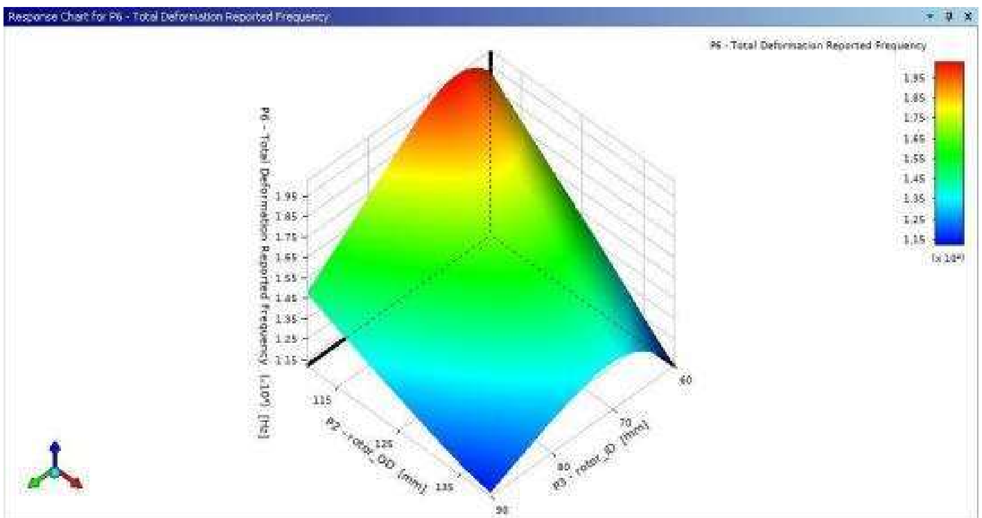
Figure 17. Verification Points

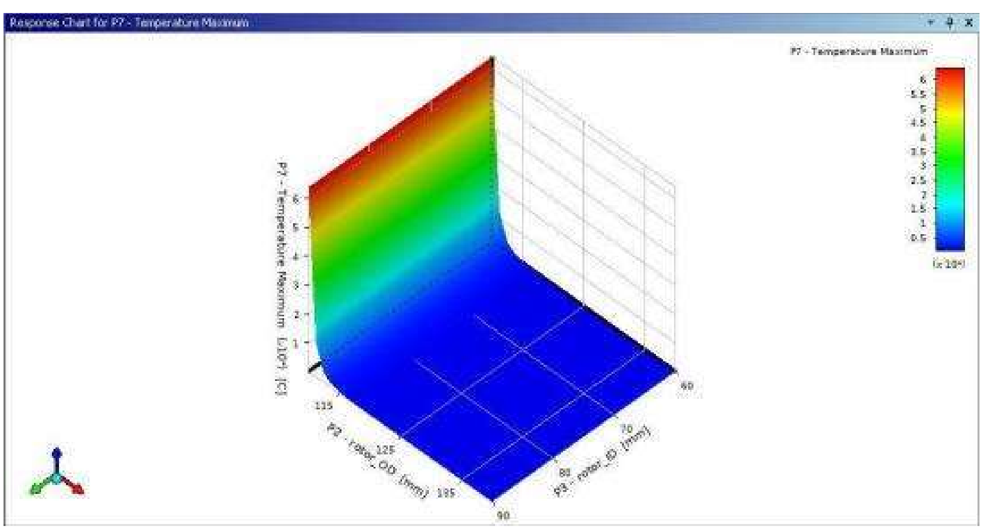
Below is a depiction of the response curves for each parameter. Figures 15, 16, 17, 18, and 20, show how monotonicity can be exhibited while still adhering to the limitations of the design points used for this simulation. Due to moments and required forces to stop the rotor, equivalent stress increases with rotor thickness. Since there is more material that can endure vibrations as rotor thickness grows, natural frequency rises. Temperature drops as rotor thickness rises, possibly as a result of better heat flux distribution throughout the rotor body.

Natural frequency drops with increasing rotor outer diameter, which is probably caused by increased moments and bigger contact and vibration surface areas. It is possible that bigger moments of inertia allowing for vibrations are the reason why the natural frequency drops as the inner diameter of the rotor grows. Regarding trends for the Solid Volume, one illustration of how an increase in the rotor's outer diameter will cause the solid volume to rise. Similar to this, as rotor thickness increases, volume also does, and as rotor inner diameter increases, material is withdrawn from the body and volume decreases.

The response charts can be seen below:







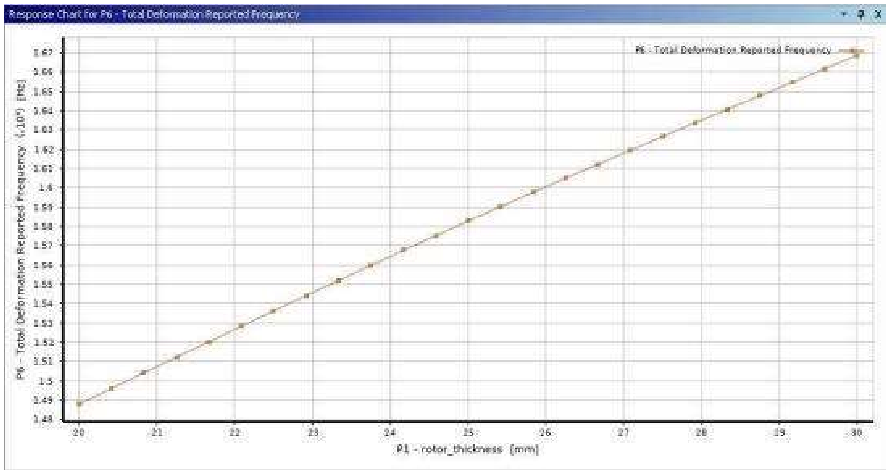


Figure 18. Response Curve for Rotor Thickness and Frequency

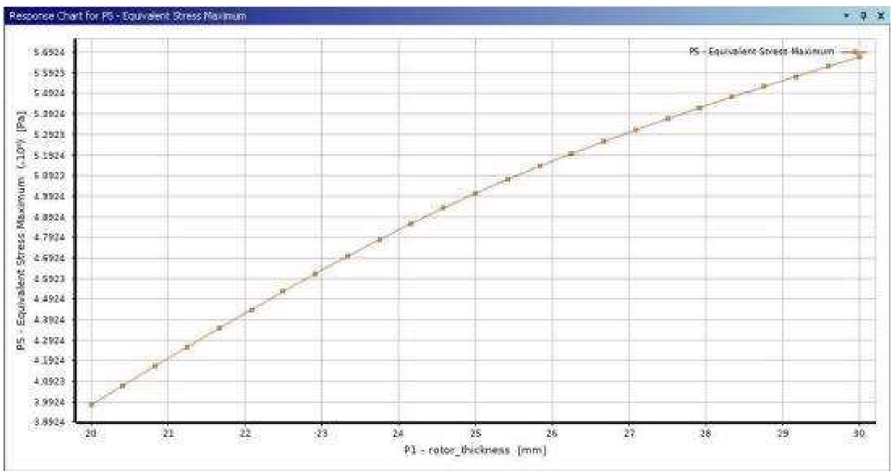


Figure 19. Response Curve for Rotor Thickness and Equivalent Stress

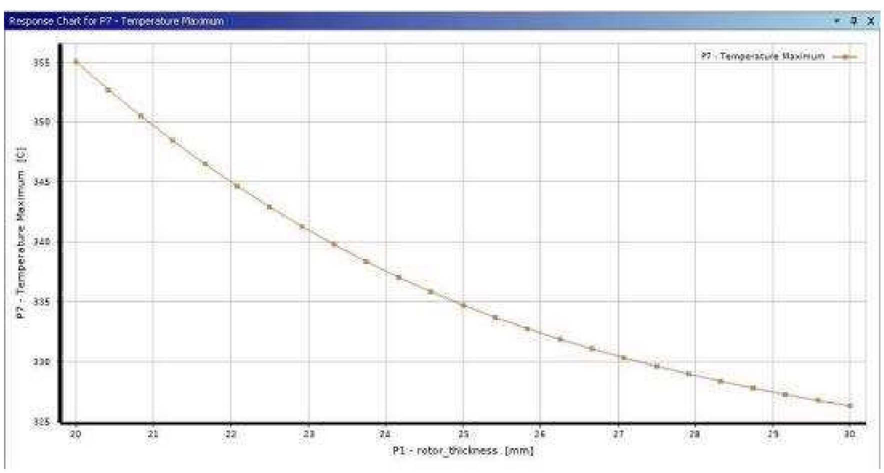


Figure 20. Response Curve for Rotor Thickness and Temperature

Optimization

The rotor thickness, rotor outer diameter, and rotor inner diameter serve as design parameters. Following is a definition of the restrictions for this problem with a single objective:

- 17 MPa is the maximum equivalent stress.
- 1100 Hz is the natural frequency.
- 400 degrees Celsius

The goal of this issue is to reduce the brake disc's volume. The following possible trade-offs are mentioned:

- Increasing rotor outer diameter, which results in a fall in natural frequency;

- Increasing rotor thickness, which results in an increase in solid volume.

- Increasing rotor thickness will improve solid volume while lowering temperature.

For the optimization curves and restrictions applied, see Figure 21.

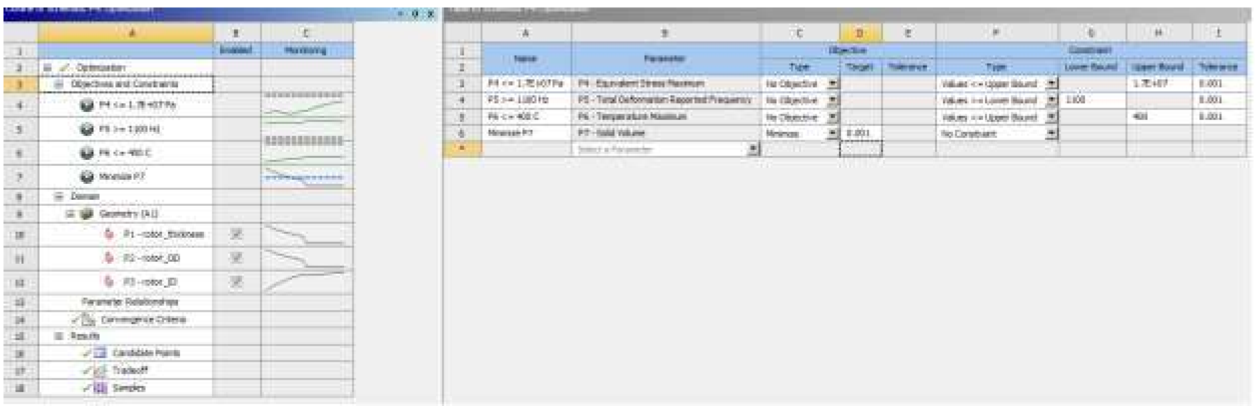


Figure 21. Optimization Curves

The candidate points are listed below:

5	⊟ Optimization Method				
6	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. It supports multiple objectives and constraints and aims at finding the global optimum.			
7	Configuration	Generate 3000 samples initially, 600 samples per iteration and find 3 candidates in a maximum of 20 iterations.			
8	Status	Converged after 8 evaluations, because all permutations have been evaluated.			
9	⊟ Candidate Points				
10		Candidate Point 1	Candidate Point 1 (verified)	Candidate Point 2	Candidate Point 2 (verified)
11	P1 - rotor_thickness (mm)	22.5		22.5	
12	P2 - rotor_OD (mm)	130		130	
13	P3 - rotor_ID (mm)	68		80	
14	P4 - Total Deformation Reported Frequency (Hz)	★★ 1539.6	★★ 1516.3	★ 1433.4	★ 1427.1
15	P5 - Equivalent Stress Maximum (Pa)	★ 1.6782E+07	★★★ 1.531E+07	★ 1.638E+07	★ 1.6437E+07
16	P6 - Temperature Maximum (C)	★★ 345.19	★★ 347.52	★★ 347.99	★★ 348.45

Figure 22. Candidate Points

Results and Discussion

The best solution found for the chosen boundaries had a substantially lower volume than the original model (given by Professor Yi Ren), but a significantly higher value of maximum temperature was produced, which should be viewed as a trade-off. A comparative study could be investigated to better understand whether a trade-off is required because the bounds taken in this study may be viewed as large.