Project 2.1: Brake Disc Design

MAE 598: Design Optimization

By: Anney Romo Herrera

CAD Model

For the CAD model in this project, the same geometry was used as the one given in the tutorial. In the geometry, the rotor thickness, outer rotor diameter, and inner rotor diameter were set as parameters. The brake disk was solid and was later assigned gray cast iron as its material. The frozen parts were the brake pads and were assigned structural steel as their material.

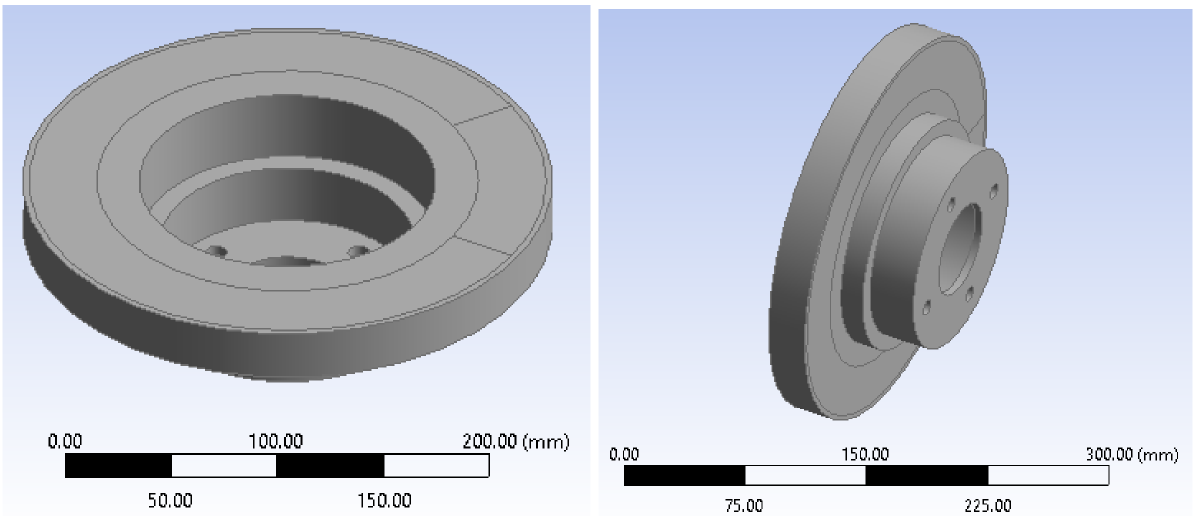


Figure 1: Solid Geometry

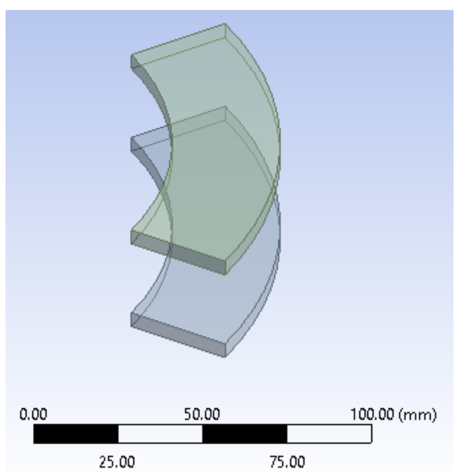


Figure 2: Frozen Parts Geometry

CAE Analysis (Structural, Modal, and Thermal)

The initial analysis shown in figures 3 - 5 below was performed in order to set the parameters: volume, maximum equivalent stress, frequency, and maximum temperature.

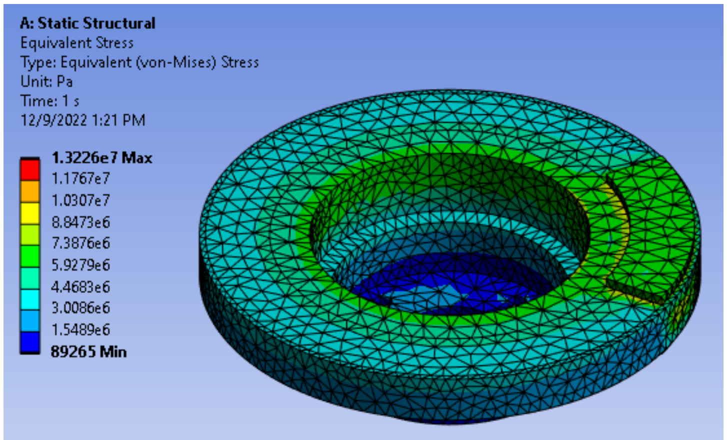


Figure 3: Initial Equivalent Stress From Static Structural Analysis

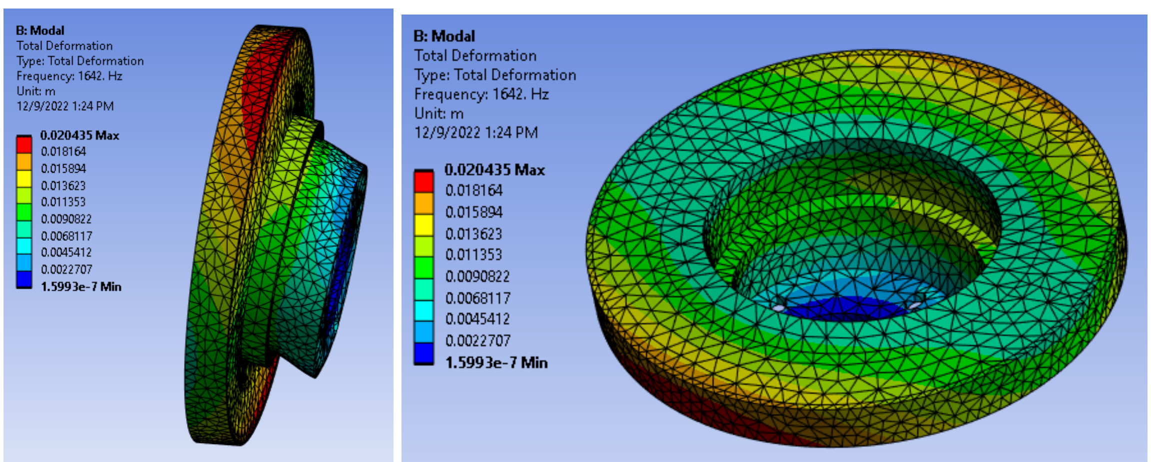


Figure 4: Initial Total Deformation From Modal Analysis

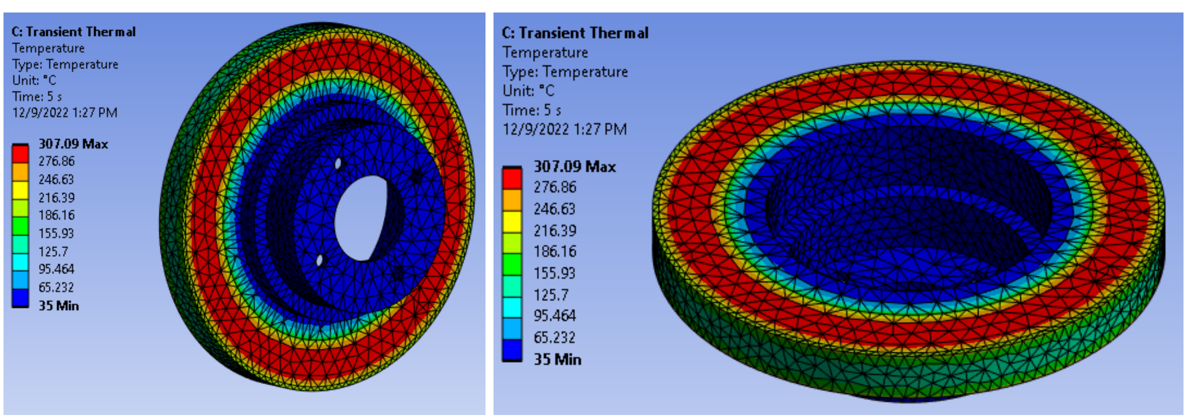


Figure 5: Initial Temperature From Transient Thermal Analysis

Design of Experiments

For the design of experiments, the Latin hypercube sampling design was used. Many samples were gathered with different bounds in order to reach a point were there were no errors in the samples. Additionally, many iterations were run to later narrow the bounds for each parameter. One of the final iterations that led to the last one was a sample of 50 with bounds of [5 27], [124 150], and [66 90] for thickness, outer diameter, and inner diameter respectively. Based on the optimization results from that sample, the final bounds were chosen. In the end, the final design points used were 20. The bounds were [12 15], [123 125], and [75 82] for thickness, outer diameter, and inner diameter respectively.

	A	B
1		Enabled
2	Design of Experiments	
3	Input Parameters	
4	Static Structural (A1)	
5	P1 - rotor_thickness	☑
6	P2 - rotor_OD	☑
7	P3 - rotor_ID	☑
8	Output Parameters	
9	Static Structural (A1)	
10	P4 - Equivalent Stress Maximum	
11	P7 - Solid Volume	
12	Modal (B1)	
13	P5 - Total Deformation Reported Frequency	
14	Transient Thermal (C1)	
15	P6 - Temperature Maximum	
16	Charts	
17	Parameters Parallel	
18	Design Points vs Parameter	

	A	B
1	Property	Value
2	Design Points	
3	Preserve Design Points After DX Run	☑
4	Retain Data for Each Preserved Design Point	☑
5	Failed Design Points Management	
6	Number of Retries	0
7	Design of Experiments	
8	Design of Experiments Type	Latin Hypercube Sampling Design
9	Samples Type	User-Defined Samples
10	Random Generator Seed	0
11	Number of Samples	20
12	Design Point Report	
13	Report Image	None

Figure 6: General Design Of Experiments Set Up

	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	DP 82	13.575	123.45	79.725	1.2218E+07	1786.8	405.58	0.00060682
3	2	DP 86	14.175	124.35	75.875	1.1582E+07	1662	391.01	0.00064653
4	3	DP 72	12.075	124.45	76.925	1.1684E+07	1647.3	432.89	0.00058103
5	4	DP 84	13.875	123.05	76.575	1.2381E+07	1719.3	402.8	0.00062116
6	5	DP 74	12.375	123.75	81.125	1.1576E+07	1786.4	428.99	0.00057253
7	6	DP 91	14.925	123.85	80.075	1.1444E+07	1792.2	381.13	0.00064778
8	7	DP 83	13.725	124.25	81.475	1.1438E+07	1787.7	399.03	0.00061374
9	8	DP 90	14.775	124.05	77.975	1.1761E+07	1739.5	382.64	0.00065376
10	9	DP 78	12.975	124.85	75.175	1.1664E+07	1597.1	411.39	0.0006169
11	10	DP 77	12.825	123.15	76.225	1.3711E+07	1683.9	422.87	0.00059248
12	11	DP 80	13.275	123.95	75.525	1.1973E+07	1646.8	408.79	0.00061594
13	12	DP 76	12.675	124.15	80.425	1.1671E+07	1761.7	420.34	0.00058667
14	13	DP 81	13.425	123.65	81.825	1.2033E+07	1811.5	407.24	0.00059805
15	14	DP 87	14.325	124.55	78.325	1.1554E+07	1724.9	387.86	0.00064497
16	15	DP 79	13.125	123.25	77.275	1.1939E+07	1719.5	415.77	0.00059935
17	16	DP 89	14.625	123.35	79.025	1.2233E+07	1785.4	388.18	0.00063758
18	17	DP 88	14.475	124.95	79.375	1.1804E+07	1738.4	384.2	0.00065016
19	18	DP 85	14.025	124.65	78.675	1.1696E+07	1726.4	392.37	0.00063606
20	19	DP 75	12.525	123.55	77.625	1.1769E+07	1706.3	426.75	0.00058399
21	20	DP 73	12.225	124.75	80.775	1.162E+07	1740.1	428.2	0.00057886

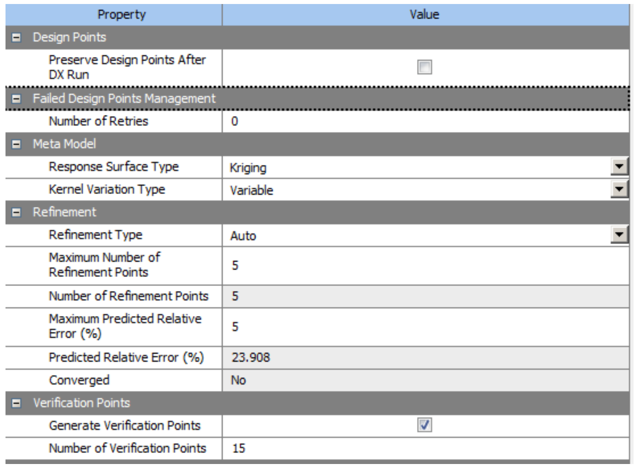
Figure 7: Final Design Points

Table of Schematic D2: Design of Experiments (Latin Hypercube Sampling Design : User-Defined Samples : Random Generator Seed = 0 : Number of Samples = 50)									
	A		B	C	D	E	F	G	H
1	Name		P1 - rotor_thic... (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	DP 16	13.14	125.82	89.28	1.7148E+07	1790.3	405.98	0.00058828
3	2	DP 16	17.1	140.9	75.84	1.1983E+07	1271.8	346.53	0.00097171
4	3	DP 14	5.66	146.1	68.16	1.1569E+07	691.93	779.59	0.00048531
5	4	DP 16	14.9	139.34	88.8	2.0614E+07	1403.5	372.65	0.00080168
6	5	DP 14	6.54	129.98	70.08	1.1402E+07	1038.3	687.82	0.00044087
7	6	DP 18	25.46	132.06	80.64	1.2795E+07	1489.1	302.91	0.0011061
8	7	DP 16	14.46	142.98	87.84	2.064E+07	1322.4	378.88	0.00083641
9	8	DP 18	25.02	139.86	66.24	2.0515E+07	1357.8	304.28	0.0013748
10	9	DP 15	9.18	133.62	73.44	1.1659E+07	1163.1	518.55	0.00056529
11	10	DP 14	7.86	149.74	68.64	1.1774E+07	753.02	587.39	0.00062726
12	11	DP 15	10.94	124.26	69.6	2.2092E+07	1383.9	464.85	0.00055726
13	12	DP 14	7.42	136.74	76.8	1.4231E+07	1085.5	616.25	0.00051591
14	13	DP 15	12.7	135.7	72.48	1.1618E+07	1214.8	410.22	0.00072777
15	14	DP 17	18.42	148.18	74.88	1.6478E+07	1144.3	334.91	0.001157
16	15	DP 15	10.5	128.94	89.76	2.6338E+07	1711.7	469.58	0.00054835
17	16	DP 18	22.38	144.54	85.92	1.8307E+07	1269.1	312.25	0.0012007
18	17	DP 17	21.5	137.26	70.56	4.4757E+07	1341.1	316.14	0.0011325
19	18	DP 16	16.66	148.7	84.96	1.7502E+07	1205.2	350.83	0.0010268
20	19	DP 14	6.98	134.66	79.68	1.1175E+07	1183	649.1	0.0004862
21	20	DP 14	6.1	149.22	81.6	1.1583E+07	852.16	729.44	0.00053387
22	21	DP 15	12.26	140.38	77.76	1.2021E+07	1206.6	419.9	0.00074705
23	22	DP 18	22.82	128.42	85.44	1.743E+07	1583.1	311.32	0.00090803
24	23	DP 18	25.9	146.62	83.04	1.8052E+07	1217.5	301.49	0.0014282
25	24	DP 14	8.3	127.38	75.36	1.1357E+07	1358	565.21	0.00048752
26	25	DP 17	19.74	137.78	69.12	2.2113E+07	1273.8	325.81	0.0010725
27	26	DP 16	16.22	134.14	79.2	1.7834E+07	1473.3	355.68	0.00082332
28	27	DP 17	21.06	133.1	83.52	1.335E+07	1510.8	318.34	0.00095244
29	28	DP 17	17.98	127.9	72.96	1.2877E+07	1534.7	339.72	0.00082762

Figure 8: Semi-final Design Points

Response Surface

For the response surface, Kringing type was chosen to compensate for the small number of samples at the end. Additionally, about ¼ of the sample size was used as verification points on every set of samples run. The figures below show the response surface configuration and final response point.



Property	Value
Design Points	
Preserve Design Points After DX Run	☐
Failed Design Points Management	
Number of Retries	0
Meta Model	
Response Surface Type	Kriging
Kernel Variation Type	Variable
Refinement	
Refinement Type	Auto
Maximum Number of Refinement Points	5
Number of Refinement Points	5
Maximum Predicted Relative Error (%)	5
Predicted Relative Error (%)	23.908
Converged	No
Verification Points	
Generate Verification Points	☑
Number of Verification Points	15

Figure 9: General Response Surface Setup

Table 1: Response Points

Name	**P1 (mm)**	**P2 (mm)**	**P3 (mm)**	**P4 (Pa)**	**P5 (Hz)**	**P6 (C)**	**P7 (m^3)**
Semi-final Response Point	16	137	78	16336176.1	1379.139738	357.0146723	0.0008594019427
Final Response Point	13.5	124	78.5	11624249.07	1735.973582	404.2538199	0.0006143285002

Sensitivity

In the final sample, the sensitivities were most monotonic. All but one parameter were mostly monotonic, which was equivalent stress. The sensitivities are shown in figures 10-14. From these figures, thickness seems to have the highest impact. For both temperature and volume, thickness has the steepest curve.

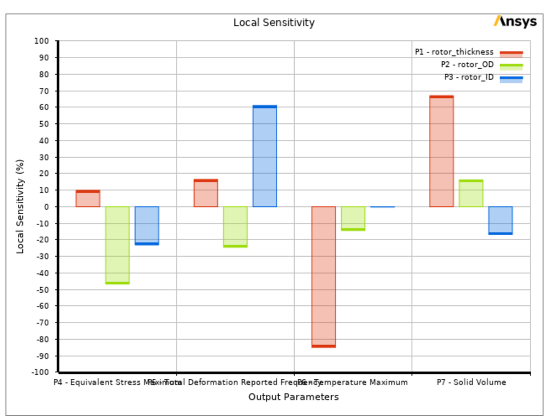


Figure 10: Local Sensitivity

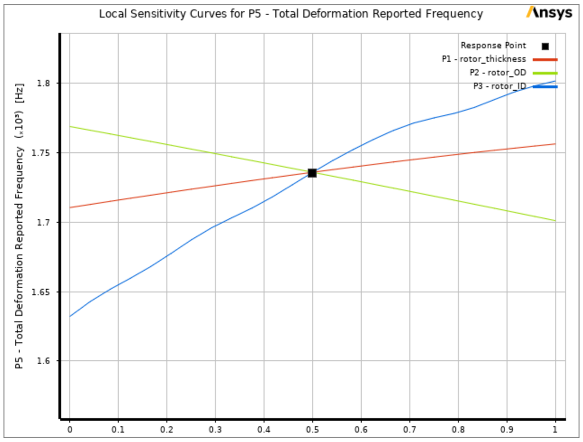


Figure 11: Frequency Sensitivity

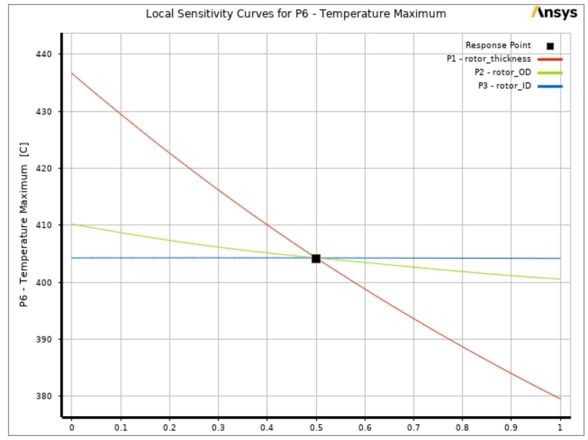


Figure 12: Temperature Sensitivity

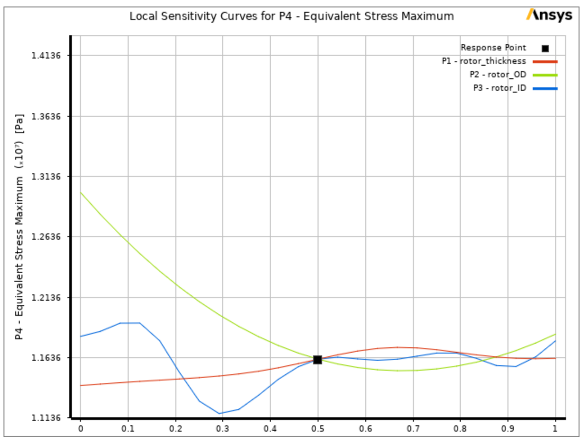


Figure 13: Equivalent Stress Sensitivity

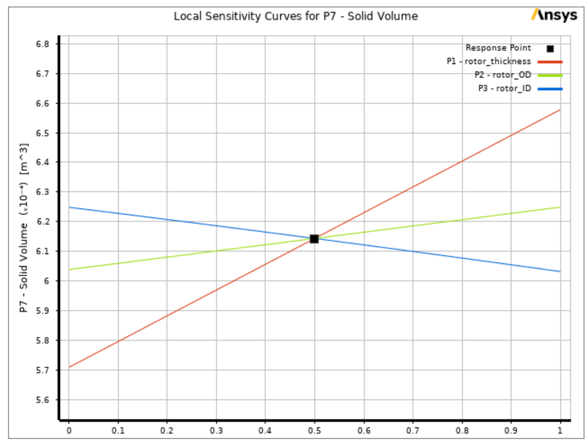


Figure 14: Volume Sensitivity

Optimization (MOGA)

For optimization, the MOGA method was used. In this method, volume was chosen as the main objective to minimize. Then, stress, frequency, and temperature were set as constraints. Their bounds were determined based on the average of the corresponding set of samples.

	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	2000
10	Tolerance Settings	☑
11	Verify Candidate Points	☑
12	Number of Initial Samples	100
13	Number of Samples Per Iteration	100

Figure 15: General Optimization Setup

Reference	Name	P1 - r… (…	P2 - r… (…	P3 - r… (…	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	12.653	124.95	83.511	1.6033E+07	14.56%	1783.9	1.28%	416.23	-0.88%	0.00058516	-0.49%
	Candidate Point 1 (verified)				1.2585E+07	-10.08%	1793.3	1.82%	417.95	-0.47%	0.00058516	-0.49%
	Candidate Point 2	12.692	124.13	80.011	1.5521E+07	10.90%	1745	-0.93%	415.69	-1.01%	0.00058806	0.00%
	Candidate Point 2 (verified)				1.3996E+07	0.00%	1761.3	0.00%	419.94	0.00%	0.00058805	0.00%
	Candidate Point 3	12.676	125.58	82.874	1.5834E+07	13.13%	1751.2	-0.57%	415.25	-1.12%	0.00059398	1.01%
	Candidate Point 3 (verified)				1.1223E+07	-19.81%	1757.3	-0.23%	415.69	-1.01%	0.00059399	1.01%

Figure 16: Candidate Points From Semi-final Optimization

Name	Parameter	Objective			Constraint			
		Type	Target	eran	Type	Lower Bound	Upper Bound	Tolerance
Minimize P7	P7 - Solid Volume	Minimize	0		No Constraint			
P4 <= 1.3226E+07 Pa	P4 - Equivalent Stress Maximum	No Objective			Values <= Upper Bound		1.3226E+07	0.001
P5 >= 1642 Hz	P5 - Total Deformation Reported Frequency	No Objective			Values >= Lower Bound	1642		0.001
P6 <= 405.9 C	P6 - Temperature Maximum	No Objective			Values <= Upper Bound		405.9	0.001

Figure 17: Objective And Constraints For Final Optimization

Reference	Name	P1 - rot… (mm)	P2 - rot… (mm)	P3 - ro… (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	13.669	123.16	81.866	1.2916E+07	-1.84%	1828.8	0.08%	405.74	0.08%	0.00059933	-0.04%
	Candidate Point 1 (verified)				1.3085E+07	-0.55%	1830.7	0.18%	405.79	0.10%	0.00059933	-0.04%
	Candidate Point 2	13.634	123.31	81.965	1.2652E+07	-3.85%	1825.1	-0.13%	405.38	-0.01%	0.00059958	0.00%
	Candidate Point 2 (verified)				1.3158E+07	0.00%	1827.4	0.00%	405.4	0.00%	0.00059957	0.00%
	Candidate Point 3	13.515	123.6	81.918	1.2141E+07	-7.73%	1814.6	-0.70%	405.8	0.10%	0.00059964	0.01%
	Candidate Point 3 (verified)				1.2204E+07	-7.25%	1815.1	-0.68%	405.83	0.11%	0.00059964	0.01%

Figure 18: Candidate Points From Final Optimization

From Figure 18 above, the variation from both candidate points to verified points and candidate points to candidate points is relatively low. This is a good indicator of approaching an optimal solution.

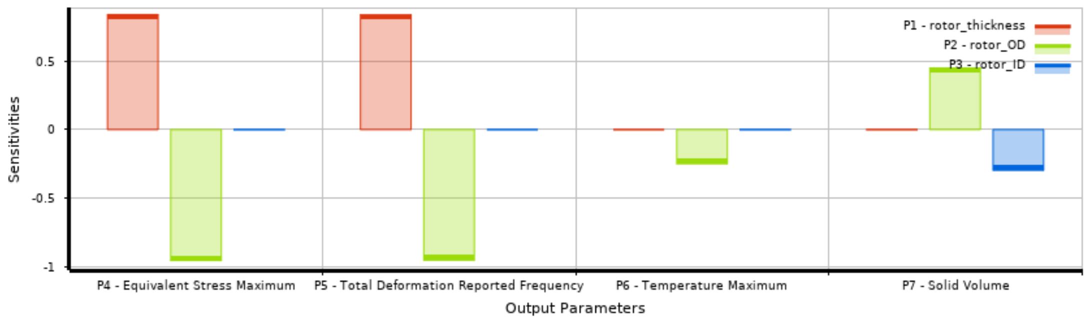


Figure 19: Sensitivities for Final Optimization

Optimal Solution

The figures below are a visual representation of the final solution.

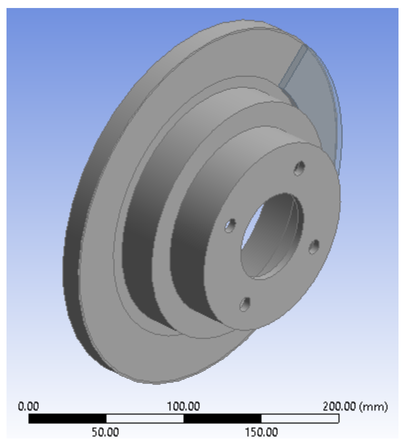


Figure 20: Final Geometry

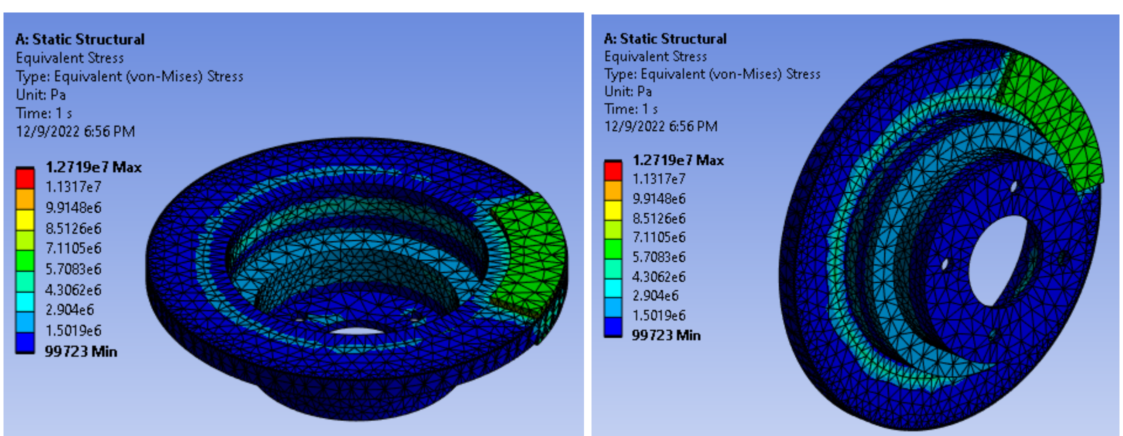


Figure 21: Final Equivalent Stress From Static Structural Analysis

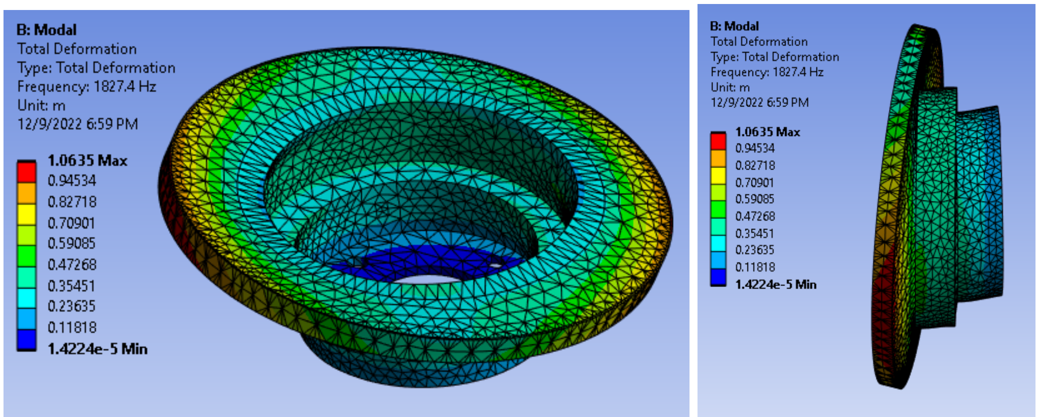


Figure 22: Final Total Deformation From Modal Analysis

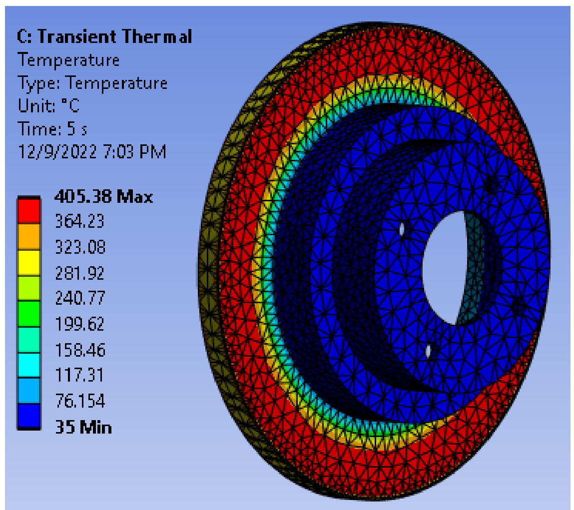


Figure 23: Final Temperature From Transient Thermal Analysis

Result Validation

The optimal solution reached was a pretty reasonable optimization of the initial design. It minimized volume, minimized stress, and maximized frequency as shown in the table below. Specifically, the main objective, the volume, was significantly improved. The only aspect in which it was unsuccessful was it increased the temperature instead of decreasing it.

Table 2: Results Comparision

Parameter	Initial Value	Optimal value	% Difference
P1 - rotor_thickness (mm)	25	13.63381702	-58.84%
P2 - rotor_OD (mm)	125	123.305501	-1.36%
P3 - rotor_ID (mm)	75	81.96505569	8.87%
P4 - Equivalent Stress Maximum (Pa)	13226000	13157839.5	-0.52%
P5 - Total Deformation Reported Frequency (Hz)	1642	1827.424017	10.69%
P6 - Temperature Maximum (C)	307.09	405.401825	27.60%
P7 - Solid Volume (m^3)	0.00099667	0.0005995741148	-49.75%

Although the design failed in one aspect, that is a tradeoff of MOGA optimization in ANSYS. You can only set one variable as the objective, the rest have to be set as constraints that can exist in the samples.

Ultimately, I believe the optimal design was reasonable based on the iterations ran. A bigger sample was first used and then the optimal design from there was used to create a new set of bounds and samples. Additionally, the sensitivity of the final sample was mostly monotonic. Finally, the variance percentage in the candidate points from optimization was pretty low.