MAE 598 DesignOptimization

Project 2

Design Optimization of a Brake Disc

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Problem Definition:

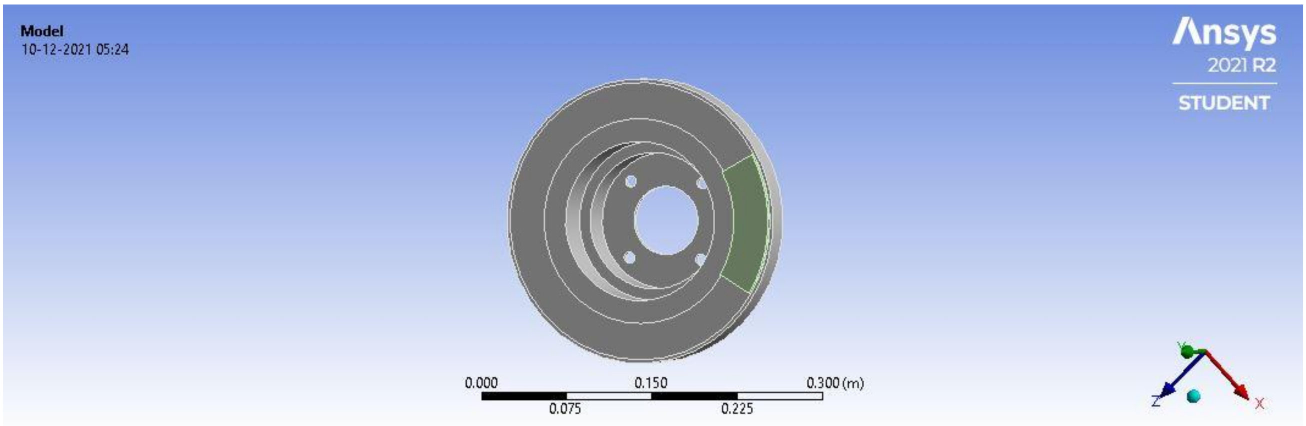
The goal of this project is to design a brake disc such that the following objectives are achieved,

- minimal volume, (i.e., thickness and inner and outer diameter of brake disc), so that we can reduce the cost of material used
- the smallest possible value of maximum stress developed so that the material should not fail under braking conditions.
- highest first natural frequency, so that the disc does not fail due to resonance and
- lowest maximum temperature developed so that contact surfaces are not damaged due to induced thermal stresses,

design optimization techniques (specifically DOE).

Setup and Analysis Results:

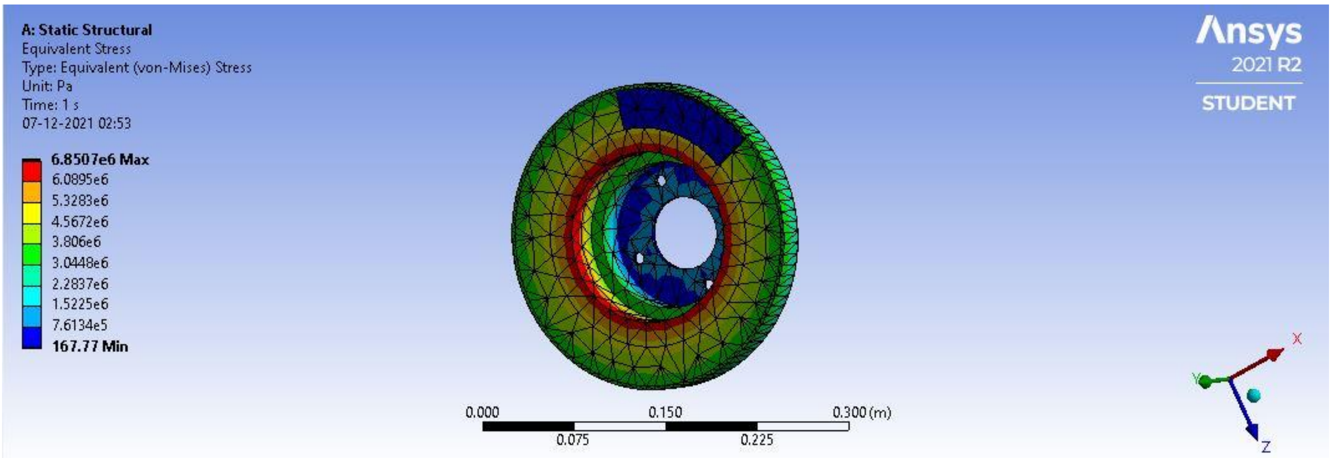
The model consists of a brake disc and brake pads. The material for the brake disc is chosen as 'Grey Cast Iron' and for the brake pad, it is considered as 'Structural Steel'. Mesh size is also kept the same.



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.



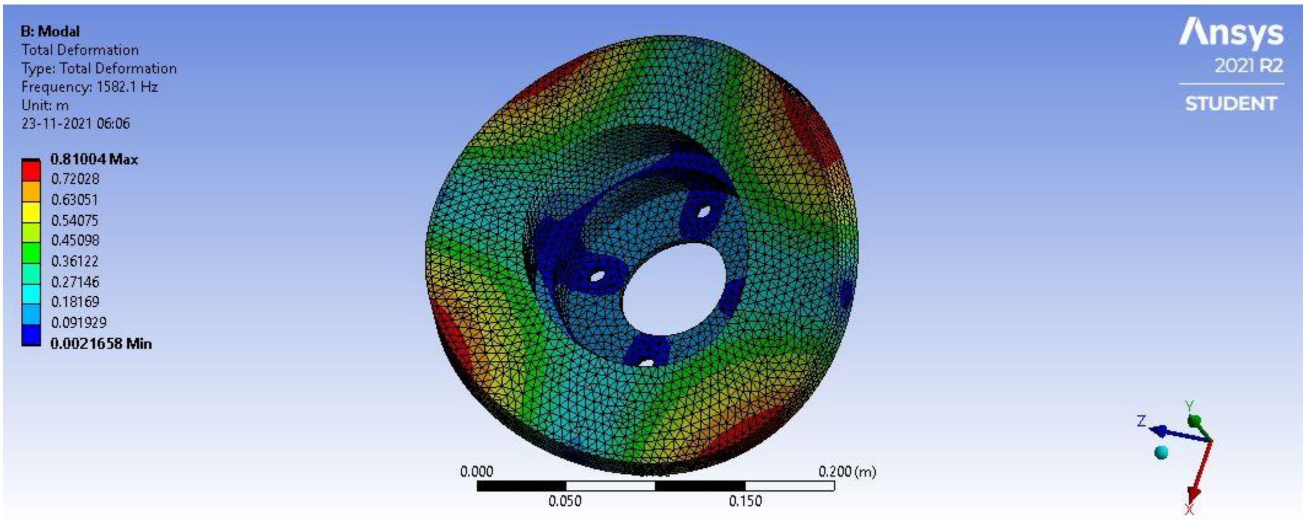
After solving, a maximum stress value of 6.8507 MPa is obtained for the given model. The lowest possible value of stress on the circular contact patch (between disc and brake pad) can be observed to be around 3.0448 MPa.

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



Tabular Data

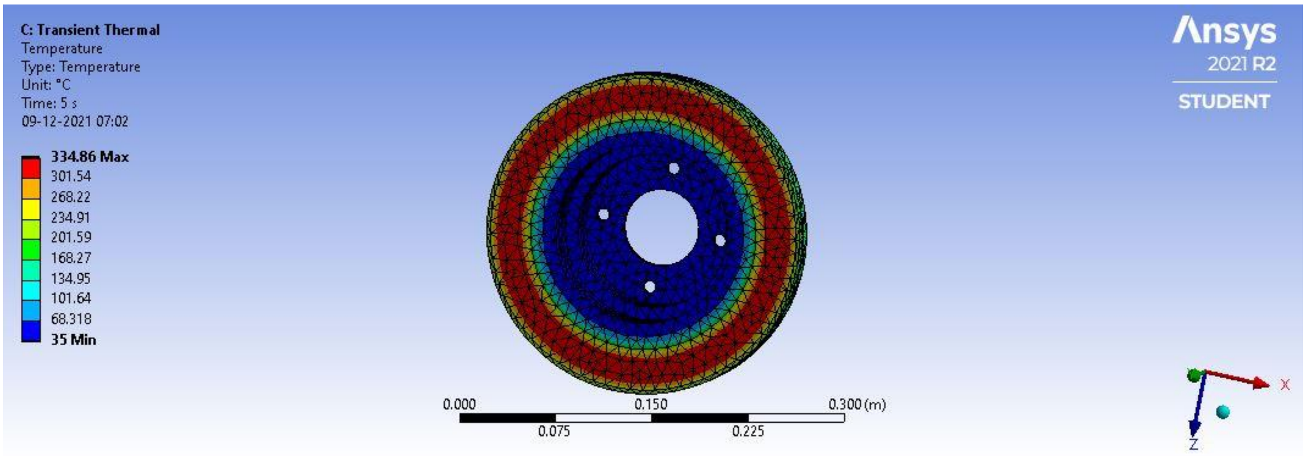
	Mode	Frequency [Hz]
1	1.	0.
2	2.	0.
3	3.	0.
4	4.	1.2895e-003
5	5.	1.5783e-003
6	6.	1.9254e-003
7	7.	1582.1
8	8.	1588.2
9	9.	2734.2
10	10.	2753.6

The first natural frequency can be observed to be 1582.1Hz for mode 7. The maximum value of deformation evaluated in the analysis is 0.81004m. The deformation is focused primarily at 90degrees from the holes in the back of the disc.

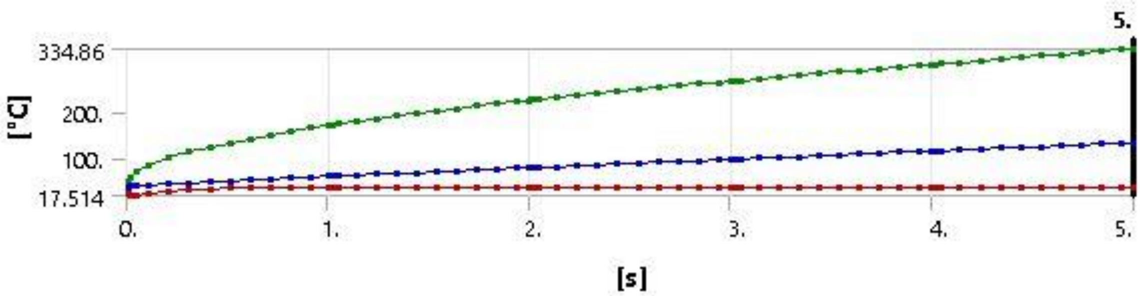
Transient Thermal Setup:

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



The maximum temperature observed is 334.86 degrees Celsius.



Design of Experiments and Optimization:

Design of experiments (DOE) is a systematic, efficient method that enables engineers to study the relationship between multiple input variables and output responses. DOE method samples a defined design space so that a statistical model can be generated to predict responses. 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.

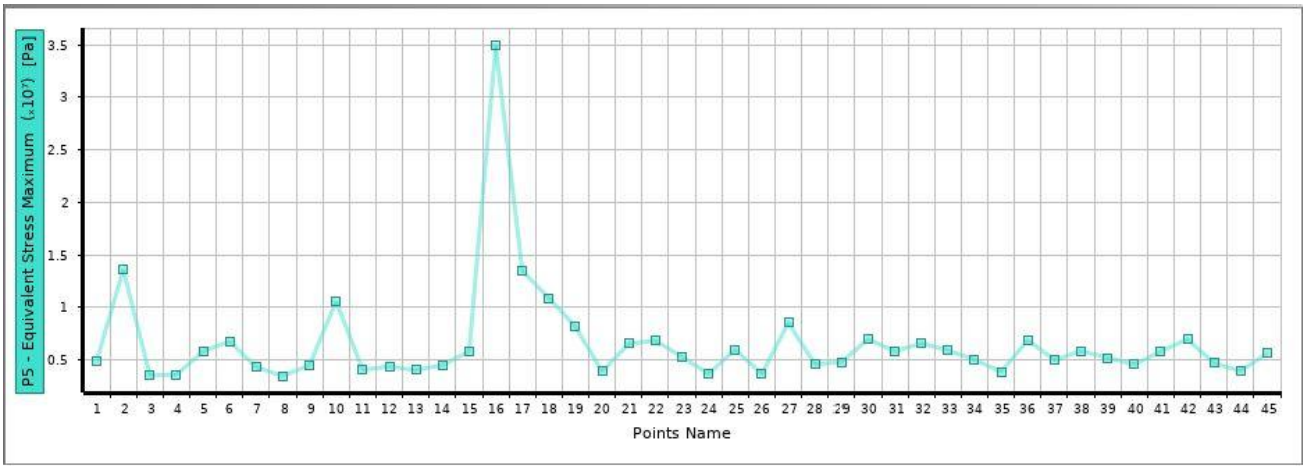
Name	*Brake disc thickness*	*Brake disc inner diameter*	*Brake disc outer diameter*
Lower Bound	*20*	*110*	*60*
Upper bound	*30*	*140*	*90*

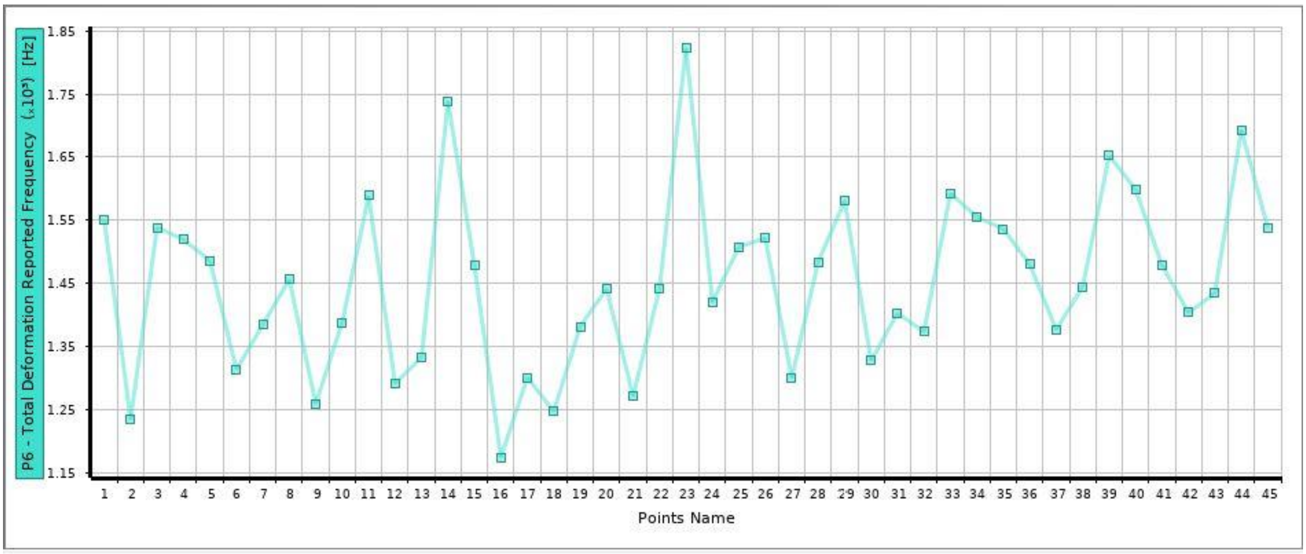
The random values generated are as follows:

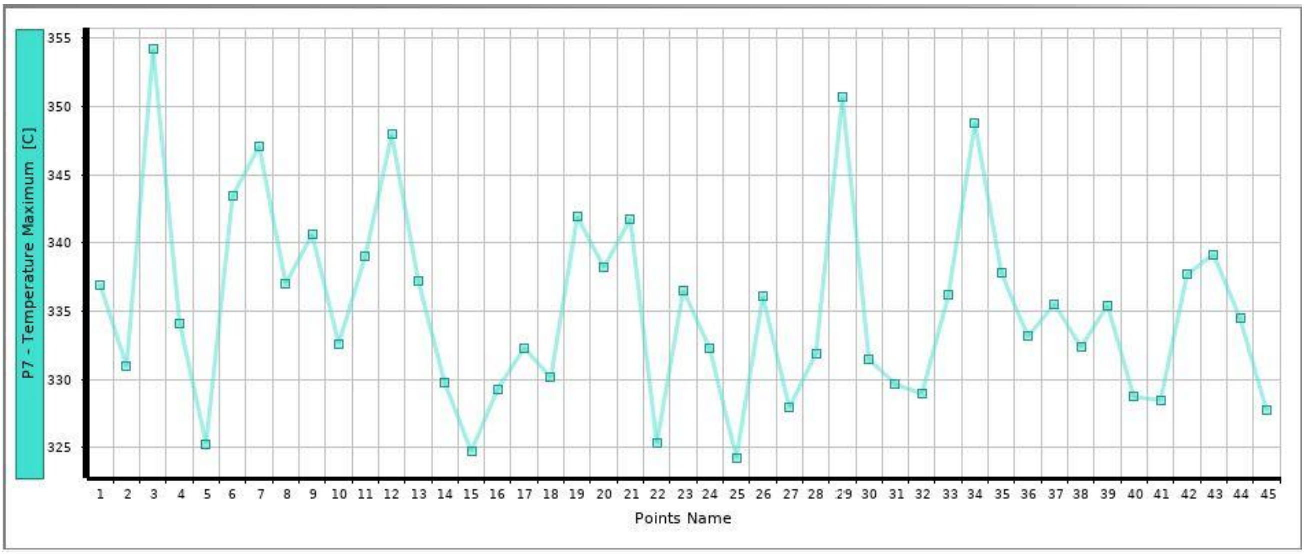
Table of Schematic D2: Design of Experiments (Custom)

	A	B	C	D	E	F	G
1	Name	P1 - rotor_thickness (mm)	P2 - rotor_OD (mm)	P3 - rotor_ID (mm)	P5 - Equivalent Stress Maximum (Pa)	P6 - Total Deformation Reported Freque...	P7 - Temperature Maximum (C)
2	1	23.667	127	73.667	4.9164E+06	1551	336.96
3	2	25.667	133.67	88.333	1.3608E+07	1234.8	330.99
4	3	20.111	125.67	69.667	3.5384E+06	1538.7	354.21
5	4	24.333	129.67	65	3.6044E+06	1519.5	334.14
6	5	29	134.33	75	5.8407E+06	1485.9	325.29
7	6	21.889	127.67	84.333	6.777E+06	1313.6	343.49
8	7	21	130.33	77.667	4.3119E+06	1384.5	347.09
9	8	23.444	129	62.333	3.4852E+06	1456.5	337.06
10	9	22.333	139.67	66.333	4.5282E+06	1259.2	340.64
11	10	27.444	123.67	86.333	1.0582E+07	1388.3	332.65
12	11	25.444	123	60.333	4.0675E+06	1589	339.03
13	12	20.778	137	73	4.4002E+06	1291.8	347.97
14	13	23.222	135	63	4.0342E+06	1332.9	337.23
15	14	28.111	124.33	70.333	4.53E+06	1738.9	329.75
16	15	29.444	138.33	67.667	5.7958E+06	1478.9	324.76
17	16	26.556	139	89.667	3.4895E+07	1174.5	329.32
18	17	25.222	128.33	87	1.345E+07	1301.1	332.33
19	18	25.889	136.33	85.667	1.0898E+07	1247.1	330.14
20	19	22.778	125	83	8.162E+06	1381.8	341.95
21	20	23	131.67	65.667	3.9074E+06	1441.7	338.23
22	21	22.111	135.67	80.333	6.555E+06	1271.2	341.76
23	22	28.778	132.33	79.667	6.8403E+06	1441.7	325.35
24	23	28.556	122.33	64.333	5.3065E+06	1822.5	336.56
25	24	25	131	61	3.6768E+06	1420.6	332.27
26	25	29.889	133	76.333	6.0049E+06	1507.8	324.28
27	26	24.111	126.33	61.667	3.6695E+06	1522	336.09
28	27	27	137.67	81.667	8.5542E+06	1300	327.96
29	28	25.083	132.92	69.75	4.5909E+06	1484.3	331.9
30	29	24.25	122.08	77.25	4.8127E+06	1580.8	350.71
31	30	25.25	133.75	81.75	6.978E+06	1327.8	331.51
32	31	26.083	137.08	72.75	5.8196E+06	1402.7	329.65
33	32	26.417	135.42	78.25	6.6002E+06	1373.6	328.98
34	33	24.083	126.25	72.25	5.9202E+06	1593	336.18
35	34	22.583	122.92	76.75	5.0341E+06	1555.1	348.79
36	35	23.25	128.75	68.25	3.8821E+06	1536.5	337.81
37	36	25.583	125.42	80.25	6.8991E+06	1480.2	333.16
38	37	23.75	136.25	71.75	5.0042E+06	1376.8	335.56
39	38	24.917	132.08	75.75	5.864E+06	1444.7	332.38
40	39	25.75	123.75	73.75	5.2236E+06	1652.5	335.46
41	40	26.75	129.58	69.25	4.5826E+06	1598.9	328.73
42	41	27.083	127.92	79.75	5.804E+06	1479.1	328.49
43	42	23.417	127.08	81.25	6.9989E+06	1403.7	337.71
44	43	22.75	131.25	74.75	4.7016E+06	1434.4	339.18
45	44	25.417	124.58	67.75	3.9675E+06	1693.2	334.5
46	45	27.25	130.42	74.25	5.6362E+06	1538.4	327.76

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


P5 - Equivalent Stress Maximum (x10⁷) [Pa]
3.5
3
2.5
2
1.5
1
0.5
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 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
Points Name

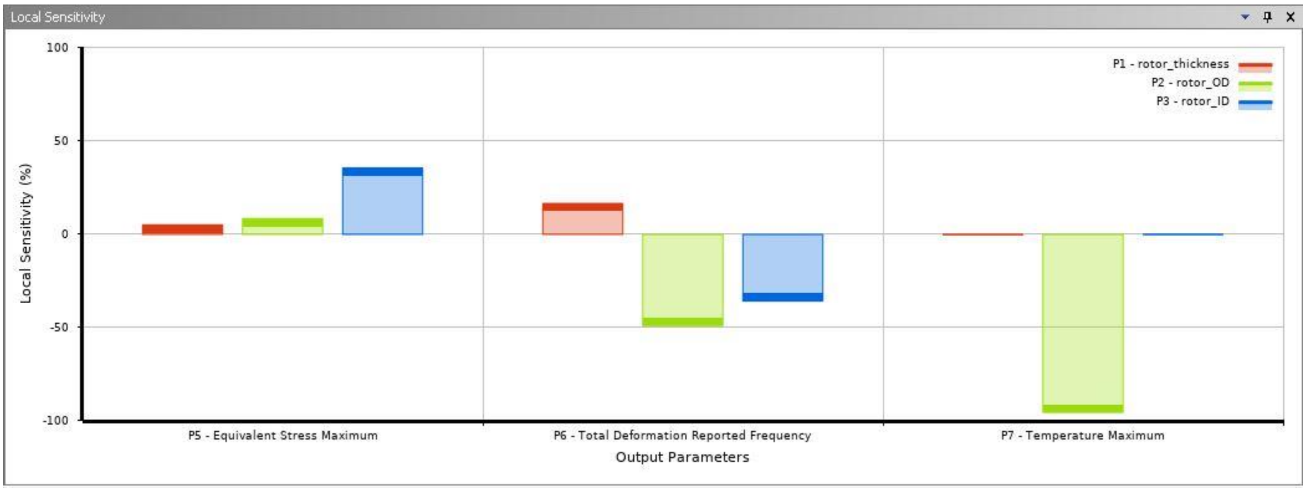

P6 - Total Deformation Reported Frequency (x10³) [Hz]
1.85
1.75
1.65
1.55
1.45
1.35
1.25
1.15
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
Points Name


P7 - Temperature Maximum [C]
355
350
345
340
335
330
325
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 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
Points Name

Response Surface and Sensitivity Analysis:

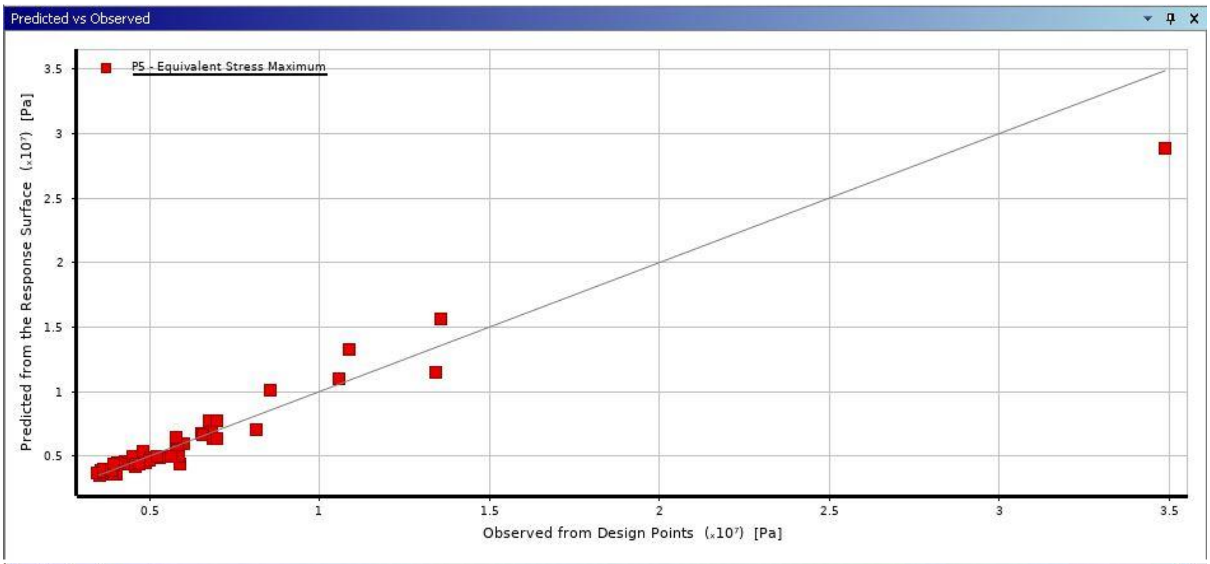
Response surface methodology explores the relationship between several explanatory variables and one or more response variables. The main idea of response surface methodology is to use a sequence of designed experiments to obtain an optimal response.

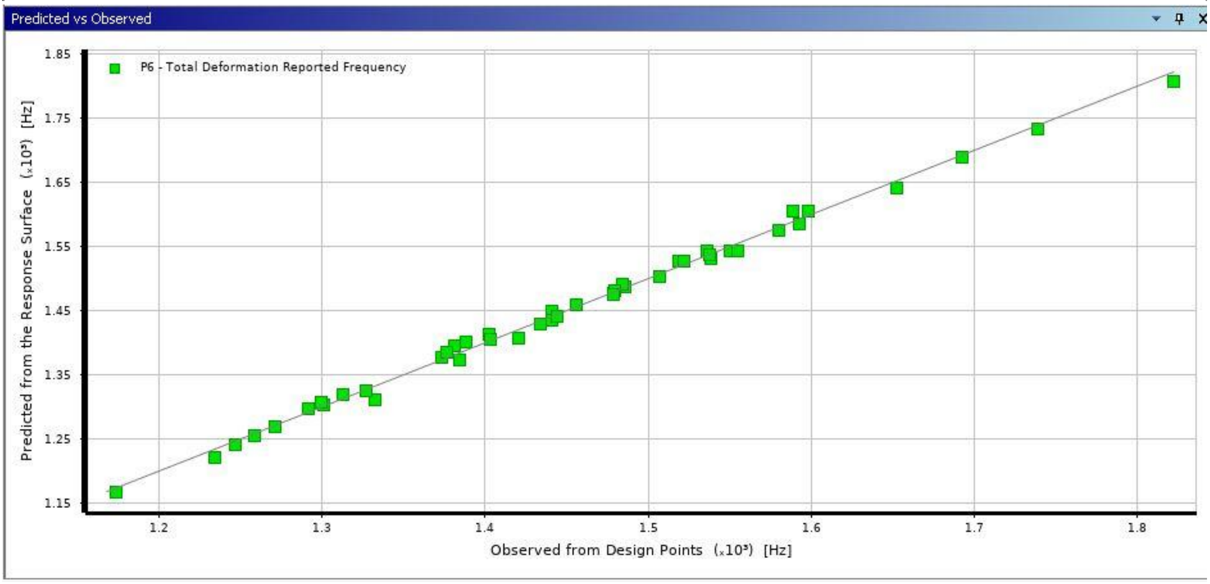
The local sensitivity can be observed below:

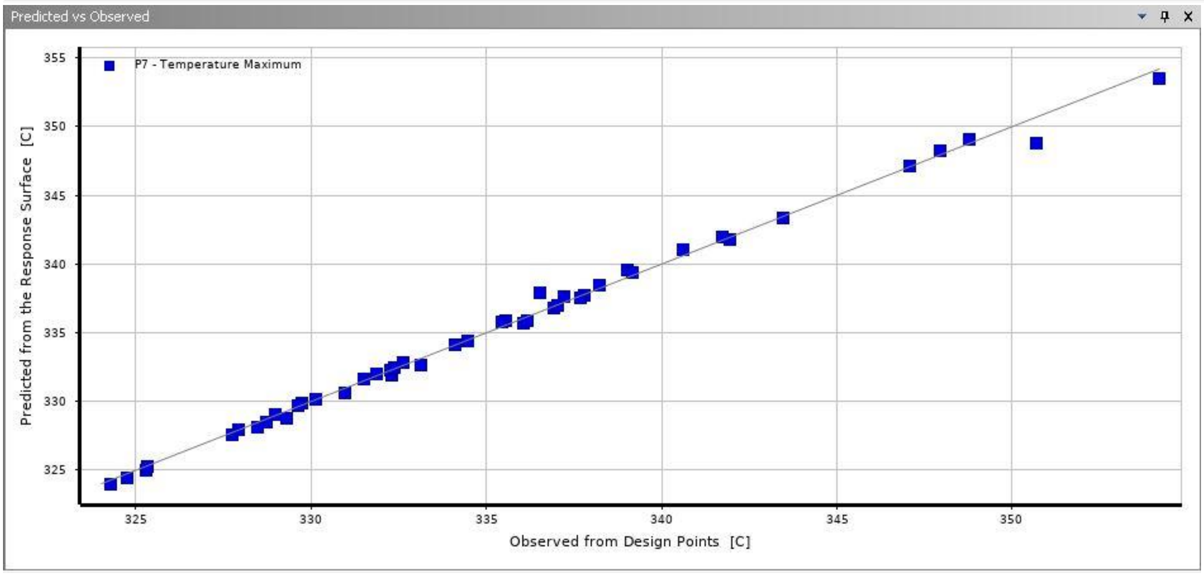


The Equivalent Stress depends largely on the variability of the inner diameter. The reported first natural frequency depends the most on the variability of the outer diameter, subsequently on the variability of inner diameter to a lower proportion, and on the variability of the thickness of disc to some extent. The temperature evaluated in the transient thermal analysis depends heavily on the variability of the outer diameter, change in thickness or inner diameter has little to no impact on the temperature.

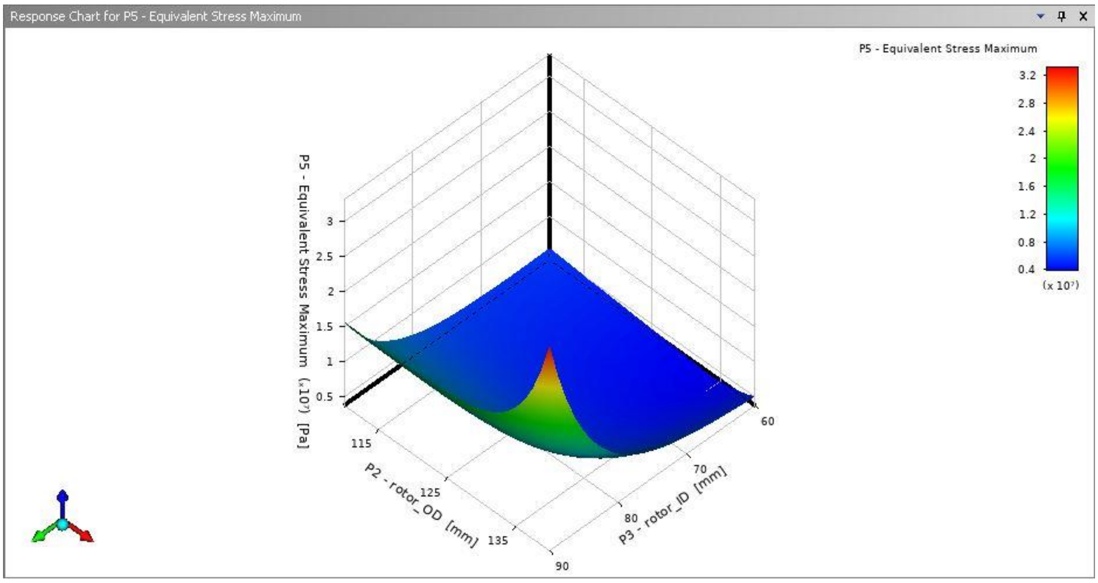
Goodness of fit can be seen below:

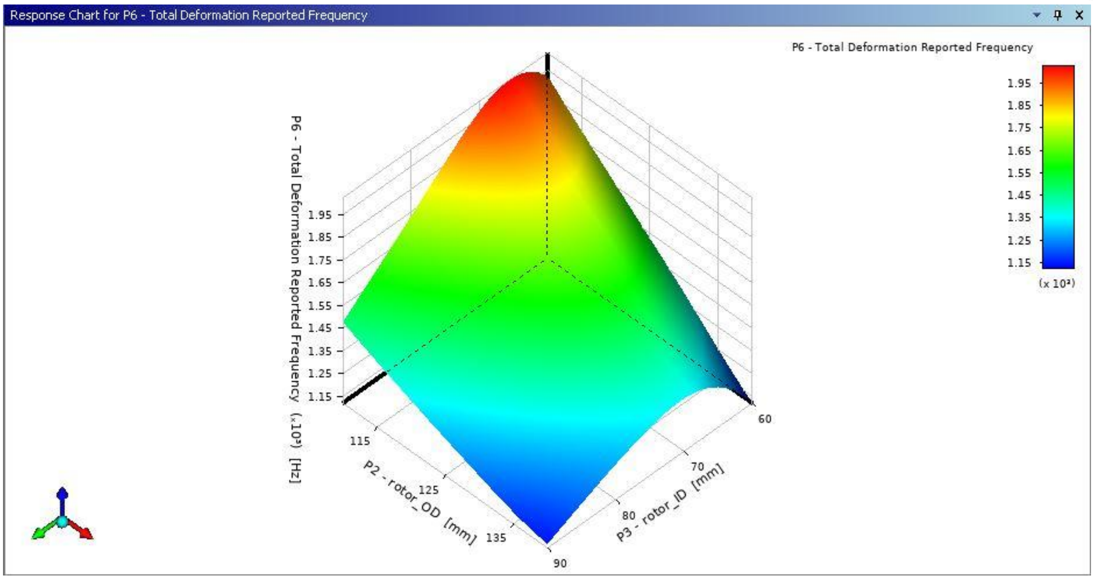


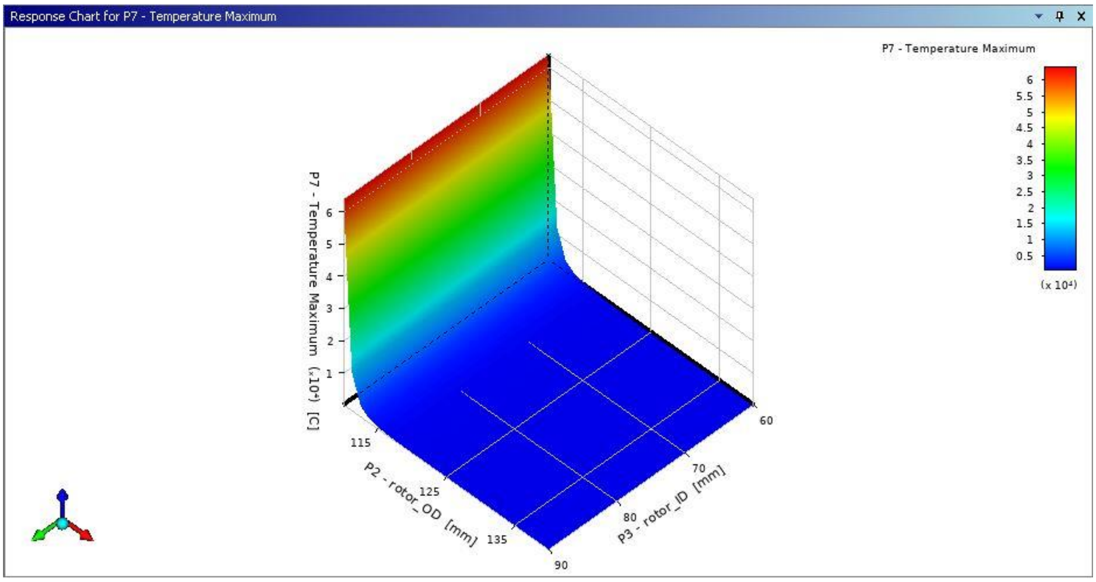


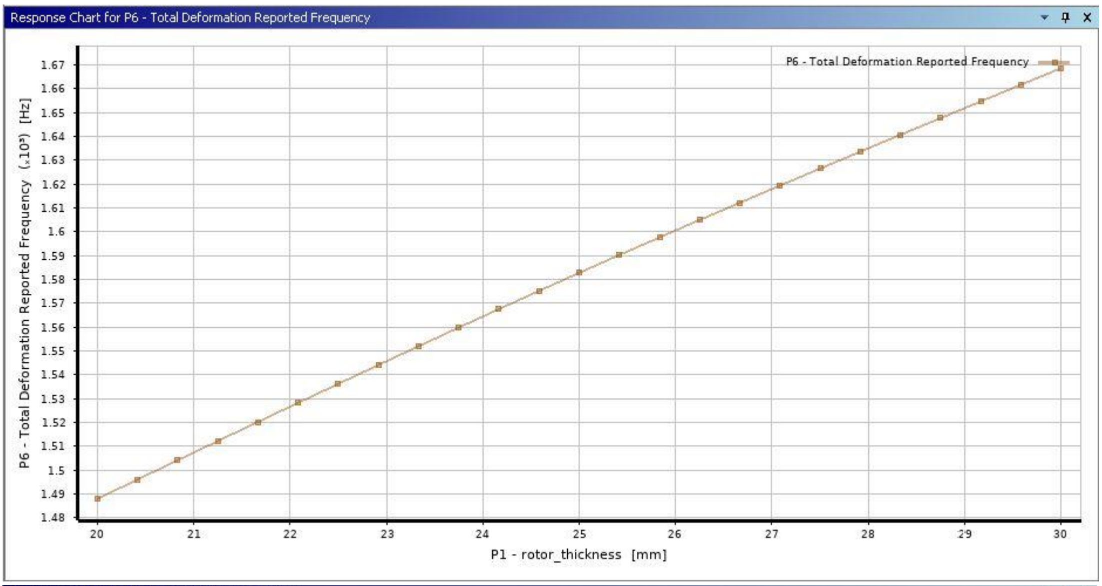


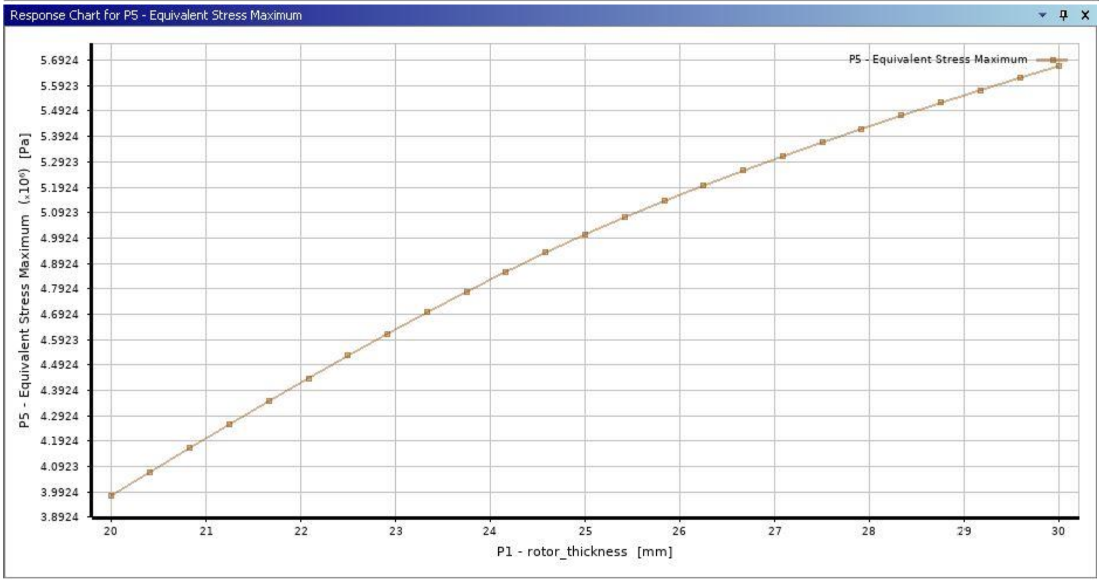
The response charts can be seen below:

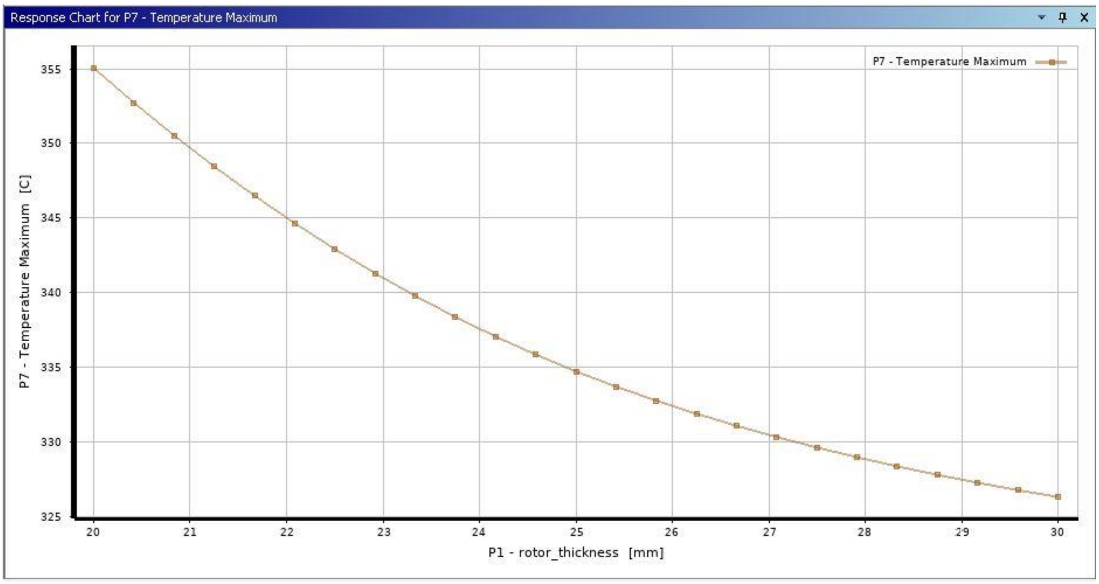







Response Chart for P6 - Total Deformation Reported Frequency
P6 - Total Deformation Reported Frequency
P6 - Total Deformation Reported Frequency (x10³) [Hz]
P1 - rotor_thickness [mm]


Response Chart for P5 - Equivalent Stress Maximum
P5 - Equivalent Stress Maximum
P5 - Equivalent Stress Maximum (x10⁹) [Pa]
P1 - rotor_thickness [mm]


Response Chart for P7 - Temperature Maximum
P7 - Temperature Maximum
P7 - Temperature Maximum [C]
P1 - rotor_thickness [mm]

Optimization:

The method used for this problem is MOGA, which is a guided random search method. It is suitable for solving multi-objective optimization-related problems with the capability to explore the diverse regions of the solution space, which helps in solving our problem. The candidate points are listed below:

	Candidate Point 1	Candidate Point 2	Candidate Point 3
P1 - rotor_thickness (mm)	✕ 20.083	✕ 20.047	✕ 20.042
P2 - rotor_OD (mm)	✕✕ 118.86	✕✕ 118.87	✕✕ 118.59
P3 - rotor_ID (mm)	✕ 60.747	✕ 61.344	✕ 60.971
P5 - Equivalent Stress Maximum (Pa)	★★ 3.7833E+06	★★ 3.7693E+06	★★ 3.7905E+06
P6 - Total Deformation Reported Frequency (Hz)	★★★ 1557.4	★★★ 1578.2	★★★ 1571.4
P7 - Temperature Maximum (C)	★★★ 436.06	★★★ 435.95	★★★ 448.48

Results and Discussion:

For the bounds taken the optimal solution obtained had a significantly reduced volume compared to the original model (provided by Professor Yi Ren), but there was significant increase in the value of maximum temperature generated, which is to be considered as a trade-off. The bounds taken in this study may be considered as large, so a comparative study could be explored to better understand, if a trade-off is necessary.