ANSYS DOE and Design Optimization on Vehicle Brake Design

PROJECT REPORT

YONESHWAR BABU

ASU ID:1220454365

MAE 598: Design Optimization (Fall2021)

November 17, 2021

Under the guidance of

YI (MAX) REN

Assistant Professor of aerospace and mechanical engineering

School for Engineering of Matter, Transport and Energy

Arizona State University

ACKNOWLEDGEMENT

I consider myself highly fortunate for the opportunity to do this project under the guidance of **YI (MAX) REN** who was kind enough to make a tutorial with perfect directions. Special thanks to **Abhijeet Durgude, Aditya Vipradas, Sharan Kishore Swapnil Nimse** for lending us their Brake design CAD model.

I extend my gratitude to our **ARIZONA STATE UNIVERSITY** for having provided me with all the facilities at the **HIGH PERFORMANCE LABORARTY** to build my project successfully.

ABSTRACT

The primary objective of this project **“ANSYS DOE and Design Optimization on Vehicle Brake Design”** determine the optimum dimensions for the brake disc for a four-wheeler vehicle using ANSYS. These dimensions are for the disc inner radius, outer radius and thickness. Static Structural, modal and Transient thermal load cases for emergency braking conditions are individually considered to determine these dimensions. The optimization objective is to minimize the stress, temperature and maximize the first natural frequency of the disc. These are accomplished using ANSYS. The system is optimized using MOGA by integrating all the load cases which is also done is ANSYS.

Design Problem Statement

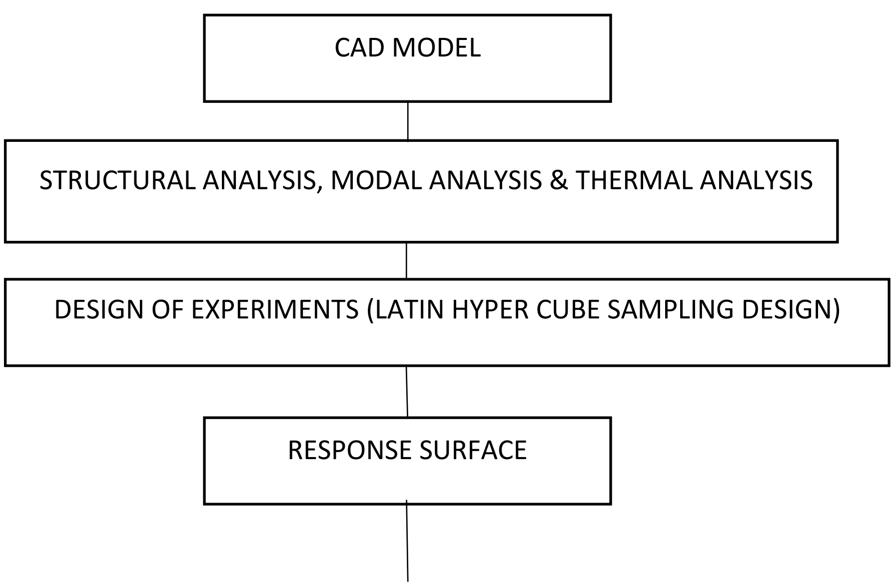
- To minimize the brake disc volume for emergency braking conditions
- Minimize the maximum stress in the brake disc
- Maximize the first natural frequency of the brake disc
- Minimize the maximum temperature in the brake disc

The three subsystems are as follows:
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.

The design optimization methodology flowchart



OPTIMIZATION

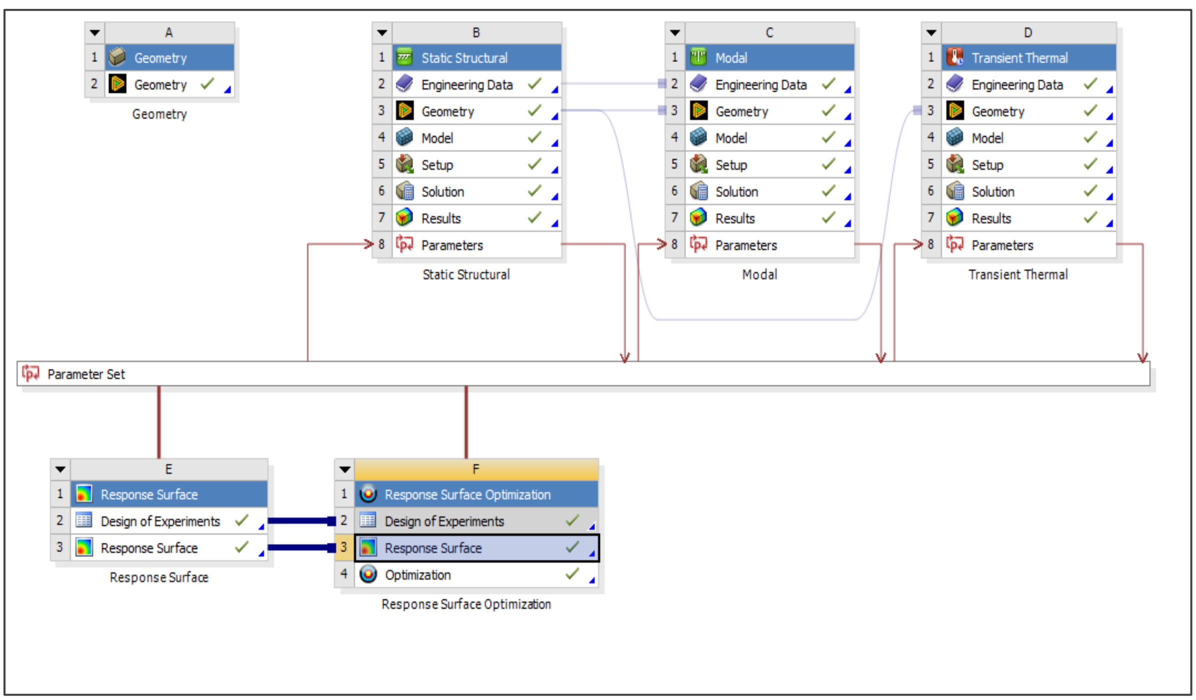
RESULT

Mathematical Model:

In this optimization study, the brake disc inner radius , outer radius and thickness are the design variables. Firstly, the static structural, modal and Transient thermal analyses are performed in ANSYS. For the given constraints, Design Of Experiment (DOE) points are generated. Mathematical model is then generated by performing regression analysis on these DOE points to obtain the volume, stress, frequency and temperature .

MODEL ANALYSIS:

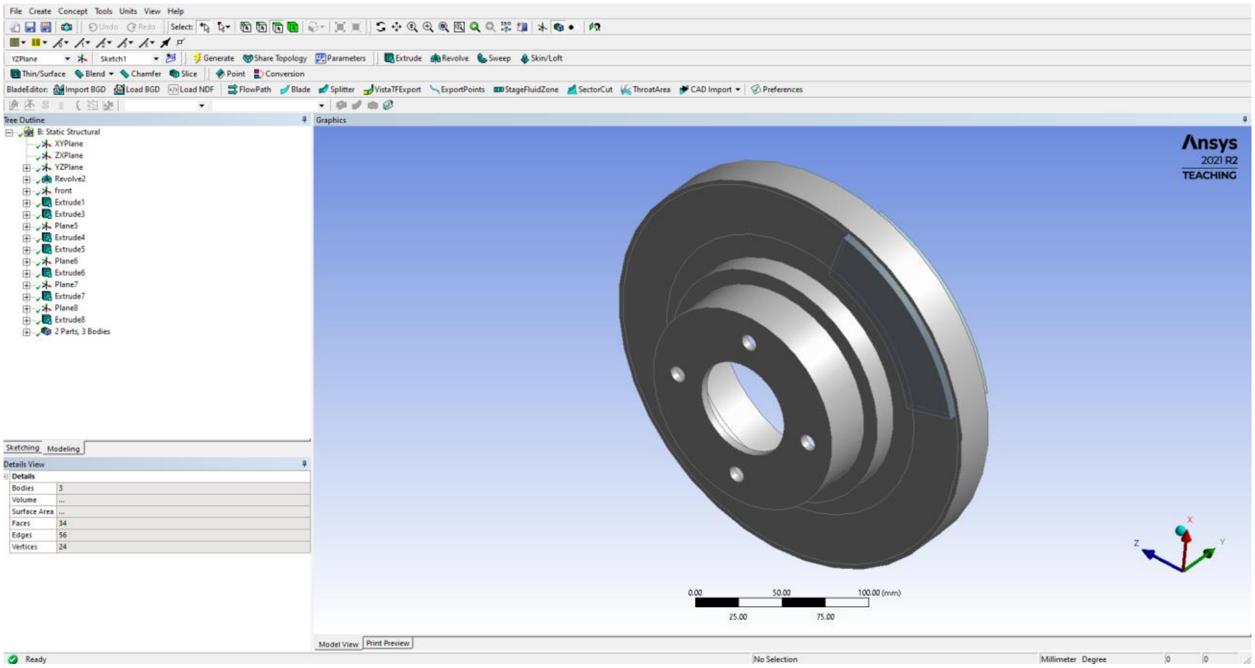
The flowchart for optimization in ANSYS is shown in the Figure. This figure pertains to the flowchart for structural analysis. Similar procedure is followed for modal and thermal analyses.



Ansys Optimization flowchart

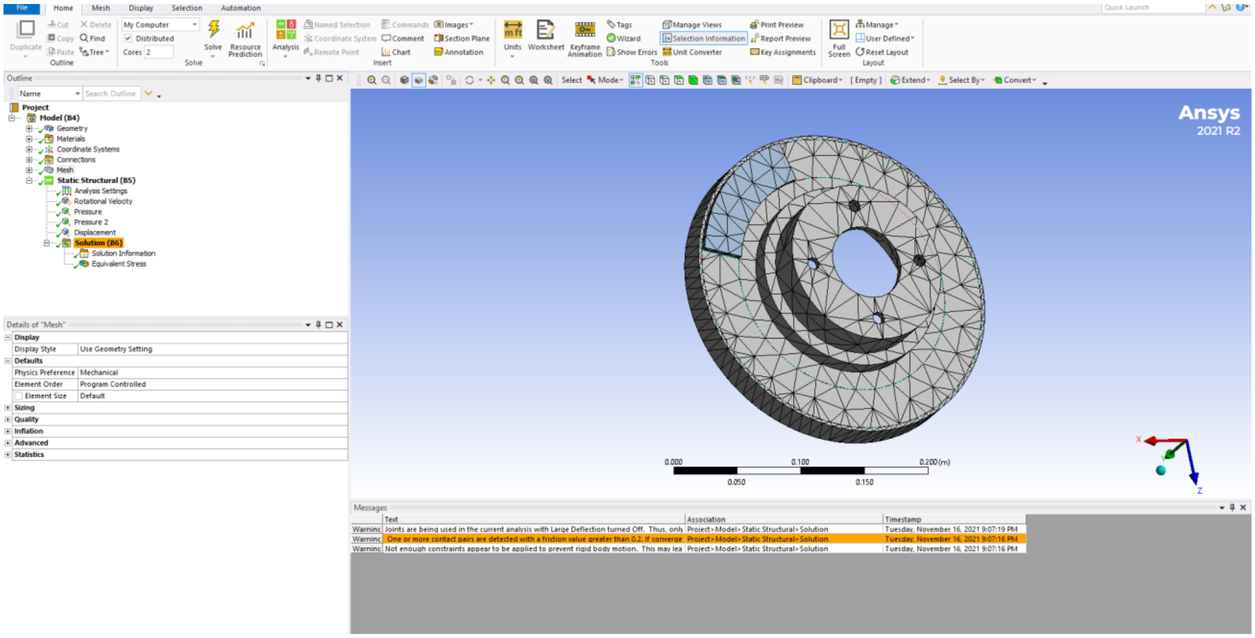
FE Model

The brake disc geometry is prepared in ANSYS Design Modeler as shown in Figure. The initial values for P1, P2 and P3 are considered as 75 mm, 125 mm and 25 mm respectively.



Disc Brake CAD Model

The CAD geometry is meshed as tetrahedron for brake disc and brake pads were meshed using 3 mm sized tetrahedral quadratic elements .



Disc Brake Mesh Model

The brake disc is made of gray cast iron. The material properties of gray cast iron are shown in Table

The assumptions made for performing the FEM analysis are as follows:

• The braking torque distribution between the front and rear axles is 70:30.

• Natural convection takes place due to the ambient air.

• The disc brake considered is of the solid type.

• Heat flux on the disc brake acts on both sides of the disc.

Structural Analysis

Given in tutorial

Calculating the disc angular velocity (ω),

$$\omega = 250 \text{rad/s}$$

Formulating the pressure exerted by one brake pad on the disc (P),

$$P = 10.495 \text{ MPa}$$

Static structural analysis is performed on the model. The boundary conditions are as follows.

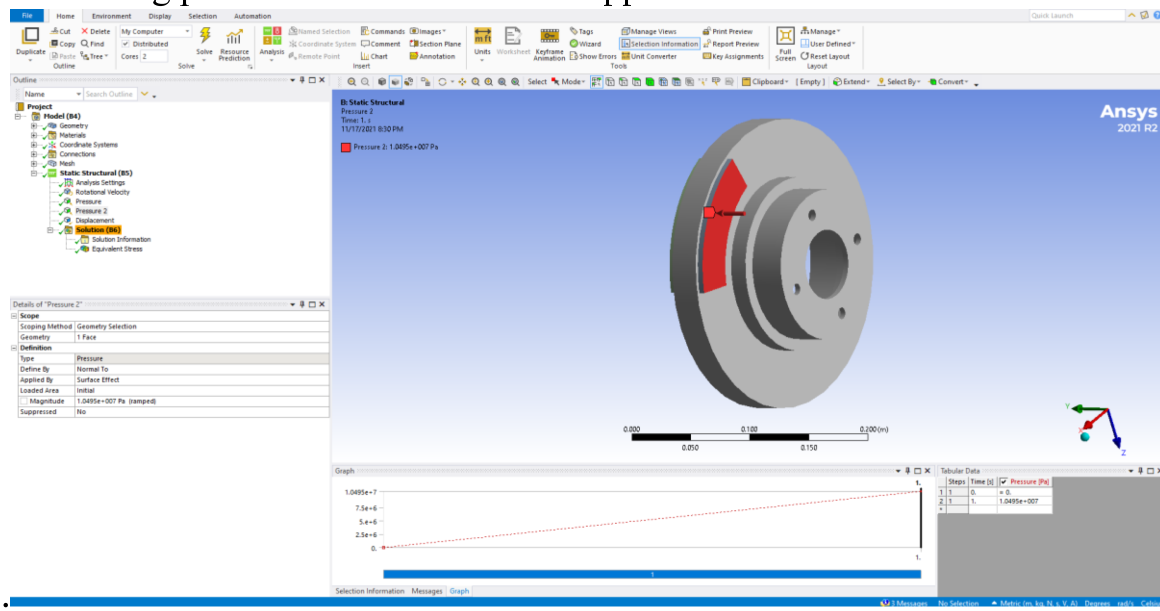
• The inner circumference of the wheel hub has a **revolute join**t applied.

• The brake caliper pads are constrained as **zero** in X and Z directions. They are kept free to move in the **Y direction**.

• The rotational velocity of **250 rad/s** is applied on the disc at the wheel hub attachment point.

• Frictional contact is provided between the brake caliper pads and brake rotor.

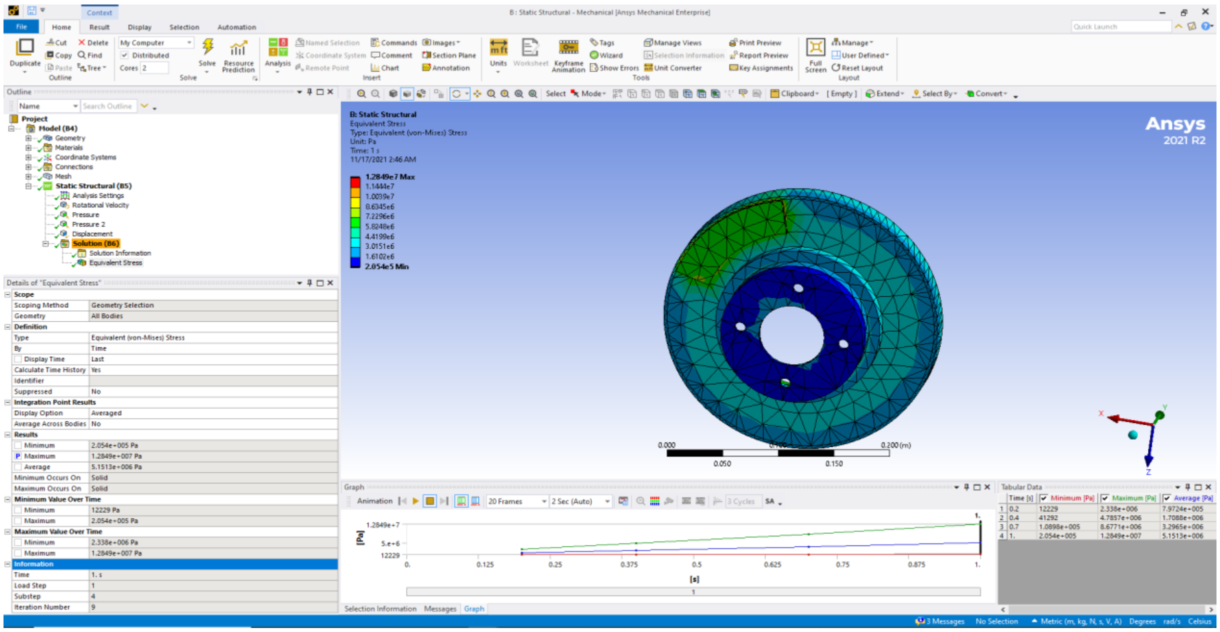
• Actuating pressure of **10.496 MPa** is applied on the outer faces of the brake pads



•

Static structural boundary conditions

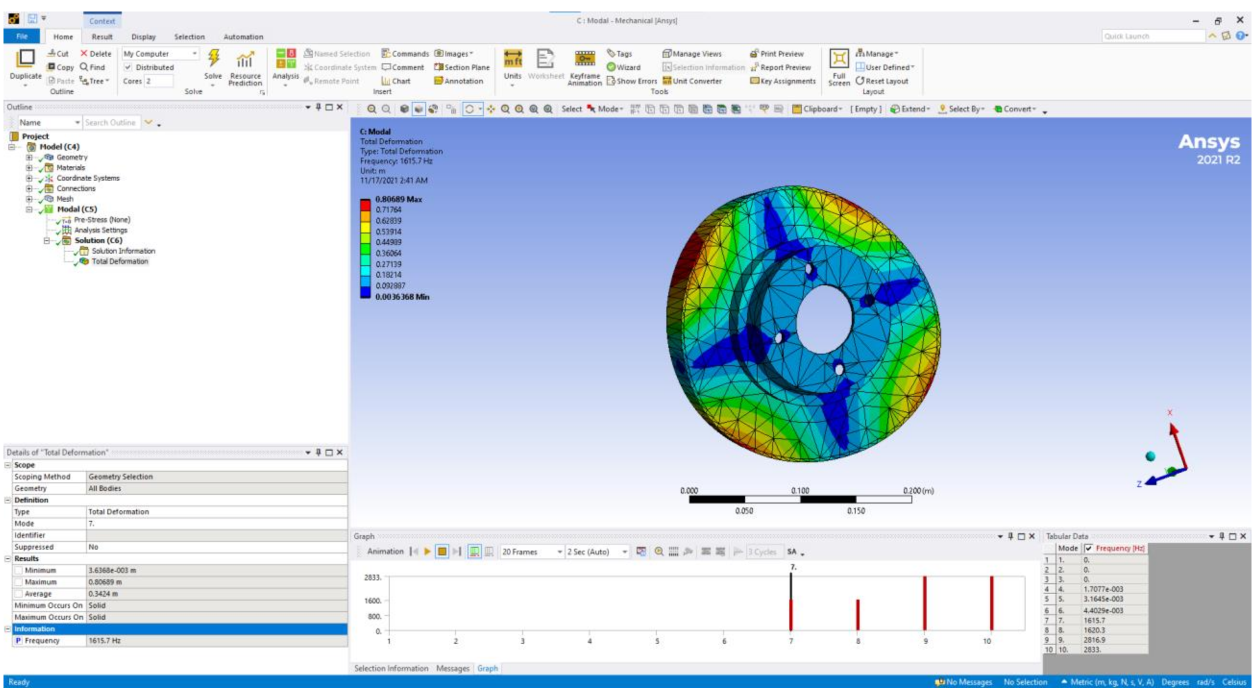
The stress plot obtained is as shown. The maximum stress of **12.849 MPa,** lets parameterize it.



Stress plot for initial conditions of the design variables

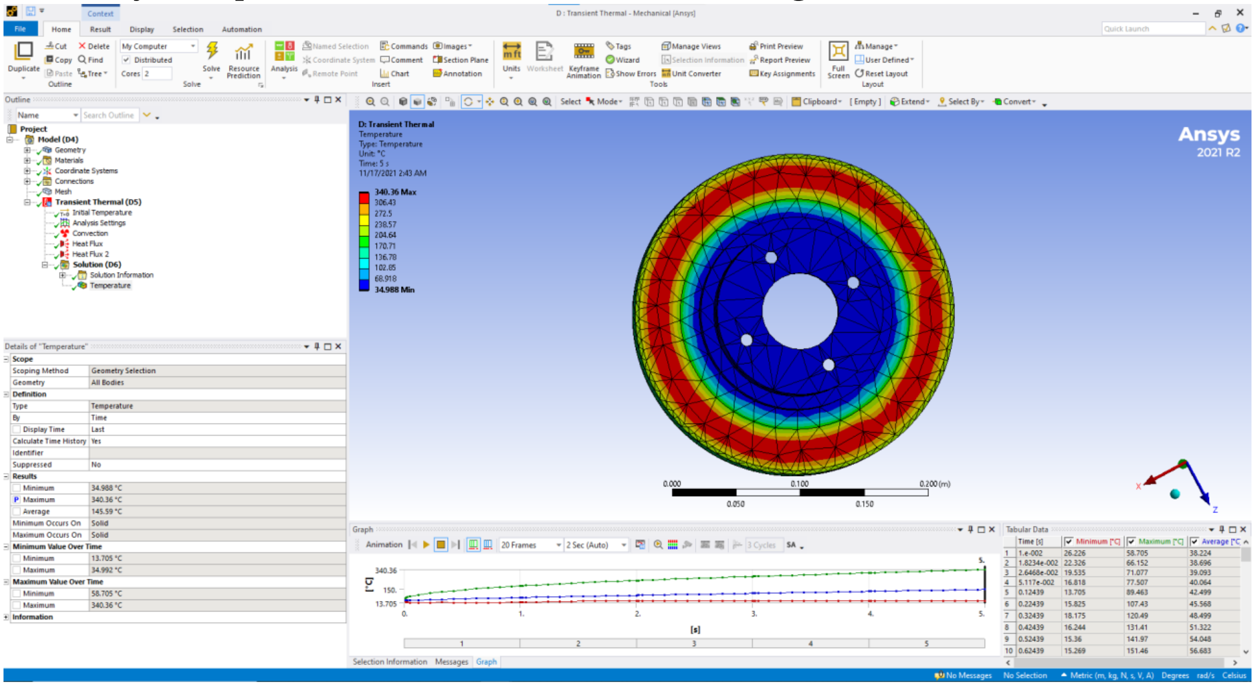
Modal Analysis

Modal analysis is performed on the brake disc to find the natural frequency.



heat flux (q) on both outer contact faces of the disc, **$1.5395e^{6}$W/m^2**

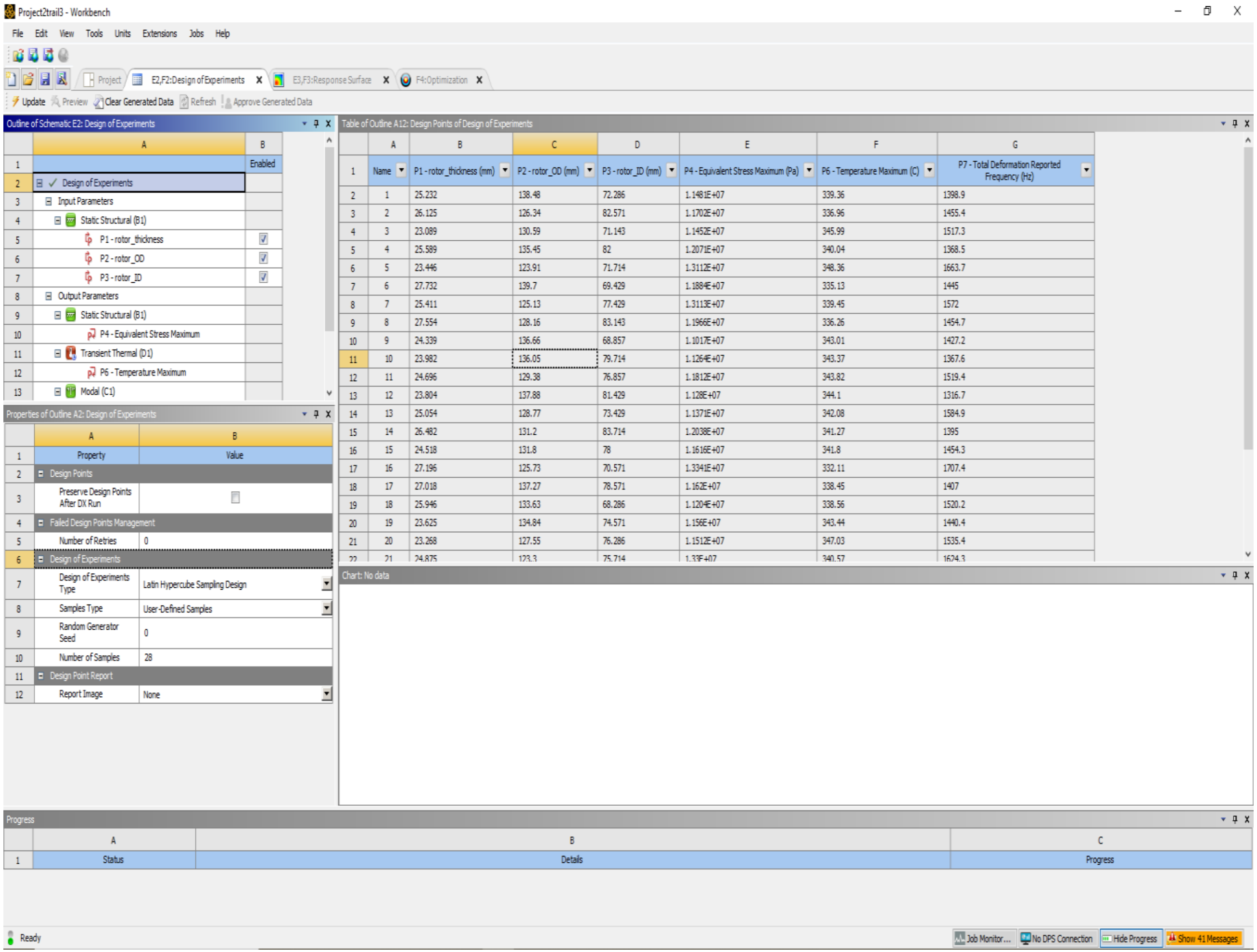
- The Convection is applied on faces of the disc with coefficient of **5** W/m^{2}K
- Initial temperature is kept as **35 ºC** as given in tutorial.
- The analysis is performed for **5 s** which is the braking time.

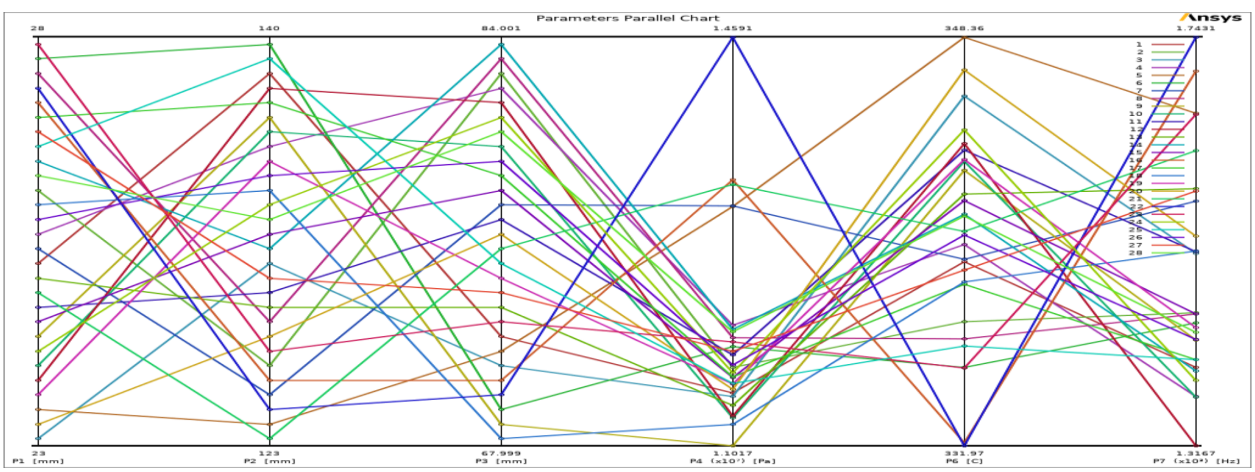


Temperature plot for initial conditions on the design variables

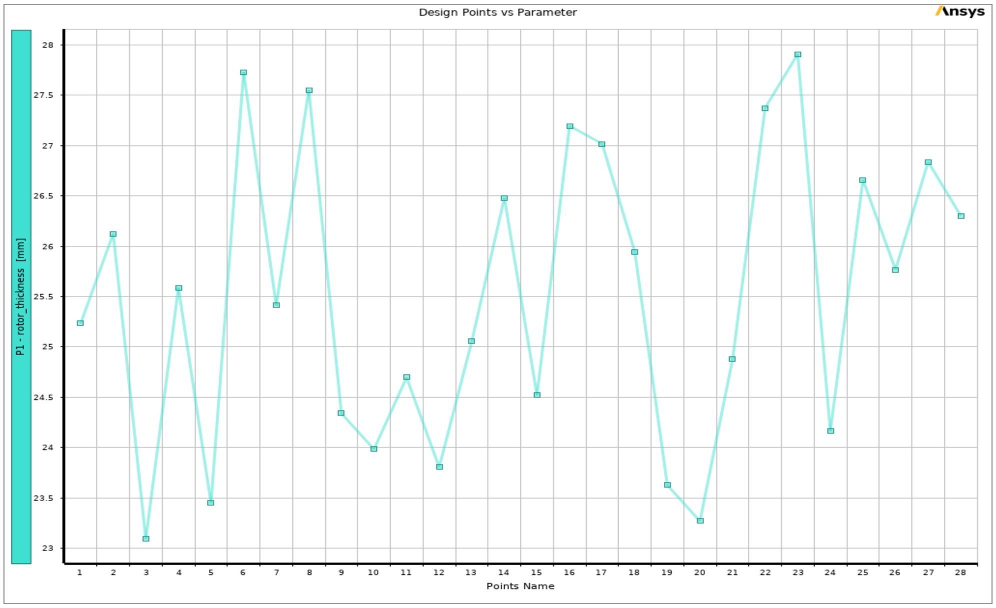
Design of Experiments:

In design of experiments part, I have chosen to do **Latin Hypercube Sampling (LHS)** technique. I have chosen with user defined sample points (28) is used to create the response surface.





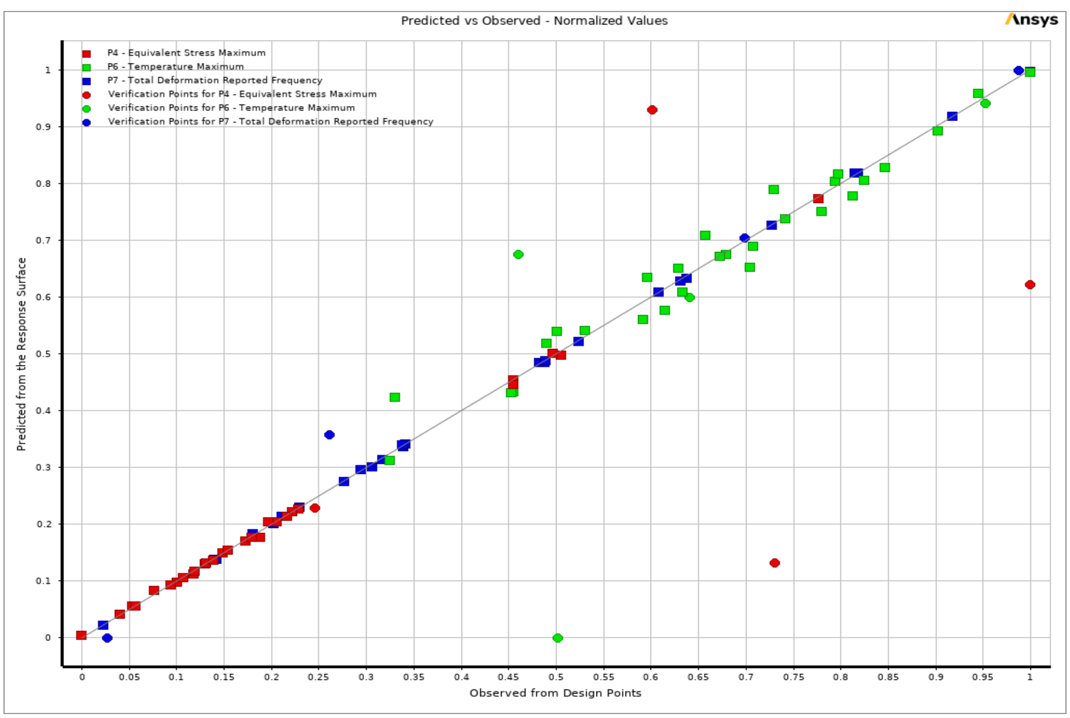
Parameters parallel



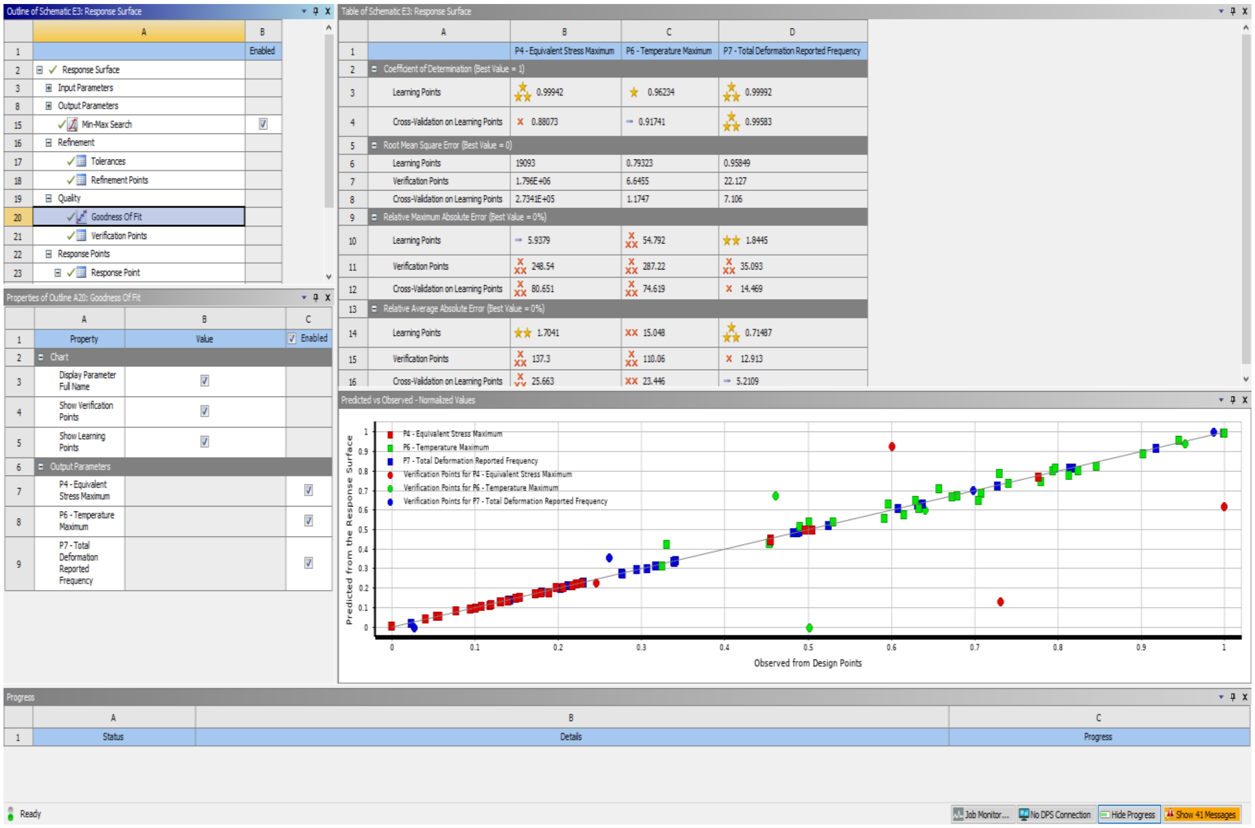
Points vs parameters

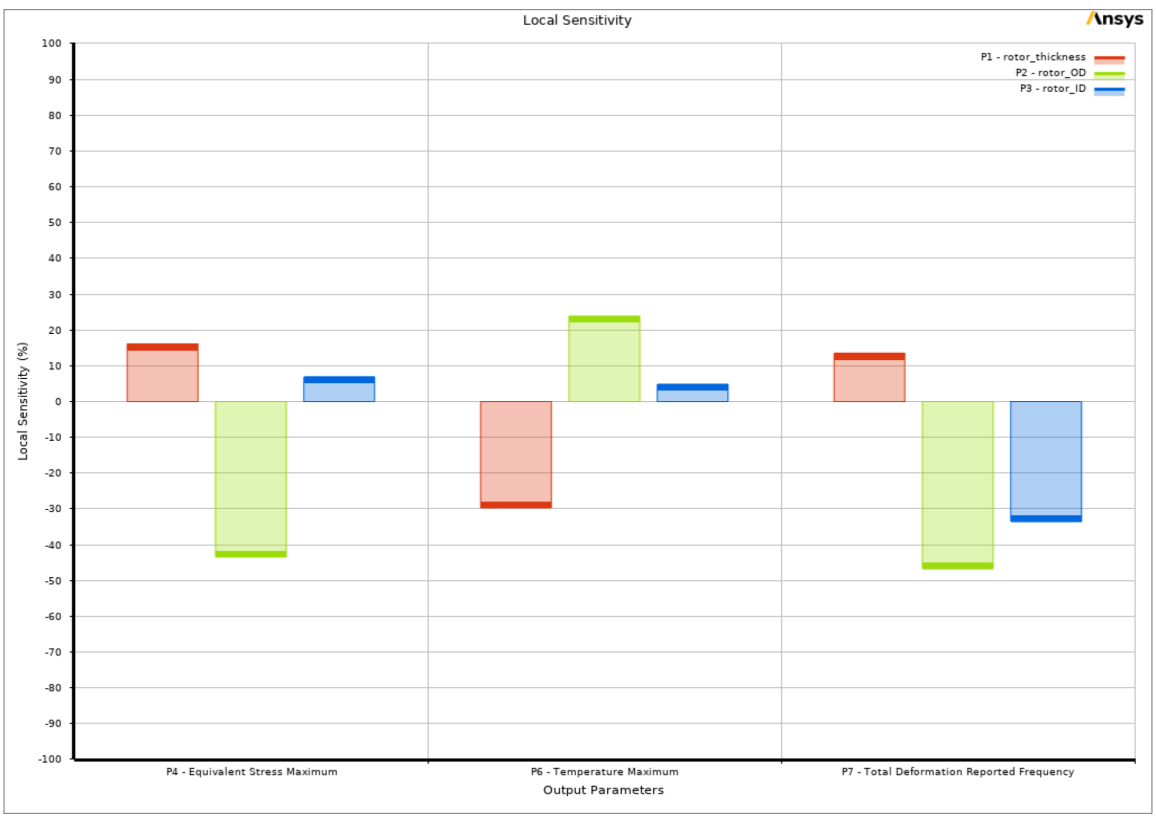
Response Surface

After DOE, I worked with response surface and took four different variations. As one can infer the goodness fit for the design parameters are not so good, so there is a necessary, to improve it in the future. I have attached graphs from the following.

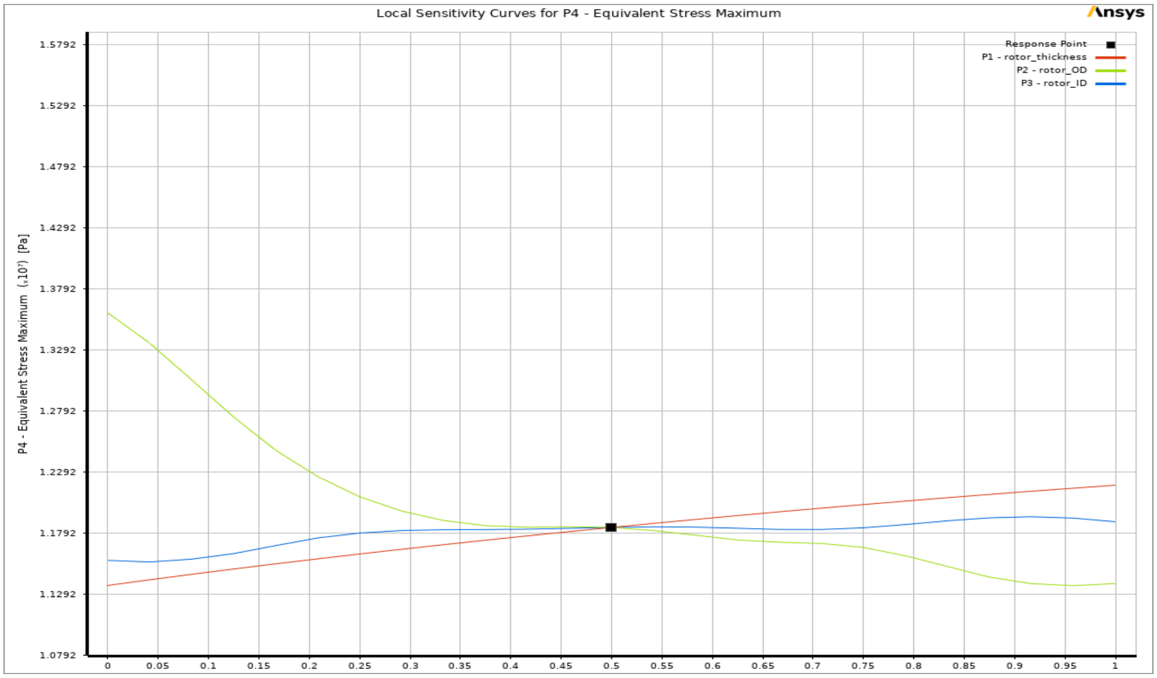


Goodness of fit plot for structural analysis

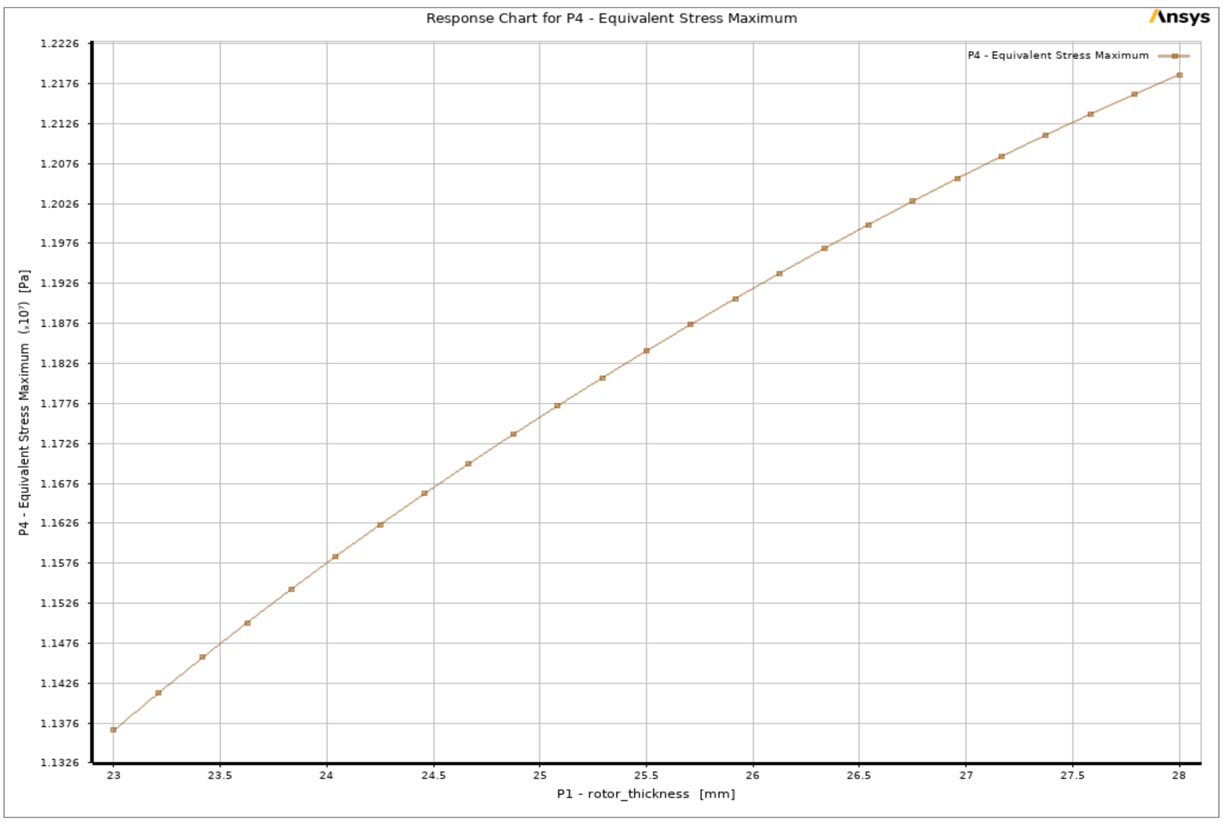




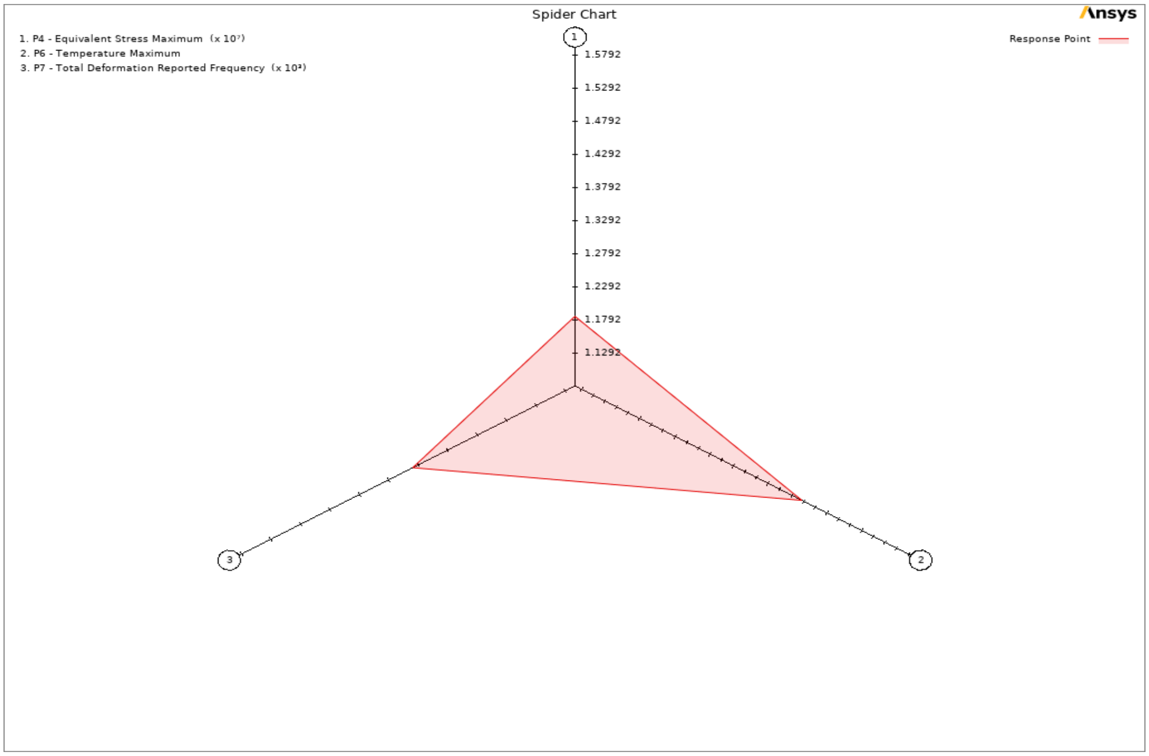
Response surface local sensitivity



Local sensitivity for Equivalent stress



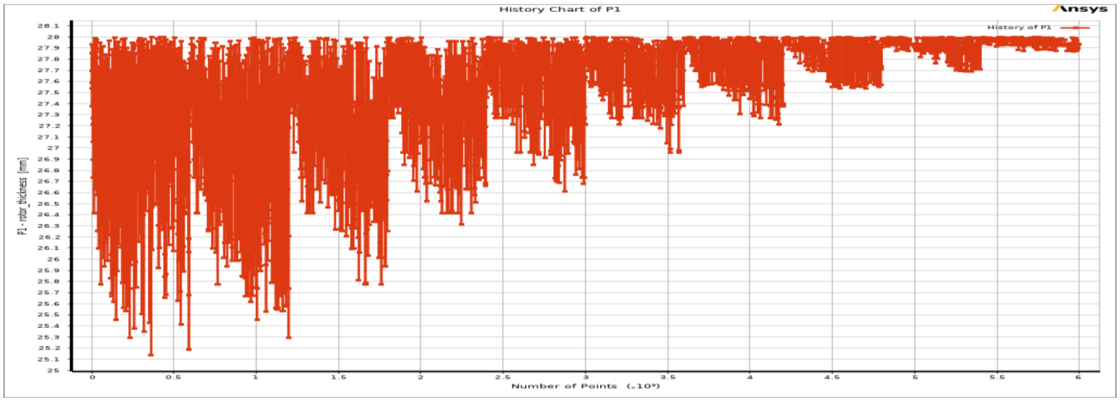
Response chart for Max stress



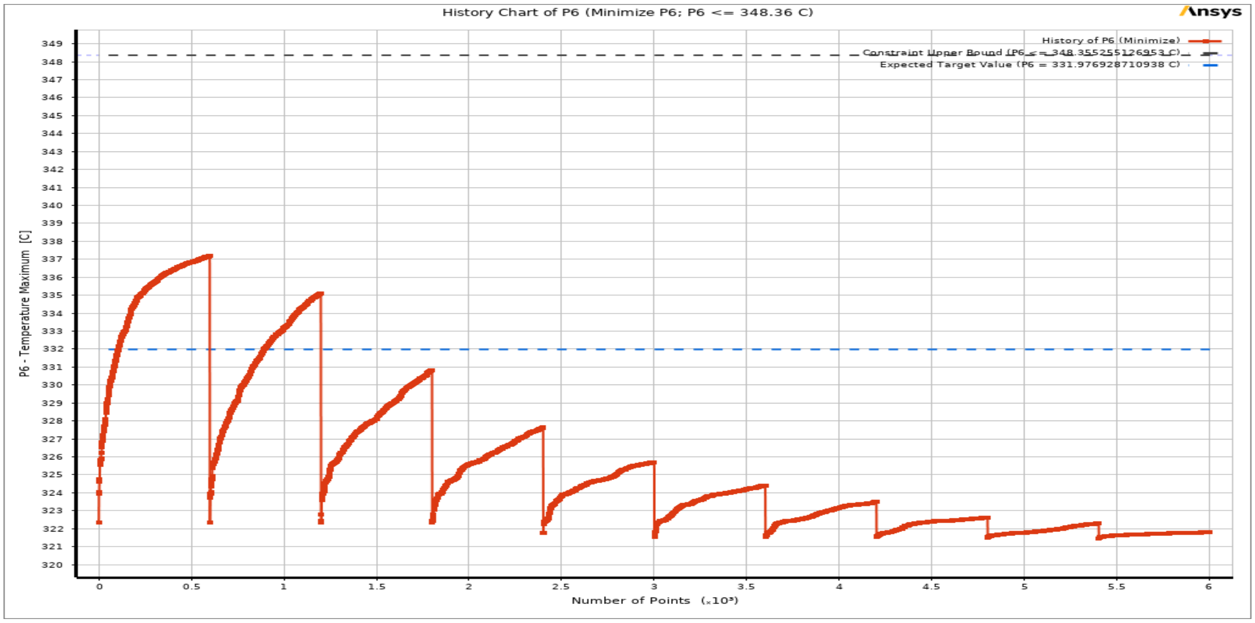
Spider chart for all stress, temperature and frequency

OPTIMIZATION

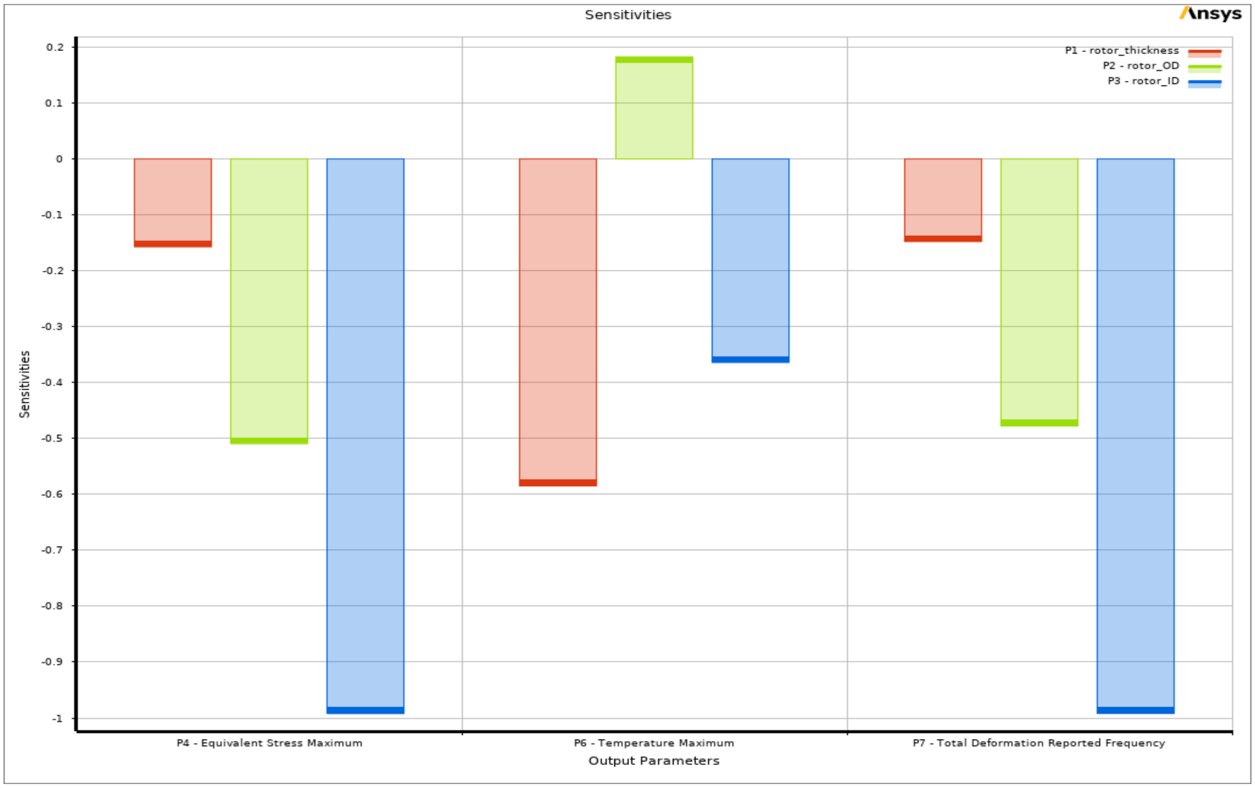
In optimization part, I did MOGA, Multi objective Genetic Algorithm, where I kept minimizing the temperature on disc as objective function and the other two as constraints. This simulation did not require as much time compared to DOE which took hours to complete, and we have arrived a convergence after several iterations. I have attached the convergence plots of few parameters, sensitivity plot and tradeoff plots.



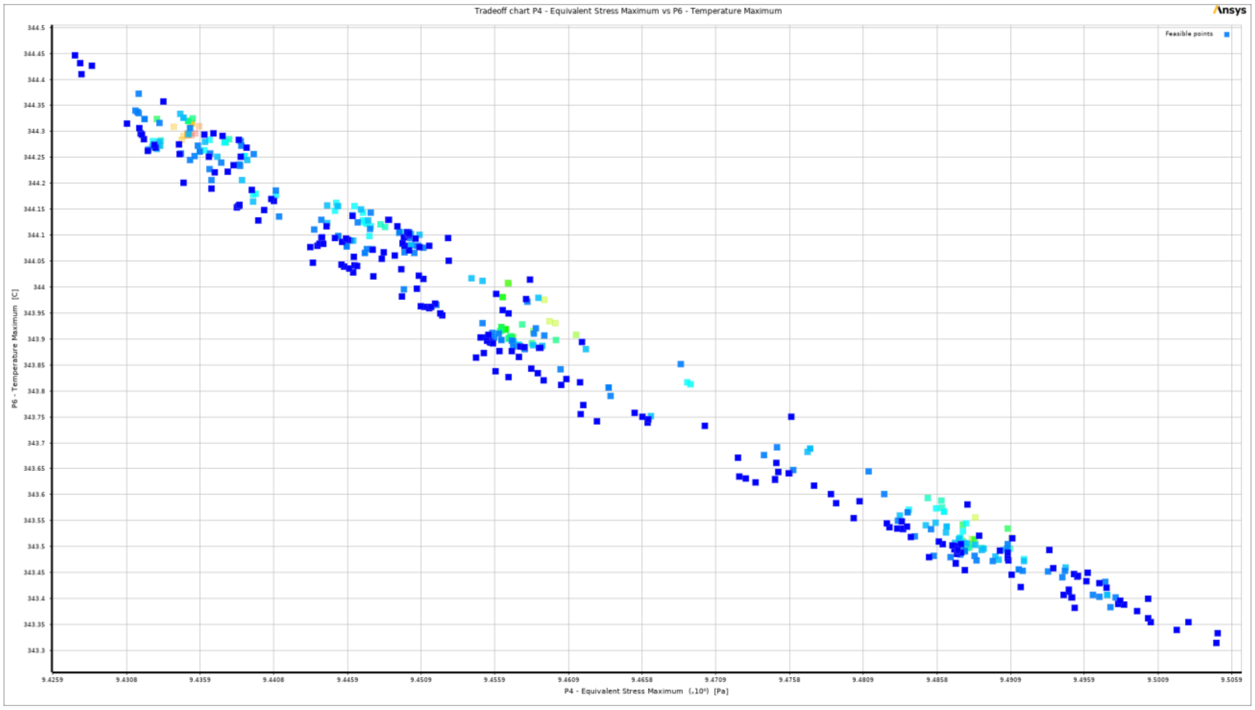
Convergence of plot for rotor thickness vs interations



Convergence plot of temperature(objective) vs no of iterations.



Senstivity plot of all the paramterized function and constraints



Tradeoff plot for the Maximum stress vs temperature

Conclusion

Once DOE, response surface and optimized are done, we receive this result where we can arrive at optimal solution for the given brake disc design. Using these values from the figure below, we can design an efficient brake disc. We can choose one of the three values from the table to modify the first initial design.

Table of Schematic F4: Optimization

	A	B	C	D
1	⊟ Optimization Study			
2	Minimize P6; P6 <= 348.36 C	Goal, Minimize P6 (Default importance); Strict Constraint, P6 values less than or equals to 348.36 C (Default importance)		
3	P4 <= 1.4591E+07 Pa	Strict Constraint, P4 values less than or equals to 1.4591E+07 Pa (Default importance)		
4	P7 >= 1316.7 Hz	Strict Constraint, P7 values greater than or equals to 1316.7 Hz (Default importance)		
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 7619 evaluations.		
9	⊟ Candidate Points			
10		Candidate Point 1	Candidate Point 2	Candidate Point 3
11	P1 - rotor_thickness (mm)	27.988	27.991	27.984
12	P2 - rotor_OD (mm)	123.01	123.01	123.01
13	P3 - rotor_ID (mm)	83.323	82.998	82.577
14	P4 - Equivalent Stress Maximum (Pa)	1.2609E+07	1.2638E+07	1.2695E+07
15	P6 - Temperature Maximum (C)	321.46	321.47	321.53
16	P7 - Total Deformation Reported Frequency (Hz)	1524.5	1530.2	1537.7

References

1.Yi Ren, MAE 598 - Design Optimization Notes and ANSYS DOE tutorial, 2021.
2. Design Optimization Of Brake Disc Geometry Report (2016) of- Abhijeet Durgude, Aditya Vipradas, Sharan Kishore Swapnil Nimse.