DESIGN OPTIMIZATION OF BRAKE DISC GEOMETRY

MAE 598 (Project #2) - Fall 2021

By

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Date of Submission: November 17, 2021

Abstract: -

The main objective of the project is to optimize the design parameters of a given brake disc by means of ANSYS. Including that several analyses were performed such as static, thermal and nodal. The design parameters consist of the rotor thickness, radius etc., Under the optimization category, DOE was performed and the response surface was generated. The geometric model of the brake disc is being generated and ready to be imported into the ANSYS Workspace, on which various analyses are performed.

Meshing of the Geometric Model: -

After importing the model into the workspace, the model is supposed to be meshed for further processing, for any kind of analysis. But the selection of the element type depends upon various factors like setup time, computational expense and numerical diffusion. Considering the above criteria, tetrahedron element is being chosen for meshing. Patch conforming method is applied for the meshing. The advantage of this method is that it enables to ignore the points which will not be required the calculation process.

Material Configuration: -

Basically, the brake disc consists of 3 parts, I.e., one brake disc and two brake pads on both the sides. The brake disc is of gray cast iron and the brake pads are of structural steel. After meshing the material properties are being assigned from Engineering Data Sources under Material option.

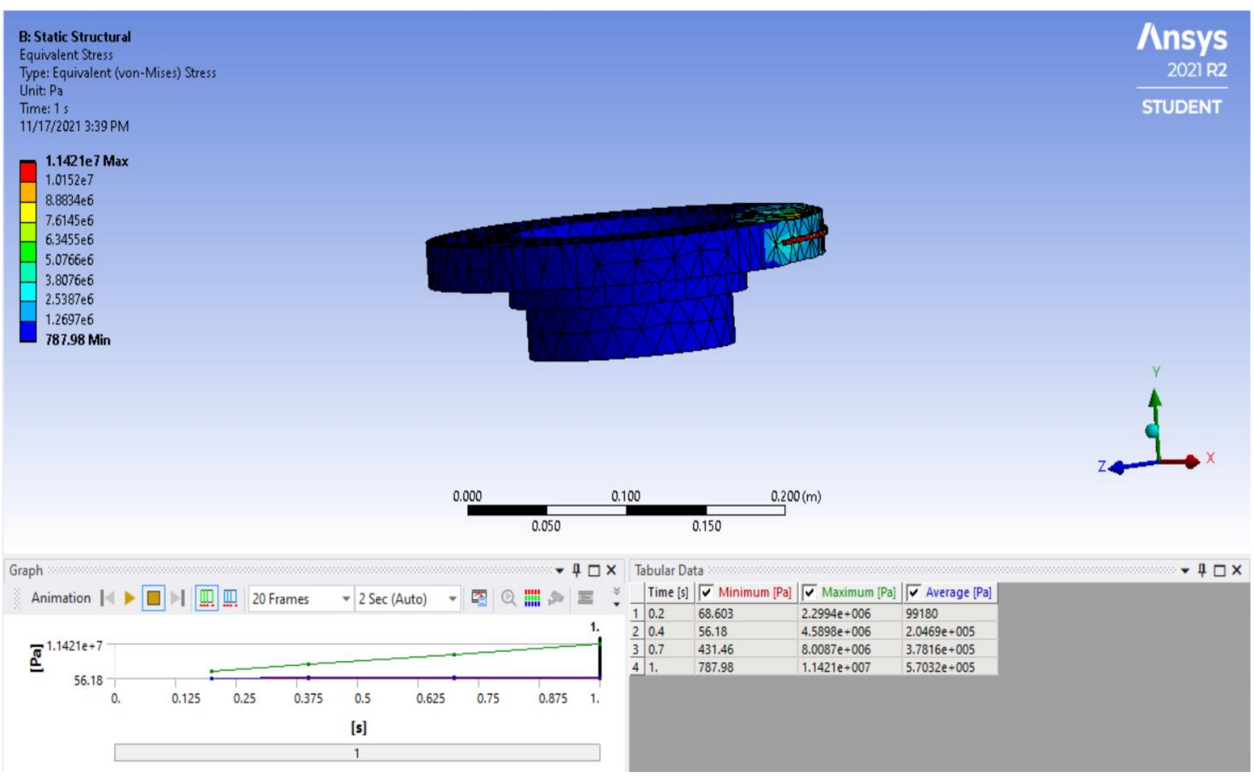
Static Structural Analysis: -

A static structural analysis determines the displacements, stresses, strains, and forces in structures or components caused by loads that do not induce significant inertia and damping effects. Steady loading and response conditions are assumed; that is, the loads and the structure's response are assumed to vary slowly with respect to time. The types of loading that can be applied in a static analysis include:

- Externally applied forces and pressures
- Steady-state inertial forces (such as gravity or rotational velocity)
- Imposed (nonzero) displacements

In the case of brake disc, a sudden braking condition is being simulated where friction is being formed between the brake disc and the brake pads. This induces stress into the structure and along with friction, a centrifugal force is also induced into the structure due to its rotation. The boundary conditions of the braking scenario are being simulated as follows.

- Firstly, the brake disc is constrained as a revolute joint by the inner radius of the brake disc.
- Then to avoid further disturbances, the X and Z axes are being constrained so that the brake disc is assumed to move just along Y axis.
- The rotational velocity of the brake disc is set to 250 rad/s at the point of revolute joint.
- The frictional coefficient is assumed to be 0.22
- The pressure applied over the brake pads are 10.495 Mega Pascals (Mpa)



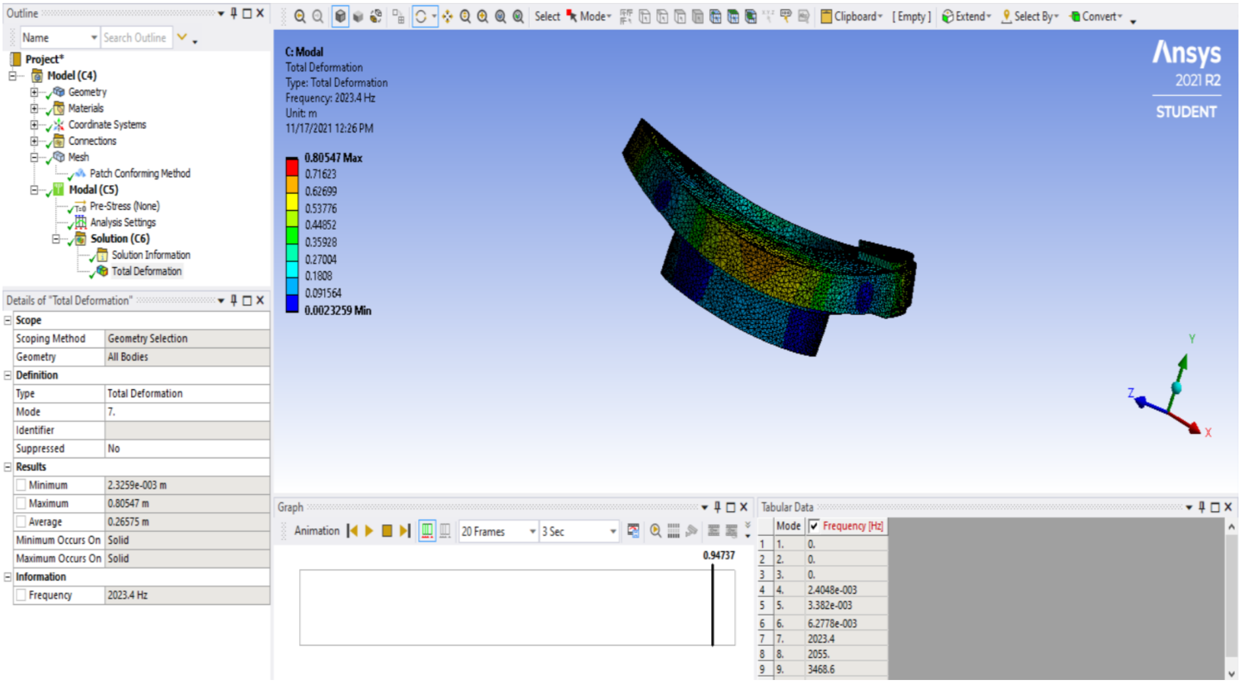
After setting up the conditions, the setup is being solved and it ended up with the following output as above. From the stress plot it is observed that the maximum stress is **11.421 Mpa** for initial conditions on the design variables.

Modal Analysis: -

Modal analysis is the fundamental dynamic analysis type, providing the natural frequencies at which a structure will resonate. These natural frequencies are of paramount importance in various engineering fields. The purpose of modal analysis in general;

- To check the connections between components if there are rigid modes in the system
- To determine whether the constraints are correct in the system
- Determining the behavior of the system under dynamic loads

Knowing the natural frequency of a structure helps to know the operating frequencies of the system under dynamic loading conditions and to predict its responses (such as resonance) at these frequencies. As similar to that, modal analysis is performed on brake disc for which the brake pad geometry is suppressed and it is observed that the natural frequency of brake disc is **2023.4 Hz.** If the natural frequency of the brake disc is lesser than the engine frequency then it will lead to failure by resonance.



Thermal Analysis: -

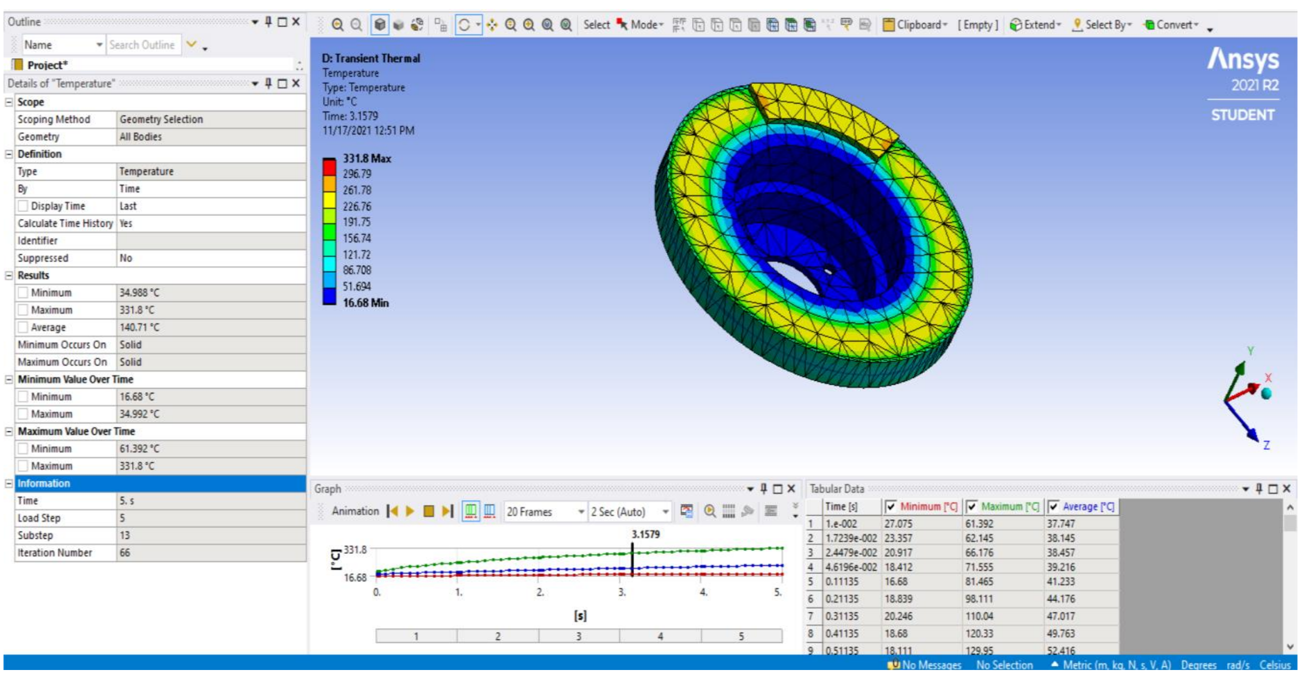
Transient thermal analysis is the evaluation of how a system responds to fixed and varying boundary conditions over time. For fixed boundary conditions, the time to reach a steady state temperature can be evaluated, as well as how long operating conditions can be sustained before reaching a threshold temperature. For time-varying boundary conditions, transient analysis can show you the resulting thermal response of the system.

Frequently, transient analysis is used to evaluate transitions in operating conditions before the system returns to steady state. In such cases, it is typical to find the steady-state solution to one set of operating conditions and then perform a transient analysis using a different set of operating conditions.

In case of brake disc in cars, when subjected to periodic or continuous braking, a large amount of heat is being generated due to friction between brake pads and rotor disc. This induces thermal stress into the structure, which leads to failure and accelerated wear. The boundary conditions of braking scenario are being simulated as follows

- The initial temperature of the structure is considered to be 35 degrees centigrade.
- The step count is being considered for 5 seconds and the number of steps is 5.
- Convection is being considered by means of air where the film coefficient is 5W/m^2K.
- The heat flux is considered to be 1.5395e6W/m^2 on both the pads where the direction of flow is towards the brake disc.

After setting up the boundary conditions, the simulation is being solved and the maximum temperature reached is **331.8 degrees centigrade** at initial conditions for the given design variables.



Design of Experiments: -

Design of Experiment (DOE) is used to sample a design space which includes all the design parameters so that a statistical model can be built in order to predict responses. Responses such as maximum and minimum stress, the maximum and minimum temperature and first natural frequency can all be determined by DOE. DOE is specifically useful when the user can sample a limited number of points. The main purpose of Design of the experiment is to spread out the samples so that the results have a low uncertainty. This also results in high accuracy and precision in prediction. Latin Hypercube Sampling is employed (LHS) is capable of generating random samples of parameter values. It is widely used in Monte Carlo simulation, because it can drastically reduce the number of runs necessary to achieve a reasonably accurate result.

After setting up the method, for each parameter I.e., design variable the upper and lower bounds are being selected. Then the DOE list is being updated where the time taken entirely depends upon the number of samples. The LHS DOE point table are as follows.

Table of Schematic E2: Design of Experiments (Latin Hypercube Sampling Design : CCD Samples : Random Generator Seed = 0)

		E	F	G	H	I	J	K
1	(mm)	P4 - rotor_thickness (mm)	P5 - rotor_OD (mm)	P6 - rotor_ID (mm)	P7 - Rotational Velocity Y Component (radian s^-1)	P8 - Equivalent Stress Minimum (Pa)	P9 - Equivalent Stress Maximum (Pa)	P10 - Equivalent Stress Average (Pa)
2		26.899	119.3	75.38	271.52	22892	1.6575E+07	1.8713E+06
3		23.228	122.47	82.025	261.39	18213	2.857E+07	1.6304E+06
4		22.848	131.33	67.785	250	24337	1.4386E+07	1.5663E+06
5		23.671	124.37	70.253	248.73	36369	1.4657E+07	1.4378E+06
6		26.582	130.7	77.278	243.04	21179	1.3582E+07	1.6705E+06
7		22.722	127.53	81.076	259.49	14394	1.5205E+07	1.6529E+06
8		25.253	132.59	69.494	228.48	17960	1.4253E+07	1.6729E+06
9		27.152	132.28	69.873	274.68	38219	1.4444E+07	1.7284E+06
10		27.405	117.72	81.646	236.08	27241	2.1391E+07	2.232E+06
11		23.481	125	78.038	232.91	24940	1.2877E+07	1.4834E+06
12		24.937	114.24	72.342	226.58	39804	3.7122E+07	2.5237E+06
13		25.316	131.65	79.937	264.56	35274	1.4865E+07	1.6745E+06
14		25.443	137.03	76.899	239.24	25230	1.3656E+07	1.6696E+06
15		22.532	112.97	68.165	255.06	32984	3.712E+07	2.363E+06
16		25.57	128.16	72.911	230.38	15784	1.2294E+07	1.6589E+06
17		23.608	115.82	71.772	229.11	37966	3.7198E+07	2.4041E+06
18		23.418	119.62	81.835	250.63	16872	1.689E+07	1.6096E+06
19		24.367	120.89	75.19	269.62	8535.8	1.4361E+07	1.5226E+06
20		24.494	133.86	76.139	251.9	39989	1.4146E+07	1.6414E+06
21		25.633	118.35	79.177	251.27	42501	2.1147E+07	2.1342E+06
22		27.025	127.22	75.57	246.84	34010	1.3673E+07	1.6253E+06
23		24.557	129.43	74.62	238.61	10965	1.3998E+07	1.6552E+06
24		25.759	136.08	71.582	245.57	22012	1.333E+07	1.5827E+06
25		27.089	124.68	76.519	262.66	36304	1.32E+07	1.5347E+06
26		23.734	116.14	78.418	243.67	43508	3.706E+07	2.4944E+06
27		24.62	123.73	80.506	252.53	14976	1.4047E+07	1.4906E+06
28		24.747	129.75	67.975	247.47	17036	1.3007E+07	1.6118E+06
29		26.266	133.54	78.228	234.81	17057	1.424E+07	1.6506E+06
30		25.506	121.84	77.468	270.25	16280	1.5001E+07	1.6492E+06
31		25.949	121.52	73.101	246.2	15757	1.3089E+07	1.6222E+06
32		24.873	126.9	71.203	231.01	23144	1.2689E+07	1.5356E+06
33		23.291	122.15	77.848	260.13	14052	1.2933E+07	1.5066E+06
34		27.215	115.19	79.367	272.78	47488	3.6933E+07	2.6952E+06
35		26.076	135.13	79.747	240.51	25311	1.4089E+07	1.6729E+06
36		26.456	126.27	70.633	274.05	31957	1.2155E+07	1.5868E+06

Table of Schematic E2: Design of Experiments (Latin Hypercube Sampling Design : CCD Samples : Random Generator Seed = 0)

		E	F	G	H	I	J	K
1	(mm)	P4 - rotor_thickness (mm)	P5 - rotor_OD (mm)	P6 - rotor_ID (mm)	P7 - Rotational Velocity Y Component (radian s^-1)	P8 - Equivalent Stress Minimum (Pa)	P9 - Equivalent Stress Maximum (Pa)	P10 - Equivalent Stress Average (Pa)
37		24.684	121.2	70.443	241.77	25845	1.3852E+07	1.4997E+06
38		26.835	120.57	75.949	262.03	13825	1.3552E+07	1.6602E+06
39		24.051	114.87	75	257.59	9567.1	3.7099E+07	2.5166E+06
40		27.468	128.48	72.152	254.43	31644	1.3082E+07	1.7361E+06
41		26.139	123.1	69.304	253.8	27191	2.4339E+07	1.5811E+06
42		23.354	123.42	76.329	234.18	29904	1.3221E+07	1.4663E+06
43		23.544	118.99	75.759	256.96	38425	2.1029E+07	1.9141E+06
44		22.785	134.49	71.392	244.3	28547	1.2493E+07	1.5099E+06
45		23.101	130.38	74.81	268.35	6065.2	1.4961E+07	1.7136E+06
46		22.911	135.44	82.405	253.16	20914	1.4807E+07	1.6621E+06
47		23.924	134.18	71.013	236.71	19386	1.2627E+07	1.5099E+06
48		25.127	116.77	77.658	239.87	53981	2.9632E+07	2.2072E+06
49		22.595	132.91	72.722	237.34	18831	1.427E+07	1.7348E+06
50		24.177	118.04	77.089	242.41	41090	2.1031E+07	2.0519E+06
51		23.861	122.78	68.544	273.42	6292.3	2.6105E+07	1.5388E+06
52		25.823	116.46	80.316	229.75	31354	3.0265E+07	2.4118E+06
53		24.241	129.11	73.671	265.19	18000	1.4086E+07	1.6908E+06
54		24.114	117.41	74.241	225.32	40794	2.1101E+07	1.9926E+06
55		26.772	136.39	70.063	231.65	32210	1.3853E+07	1.6667E+06
56		26.013	127.85	67.595	268.99	32857	1.3886E+07	1.6147E+06
57		22.975	112.66	68.734	267.72	53818	3.7227E+07	2.4765E+06
58		25.886	133.23	70.823	256.33	33327	1.4051E+07	1.7118E+06
59		27.342	118.67	73.291	263.29	26477	2.1157E+07	2.158E+06
60		24.81	113.61	81.266	266.46	61133	3.707E+07	2.6014E+06
61		22.658	125.95	74.43	225.95	29344	1.2208E+07	1.5463E+06
62		23.038	119.94	68.354	260.76	19244	1.7463E+07	1.4012E+06
63		25.19	137.34	81.456	258.23	35871	1.523E+07	1.6672E+06
64		25.063	120.25	82.215	227.85	25335	1.5226E+07	1.6581E+06
65		27.278	126.58	71.962	244.94	19715	1.2722E+07	1.5469E+06
66		23.987	136.71	72.532	241.14	29509	1.4745E+07	1.5406E+06
67		25.696	114.56	78.987	249.37	73509	3.7061E+07	2.6796E+06
68		26.646	131.96	73.481	237.97	16363	1.3205E+07	1.7064E+06
69		24.43	125.32	69.114	272.15	26526	1.2157E+07	1.4734E+06
70		25	128.8	76.709	263.92	17832	1.5141E+07	1.6809E+06

Response Surface and Sensitivity Analysis: -

Response surface explores the relationships between several explanatory variables and one or more response variables. The main idea of response surface is to use a sequence of designed experiments to obtain an optimal response. This model is only an approximation, but they use it because such a model is easy to estimate and apply, even when little is known about the process. After the completion of DOE table, in the response surface the DOE data points are being updated, sensitivity analysis is performed. Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system (numerical or otherwise) can be divided and allocated to different sources of uncertainty in its inputs. From the analysis we get the following outputs

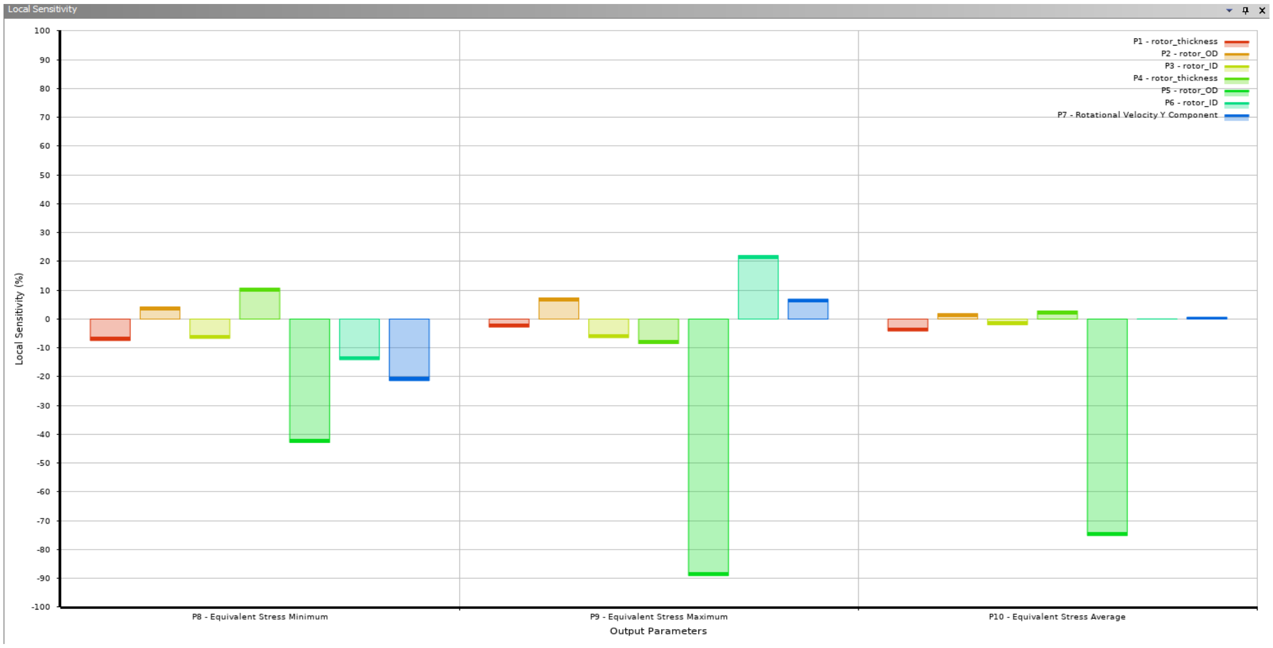
- Local Sensitivity: It shows the norm of the partial derivatives of the chosen objective with respect to the selected variable.

- Local Sensitivity Curve: It shows the response curve of the chosen objective (Y-axis) with respect to the selected variables (X-axis).

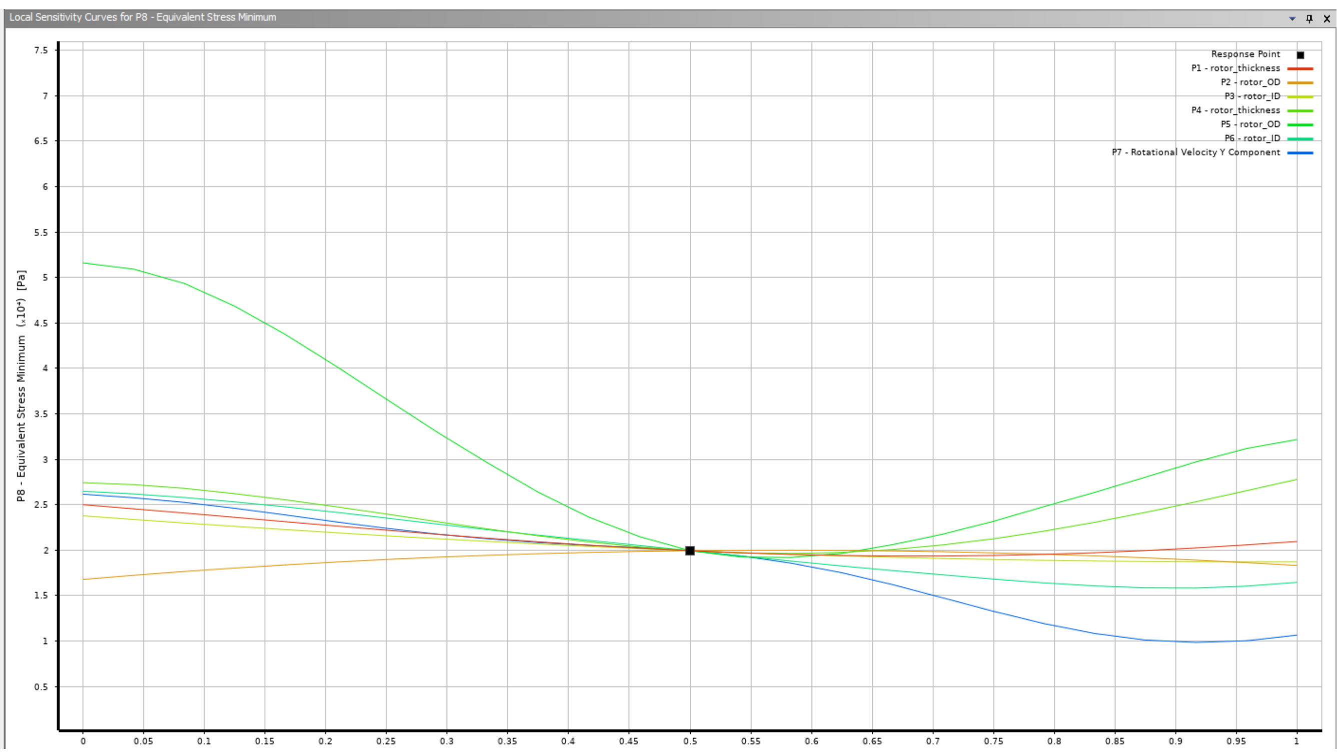
- Response: It shows the relationship between the output value and the input value.

- Spider: It shows the relationship between the output values post sensitivity analysis

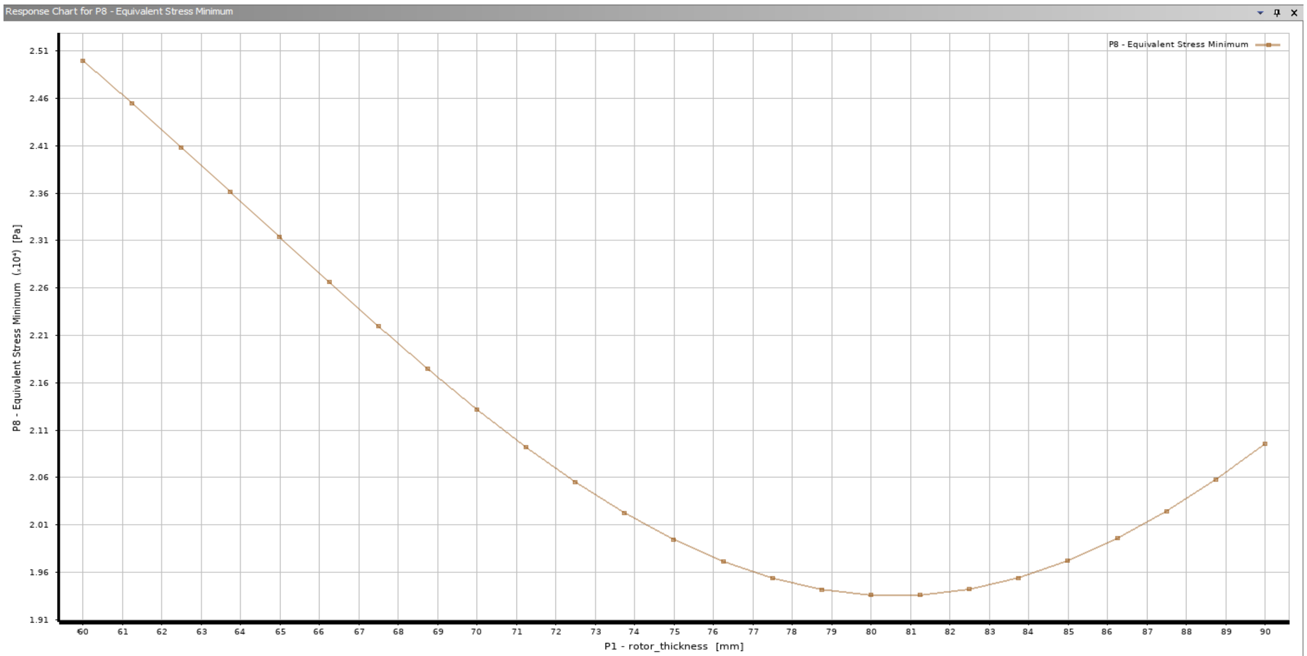
Local Sensitivity: -



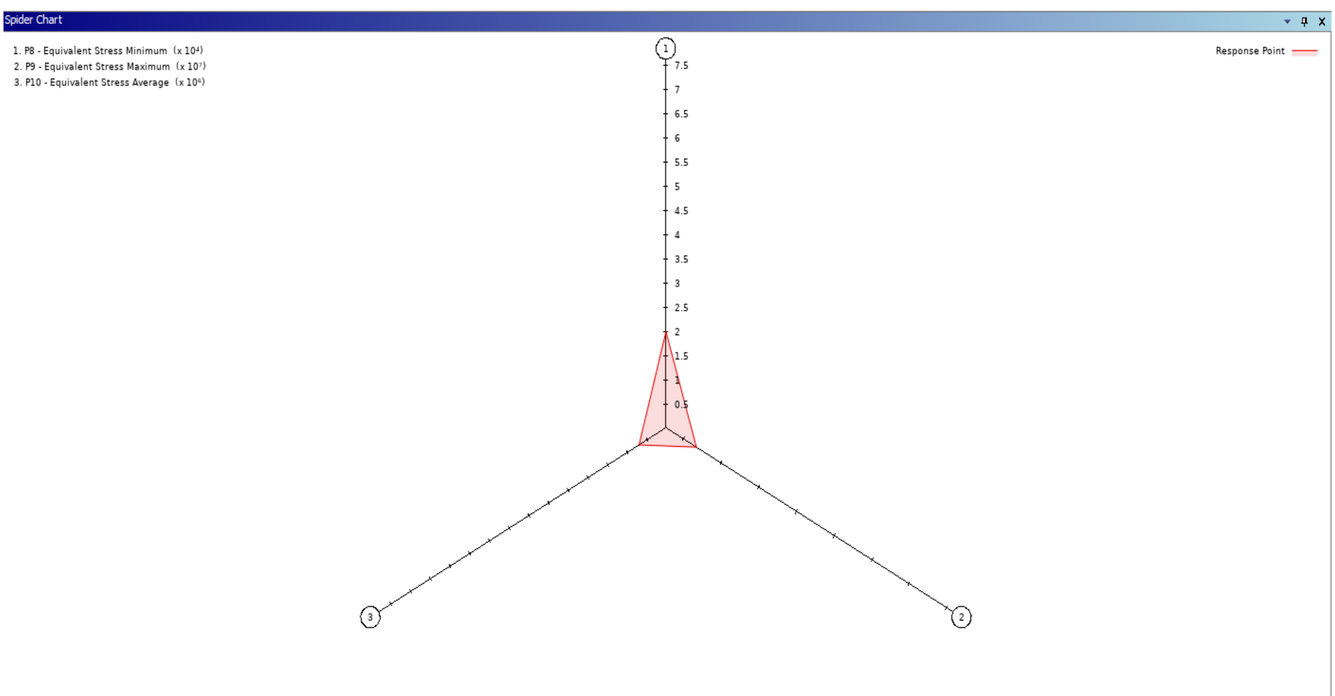
Local Sensitivity Curves: -



Response: -



Spider: -



Conclusion: -

At the end of various analyses, it was possible to determine the critical factors which might contribute to the failure of the structure. In addition to that, by means of DOE and Sensitivity Analysis it was possible to understand the relationship between the input variables and output variables. This would further help in optimizing the structure as per the environment conditions.