MAE 598 - DESIGN OPTIMIZATION

PROJECT -2
DESIGN OPTIMIZATION OF BRAKE DISC GEOMETRY

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ABSTRACT

The aim of this project is to solve the brake disc assemble for the different conditions like Stress ,Modal and Thermal and doing the optimization using these values. The optimization is carried out to find the best suitable dimensions. The optimization objective is to minimize the stress, temperature and maximize the first natural frequency of the disc. These goals are accomplished using optimization algorithm and the results are correlated with the values obtained from ANSYS. The system optimization is performed using Kriging method and by using the load cases.

ACKNOWLEDGEMENT

I primarily would like thank Dr.Yi Ren for his time in teaching and giving me the right resources to understand this class in the better way. The High computing laboratory from Arizona State University was of major assistance in carrying out the simulation.

Introduction

Brake design analysis is going to be done ANSYS Design of Experiment (DOE) and Optimization tools which will allow you to better validate and understand your engineering model and further refine your design for specific properties

the brake design problem has the following objectives:

- Design a brake disc for emergency braking conditions with minimal volume
- 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.

Significance of Analysis :

Structural Analysis

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Modal Analysis

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Glossary of terms used :

- V: Volume (mm3)
- α: Regression coefficients for volume
- S: Stress (MPa)
- β: Regression coefficients for stress
- F: First natural frequency (Hz)
- γ: Regression coefficients for frequency
- T: Temperature (oC)
- δ: Regression coefficients for temperature 7
- P1: Inner disc radius (mm)
- P2: Outer disc radius (mm)
- P3: Disc thickness (mm)
- d: Braking distance (m)
- te: Braking time (s)
- u: Initial vehicle velocity (kmph)
- m: Vehicle mass (kg) ν: Coefficient of friction

- w: Disc rotational velocity (rad/s)
- Ravg: Average of P1 and P2 (mm)
- KE: Vehicle kinetic energy (J)
- Fb: Total braking force on the disc (N)
- P: Pressure acting on the disc due to one brake pad (Pa)
- Ap: Brake pad area (mm2)
- Asp: Brake pad swept area (mm2)
- q: Heat flux (W/m2)
- Tamb: Ambient temperature (oC)

Mathematical Model :

- The brake disc inner radius (P1), outer radius (P2) and thickness (P3) are the design variables in this optimization study. Initially, structural, modal, and thermal analyses are performed in ANSYS. For the assumed geometric constraints, Design of Experiment (DOE) points are generated. Mathematical model is then generated by performing a 2nd order regression analysis on these DOE points to obtain the volume, stress, frequency, and temperature quadratic functions. The objective function is designed as follows:

$$\text{Min } V = \sum_{n=1}^{n=3} \alpha_n x_n + \sum_{n=4}^{n=6} \alpha_n x_n^2 + \alpha_7; (R_{\text{volume}}^2 = 0.98)$$

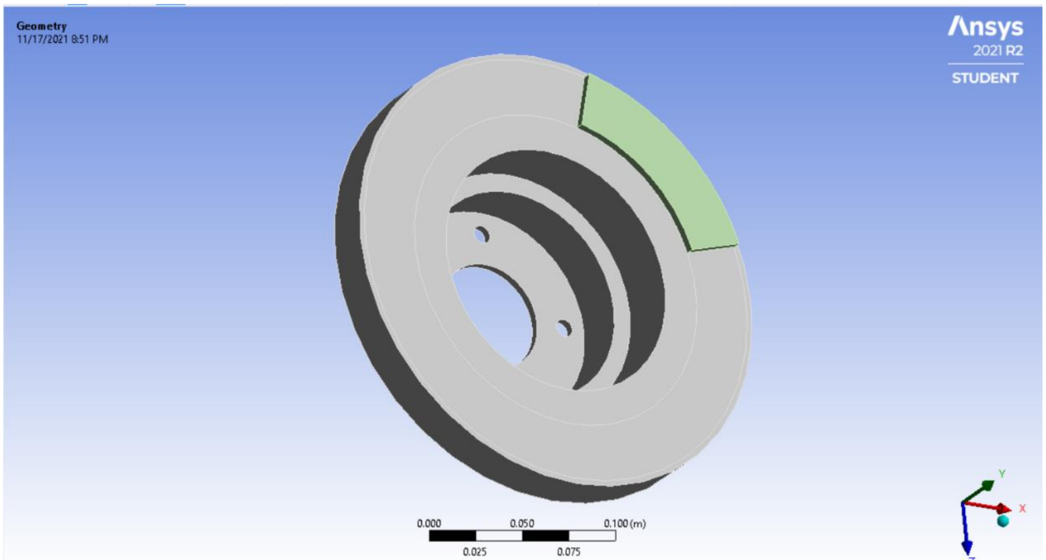
Geometric Constraints for these Analysis

I have given the following constraint for my model in order to have the desired data during the optimization formulation using the response surface.

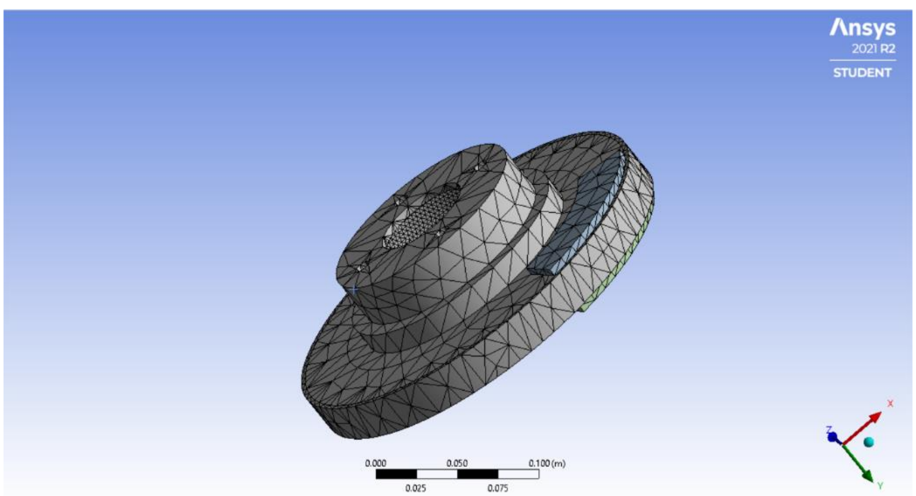
$$g1 : -P1 \leq -60$$
$$g2 : P1 \leq 87$$
$$g3 : -P2 \leq -124$$
$$g4 : P2 \leq 153$$
$$g5 : -P3 \leq -10$$
$$g6 : P3 \leq 30$$

Finite Element Model

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 75 mm, 125 mm and 25 mm respectively.



The CAD geometry is meshed tetrahedral quadratic elements as shown in Figure. The reason for the choosing this shape is that the node which are unrealistic won’t be considered which removes complexity.



The brake disc is made of gray cast iron and the part are made of Structured Steel.
The assumptions made for performing the FEM analysis are as follows:

- 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.

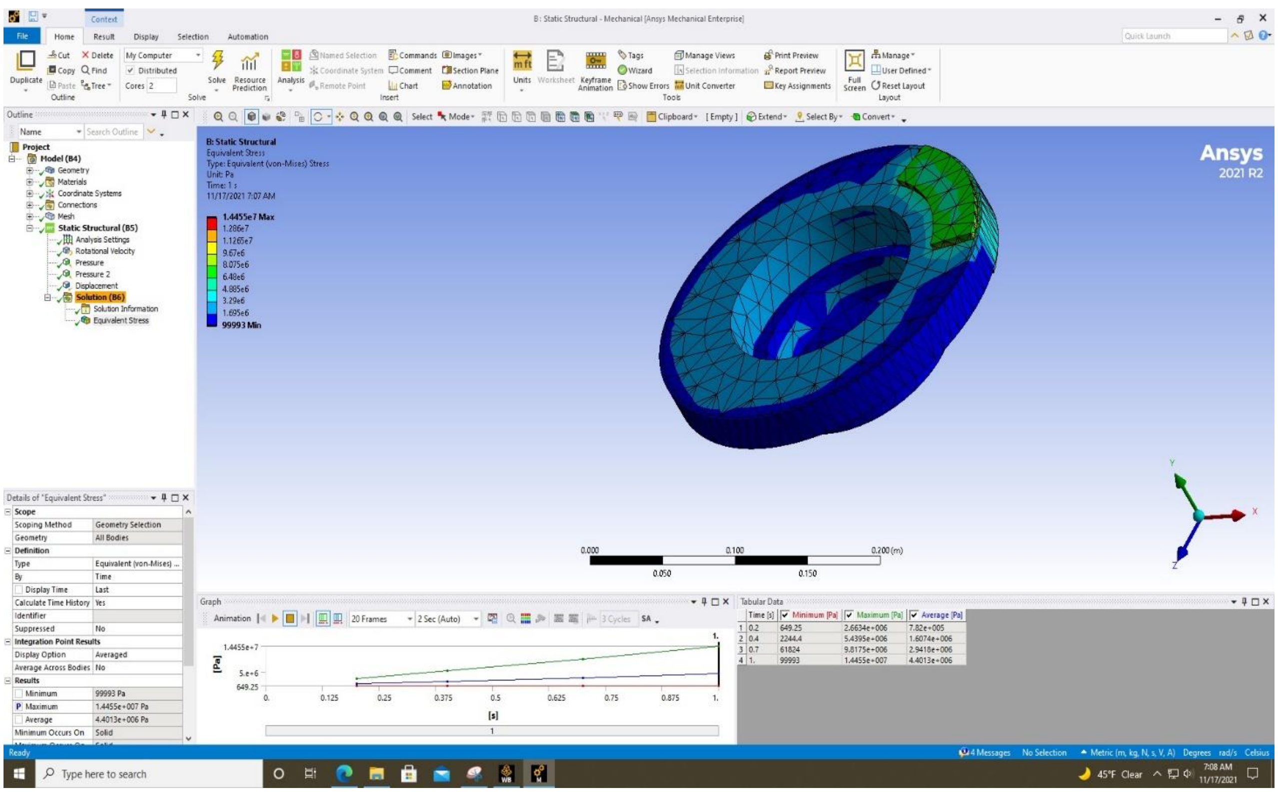
Structural Analysis:

Considering the emergency braking distance of 0 m with stopping time of 5 seconds for a vehicle with initial velocity of 100 km/hr, the braking pressure required is calculated. This pressure will act as one of the boundary conditions for the simulation.

Using this, the pressure on each pad is calculated by considering the coefficient of friction.
Here, d = 10m;te = 5s; u = 90kmph; m = 1500kg; v = 0.22; Ap = 3552mm2 .

<u>Stress distribution of the Structural Analysis</u>

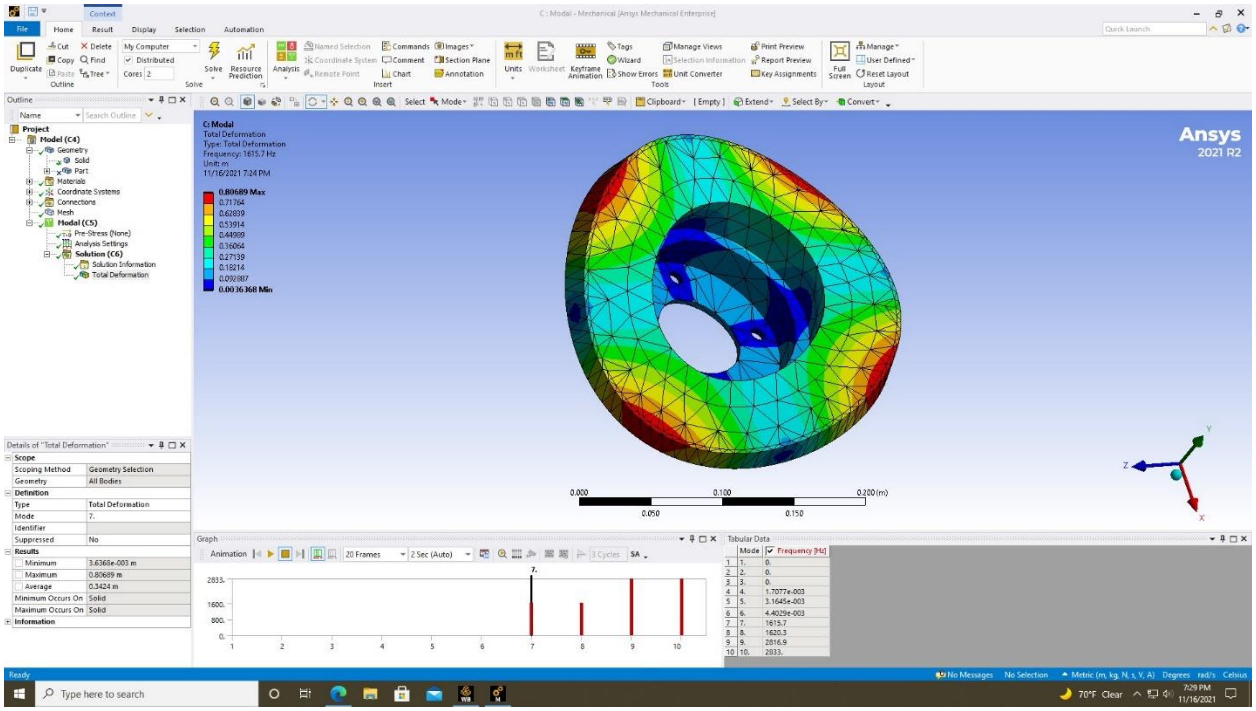
Calculating the disc angular velocity (ω), ω = u/Ravg = 250rad/s.



The max stress obtained is 1.4455e+007.

Modal Analysis:

Modal Analysis Modal analysis is performed on the brake disc to determine its free natural frequency. The brake caliper pad geometry is suppressed while performing this analysis because the natural frequency of the brake disc is to be determined. The following figure shows the first natural frequency and its mode shape. The frequency obtained is 1614 Hz

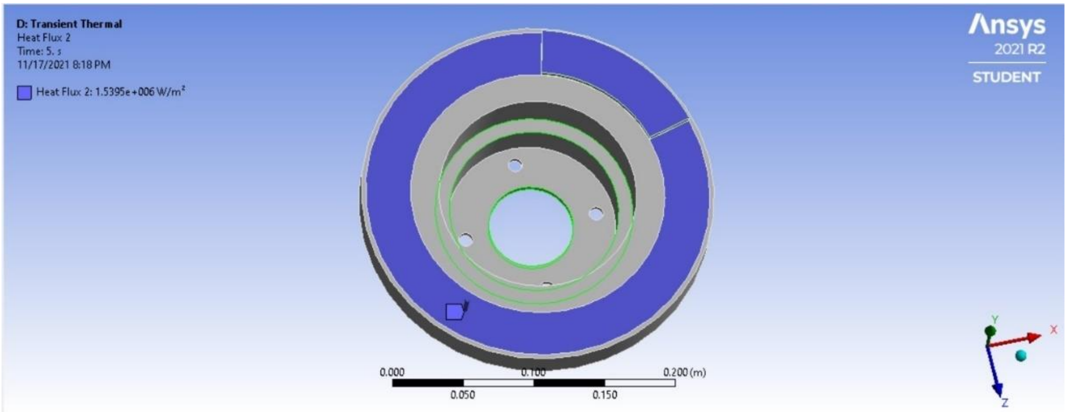


Modal Plot for the defined input parameter

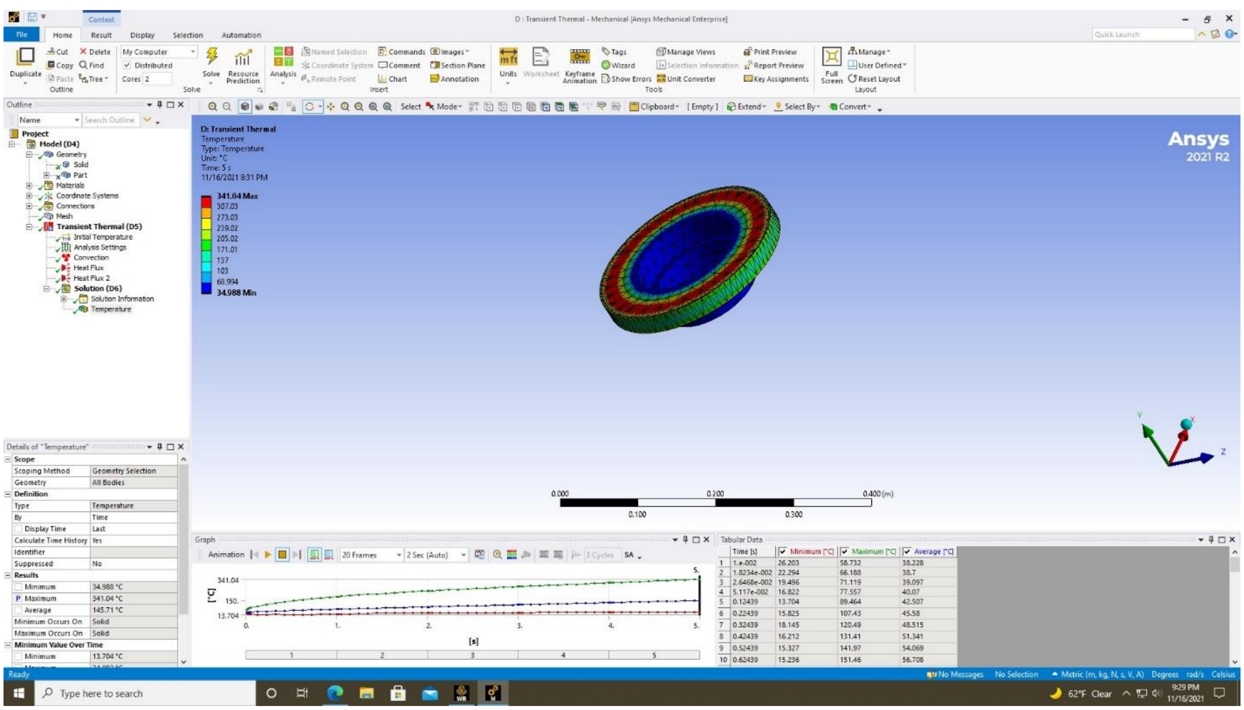
Thermal Analysis

Transient thermal analysis is performed on the disc to observe the maximum temperature rise after the braking operation. The brake caliper pad geometry is suppressed while performing this analysis.. It is assumed that 70% of the braking power is in the front axle of a four-wheeler vehicle. The total heat flux is also multiplied by 0.5 to get the flux generated by a single pad on the disc brake. Here, te = 5s; Asp = 0.021m^2 ; Tamb = 35 deg C.

The Heat flux is obtained as ,

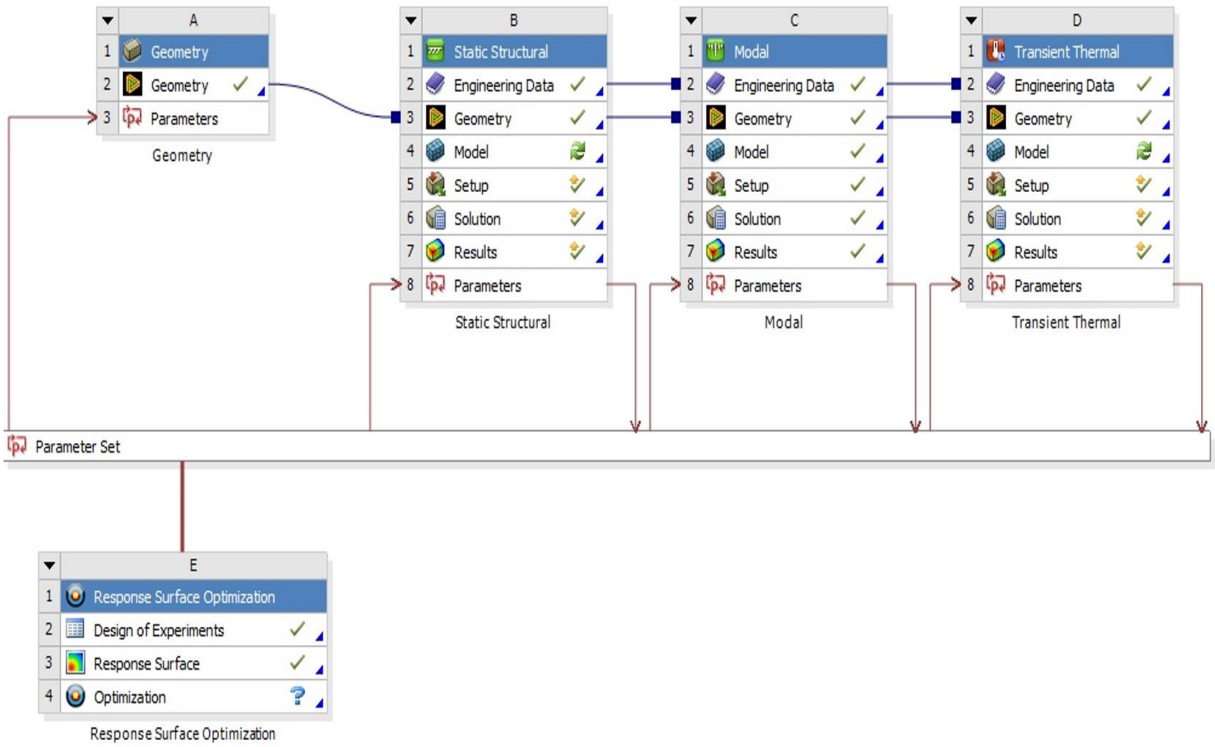


The temperature plot obtained . As observed, the maximum temperature of 341 deg C is obtained for initial conditions on the design variables.



Full Brake Model:

The model of the brake is analyzed in stages and the model is fed into next stages with the existing geometry and meshing conditions in the setup.



Design of Experiments:

It allows for multiple input factors to be manipulated, determining their effect on a desired output (response). By manipulating multiple inputs at the same time, DOE can identify important interactions that may be missed when experimenting with one factor at a time. All possible combinations can be investigated (full factorial) or only a portion of the possible combinations (fractional factorial).

A strategically planned and executed experiment may provide a great deal of information about the effect on a response variable due to one or more factors. Many experiments involve holding certain factors constant and altering the levels of another variable. This "one factor at a time" (OFAT) approach to process knowledge is, however, inefficient when compared with changing factor levels simultaneously.

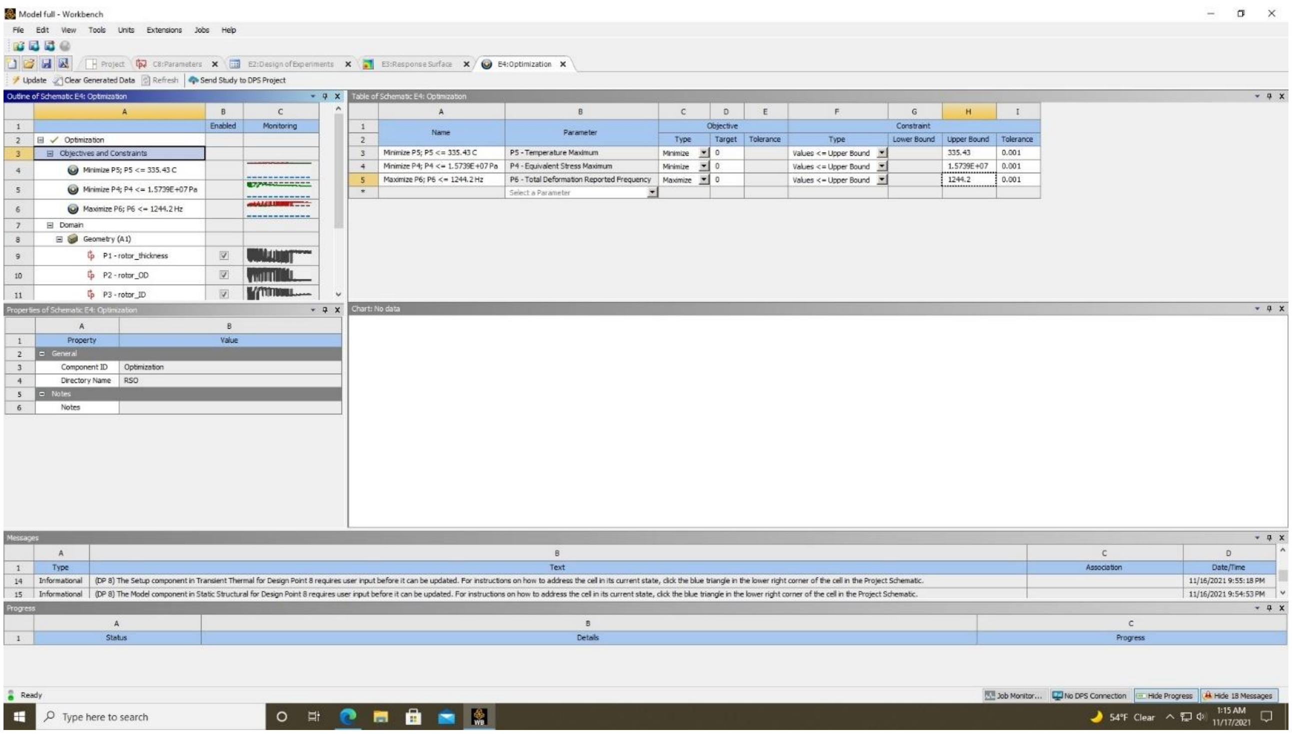
Many of the current statistical approaches to designed experiments originate from the work of R. A. Fisher in the early part of the 20th century. Fisher demonstrated how taking the time to seriously consider the design and execution of an experiment before trying it helped avoid frequently encountered problems in analysis. Key concepts in creating a designed experiment include blocking, randomization, and replication.

Blocking: When randomizing a factor is impossible or too costly, blocking lets you restrict randomization by carrying out all of the trials with one setting of the factor and then all the trials with the other setting.

Randomization: Refers to the order in which the trials of an experiment are performed. A randomized sequence helps eliminate effects of unknown or uncontrolled variables.

Replication: Repetition of a complete experimental treatment, including the setup.

The upper and lower bound limits for each of the following analysis is given and the DOE points are generated.



DOE results after the simulation for the given lower and upper bound values.

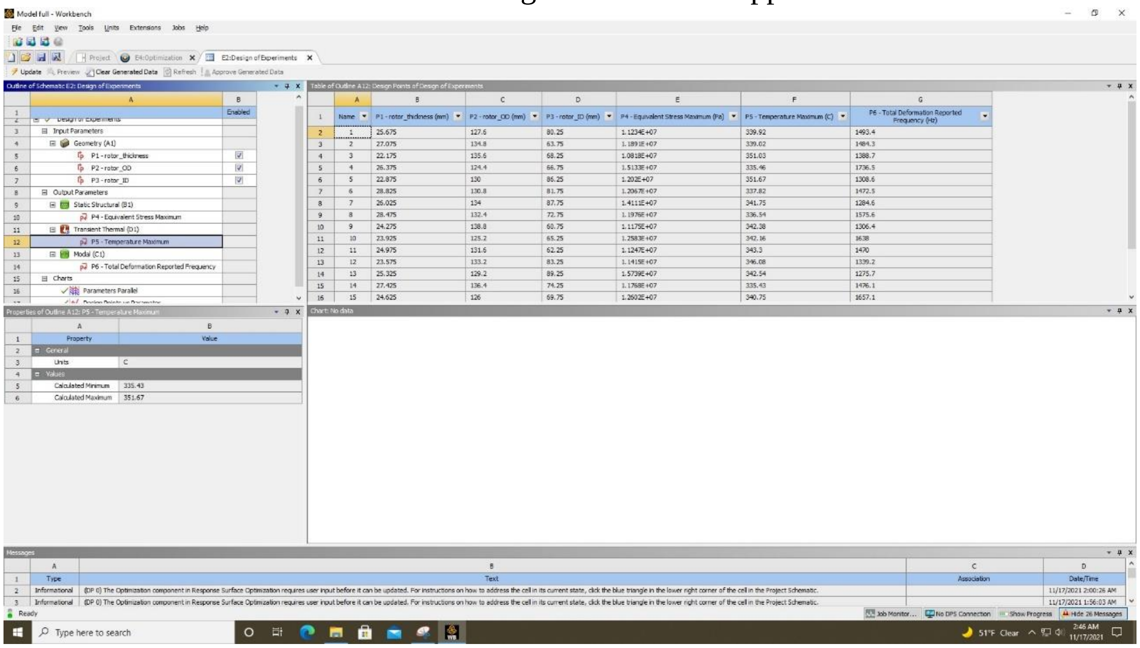
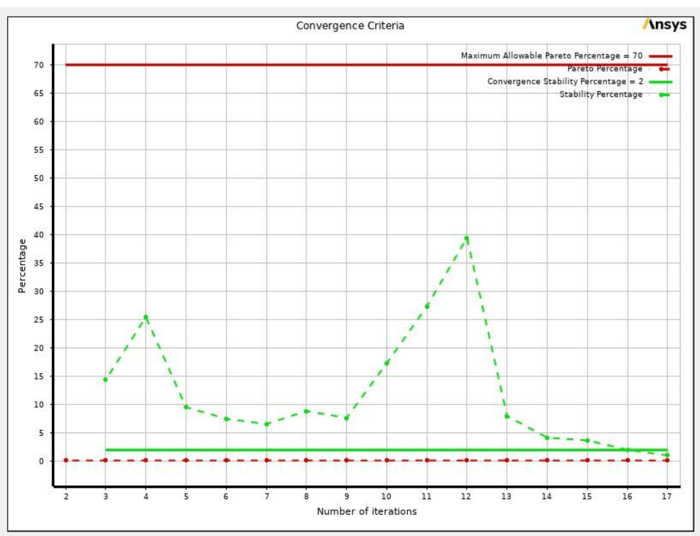


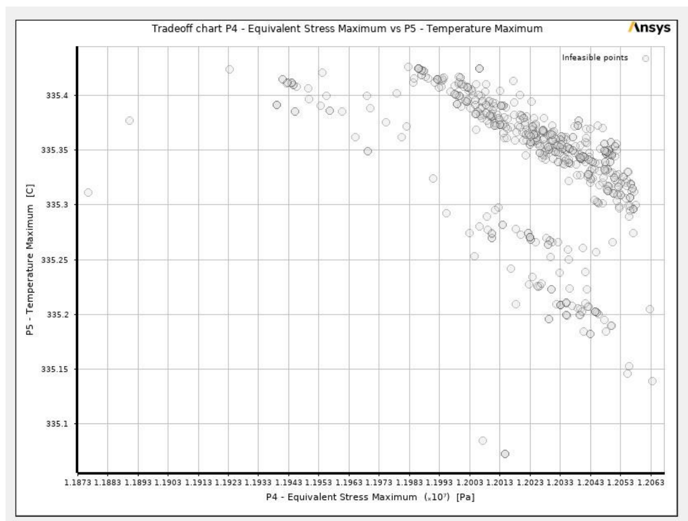
Table of Outline A12: Design Points of Design of Experiments

Name	P1 - rotor_thickness (mm)	P2 - rotor_OD (mm)	P3 - rotor_ID (mm)	P4 - Equivalent Stress Maximum (Pa)	P5 - Temperature Maximum (C)	P6 - Total Deformation Reported Frequency (Hz)
1	25.675	127.6	80.25	1.1234E+07	339.92	1493.4
2	27.075	134.8	63.75	1.1891E+07	339.02	1484.3
3	22.175	135.6	68.25	1.0818E+07	351.03	1388.7
4	26.375	124.4	66.75	1.5133E+07	335.46	1736.5
5	22.875	130	86.25	1.202E+07	351.67	1308.6
6	28.825	130.8	81.75	1.2067E+07	337.82	1472.5
7	26.025	134	87.75	1.4111E+07	341.75	1284.6
8	28.475	132.4	72.75	1.1976E+07	336.54	1575.6
9	24.275	138.8	60.75	1.1175E+07	342.38	1306.4
10	23.925	125.2	65.25	1.2583E+07	342.16	1638
11	24.975	131.6	62.25	1.1247E+07	343.3	1470
12	23.575	133.2	83.25	1.1415E+07	346.08	1339.2
13	25.325	129.2	89.25	1.5739E+07	342.54	1275.7
14	27.425	136.4	74.25	1.1768E+07	335.43	1476.1
15	24.625	126	69.75	1.2602E+07	340.75	1657.1

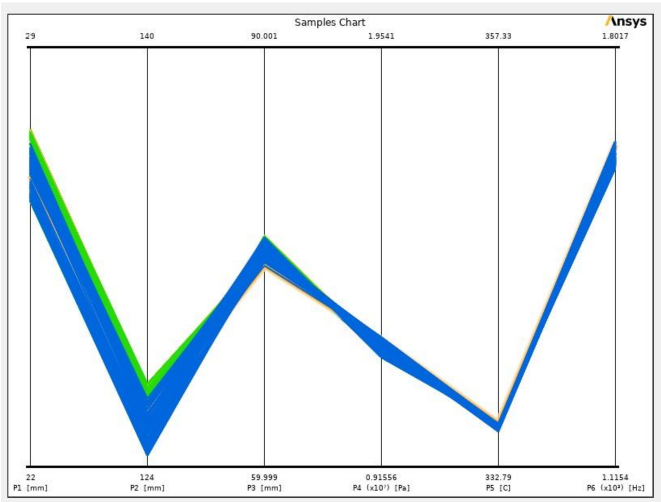
Response Surface:

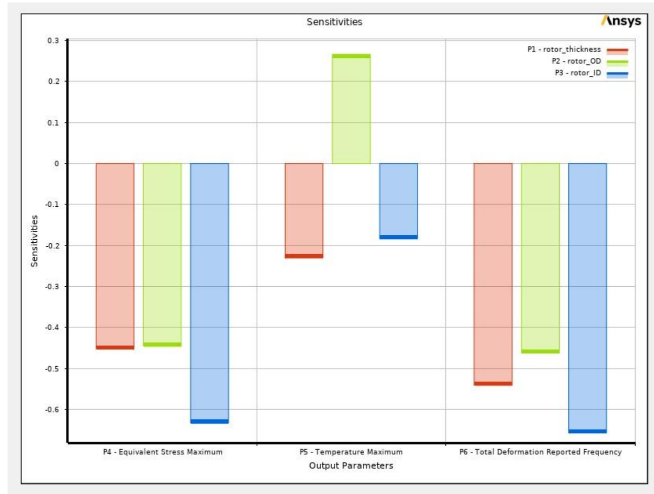
After DOE, a response surface is generated for all the input and output values using the least squares methodology. The data points are fitted with a standard 2nd order model. The plots are generated for the convergence, Trade Off & Sensitivity.





The response surface enables us to track the change of the objective with respect to variable. When many variables exist, sensitivity analysis allows us to reduce the computational cost of the optimization.





Response Surface Optimization Study :

Single objective vs. Multi-objective

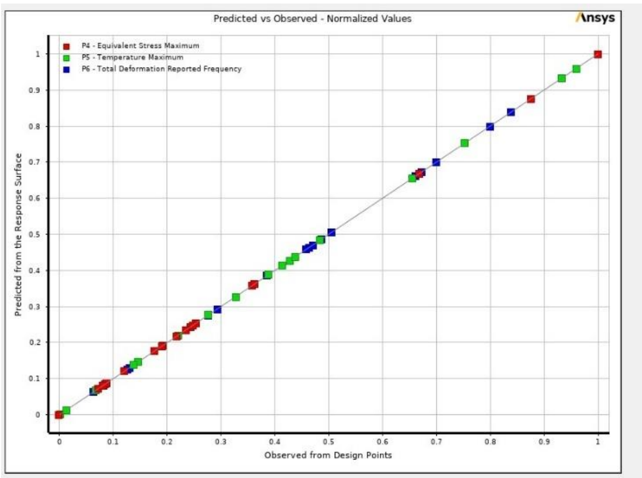
There is rarely a design case where we only want to optimize a single response. In the running example, a set of objectives are listed.

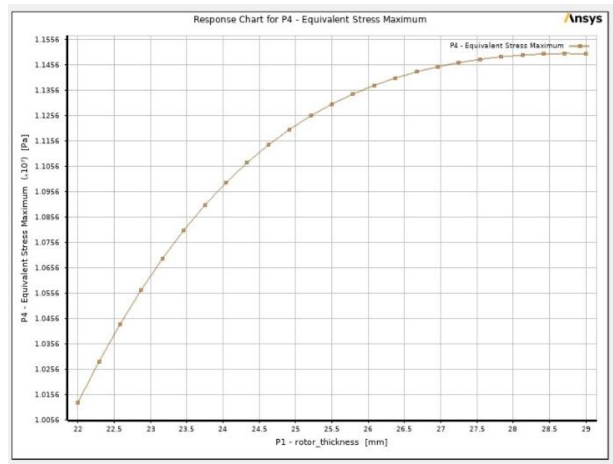
ANSYS provides a list of optimization algorithms:

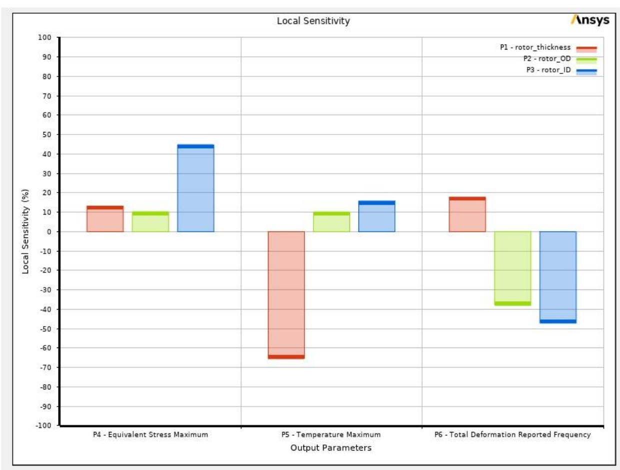
- **Screening**: Randomly sampling the space and pick out the good ones. Use this as an initial trial to make sure everything is setup correctly, e.g., does your simulation give reasonable results?
- **Multiobjective Genetic Algorithm (MOGA)**: Simultaneously find Pareto-optimal designs. Use this when you have multiple objectives. This is not the only choice for this situation though, see discussion above.
- **Nonlinear Programming by Quadratic Lagrangian (NLPQL)**: Fast local search. Use this when (1) there is only one objective (but you can set other objectives as constraints), (2) the simulation does not take too long (in minutes), (3) the number of variables is small (less than 10).
- **Mixed-Integer Sequential Quadratic Programming (MISQP)**: Similar to NLPQL, but allows integer variables. Note that the addition of integer variables will often significantly increase the computation time.
- **Adaptive Single-Objective Optimization (ASO)**: This method uses Optimal Space Filling for DOE, Kriging as a response surface, and MISQP for finding local optimal solutions from the response surface. Use this when the evaluation of objective/constriants are expensive and you have limited budget/time for optimization.

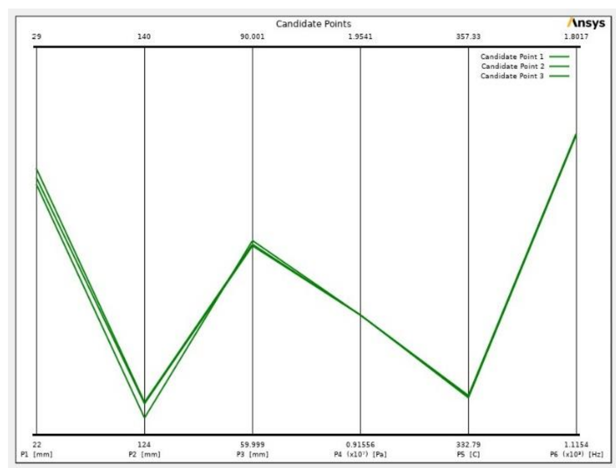
- **Adaptive Multi-Objective Optimization (AMO)**: Similar to ASO, this one uses Kriging and MOGA.

Rather than generating the plots of Response Surface , The response surface optimization method is used here. The models are solved for the existing conditions with Kriging Method and the responses from the same are recorded .





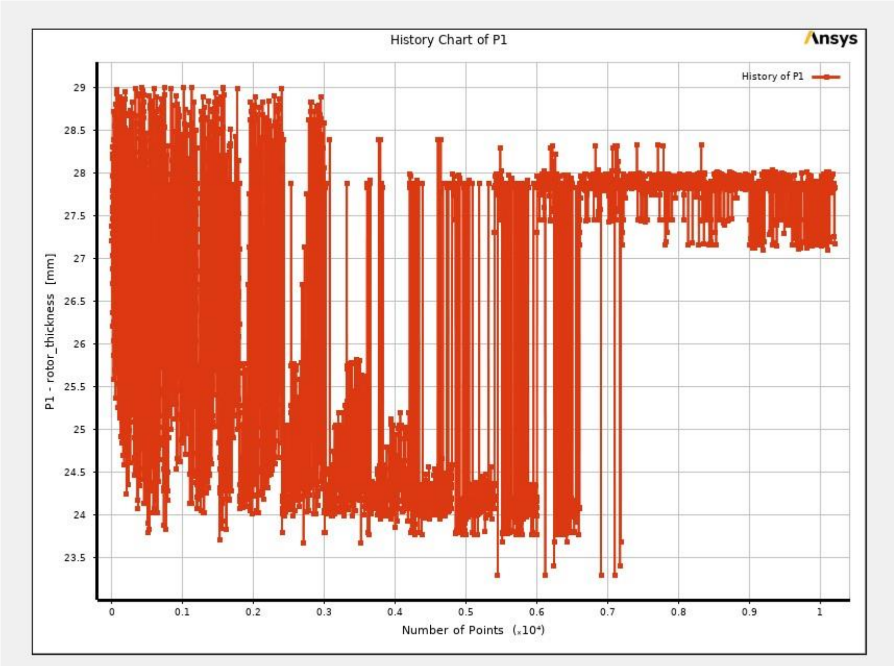




Figures depicting Convergence , Response Chart , Local Sensitivity & Candidate points for the optimization…

OPTIMIZATION RESULTS:

I used Kriging method / MOGA (Multi Objective Genetic Algorithm) to reduce my temperature , stress and modal frequency which are treated as objective functions and the other two as constraints . I am attaching the trade off points , convergence plots for the rotor thickness as well.



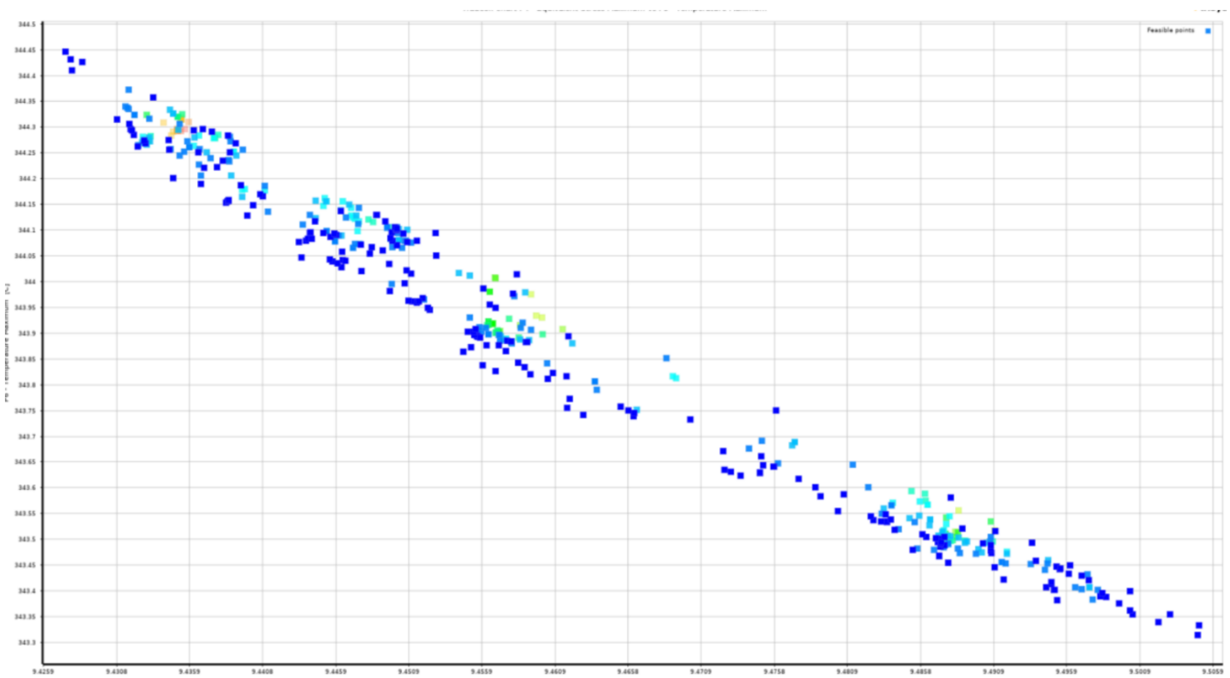
Rotor Thickness convergence vs Iterations

The above rsult is for the P1 rotor and the results for the other two rotors are similar in nature as the consditions and forces are same. We can notice the convergence of the pattern in the above image which tells us that the parameter that we are calculating are being minimized which is the optimization criteria.

	A	B	C	D
1	⊟ Optimization Study			
2	Minimize P4; 1.0818E+07 Pa <= P4 <= 1.5739E+07 Pa	Goal, Minimize P4 (Default importance); Strict Constraint, P4 values between 1.0818E +07 Pa and 1.5739E+07 Pa (Default importance)		
3	Minimize P5; 335.43 C <= P5 <= 351.67 C	Goal, Minimize P5 (Default importance); Strict Constraint, P5 values between 335.43 C and 351.67 C (Default importance)		
4	Maximize P6; 1244 Hz <= P6 <= 1736.5 Hz	Goal, Maximize P6 (Default importance); Strict Constraint, P6 values between 1244 Hz and 1736.5 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 6609 evaluations.		
9	⊟ Candidate Points			
10		Candidate Point 1	Candidate Point 2	Candidate Point 3
11	P1 - rotor_thickness (mm)	26.649	26.524	26.799
12	P2 - rotor_OD (mm)	125.3	124.72	125.38
13	P3 - rotor_ID (mm)	74.636	75.076	74.774
14	P4 - Equivalent Stress Maximum (Pa)	★★ 1.2372E+07	★★ 1.2376E+07	★★ 1.2366E+07
15	P5 - Temperature Maximum (C)	× 335.34	× 335.27	× 335.15
16	P6 - Total Deformation Reported Frequency (Hz)	★★ 1649.5	★★ 1649.5	★★ 1647.3

Optimization Window with results

The above the values of optimization after the lower and upper bound conditions are specified.



Trade off - Stress vs Temperature

The sensitivity plot is already shown in the former discussion. The Sensitivity Graph tool is designed to allow you to review the results of sensitivity simulations. When sensitivity results have been stored for a variable, the Sensitivity Graph will show confidence bounds or multiple traces.

CONCLUSION

The critical factors can be determined by this analysis of Stress , Modal & Thermal. The purpose of Design of Experiments and the sensitivity analysis is to find a relationship between the input and the output parameter. The purpose of optimization is to achieve the "best" design relative to a set of prioritized criteria or constraints. These include maximizing factors such as productivity, strength, reliability, longevity, efficiency, and utilization. The basic idea of kriging is to predict the value of a function at a given point by computing a weighted average of the known values of the function about the point. The method is mathematically closely related to regression analysis

References

1 Prof Yi Ren’s Tutorial on the Design and Analysis in ANSYS in GitHub.
2 Project report by A. Durgude, A. Vipradas, S. Kishore, and S. Nimse.