DESIGN OPTIMIZATION OF BRAKE DISC GEOMETRY

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1. Problem Statement

The purpose for this project is to design a brake disc for emergency braking conditions with minimal volume. Three subsystems are required. 1. Minimize the maximum stress in the brake disc. 2. Maximize the first natural frequency of the brake disc. 3. Minimize the maximum temperature in the brake disc. The simulation is performed on Ansys.

2. Analysis Model

The brake disc model is provided by Dr. Ren shown in **Figure 1**. It has two parts, the Gray Cast Iron disc and the Structural Steel pads. The design variable of brake disc optimization problem is the outer diameter of the disc(P8), inner diameter of the disc(P9) and the thickness of the disc(P7). The initial values are 125mm, 75mm and 25mm respectively.

2.1 Structural Analysis Model

In this model, we mesh the disc with Tetrahedrons. the inner faces of the brake pads and set element size to 3 mm to better analyze the high stress concentration at this part. The brick disk is set to be rotated at 250 rad/s in y direction. The revolute joint is set at inner diameter. Pressure is applied on both outer brake pad faces with value equals to 1.0495*10^7pa. There is a frictional contact between disc and pads with friction coefficient 0.22. The displacement of the disc is fix in x and z direction.

The Equivalent von-Mises stress is calculated under previous condition shown in Figure 2. Here we can see the max stress is located between the pads and disc. The max value is 1.3443e+007 Pa.

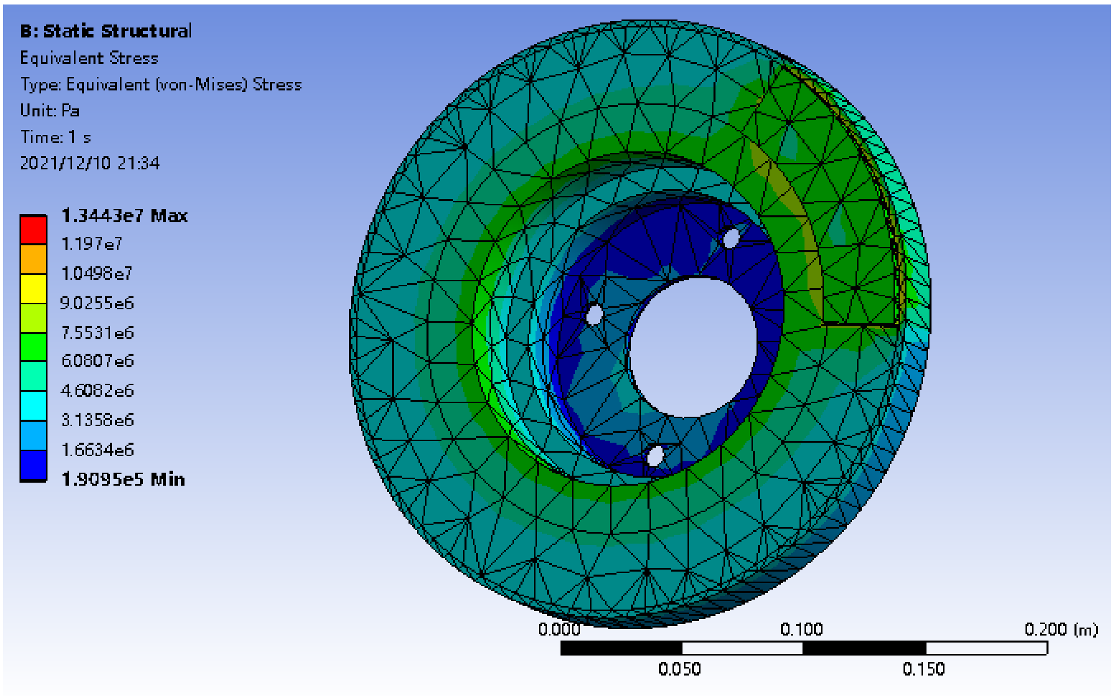

Figure 2 Equivalent von-Mises stress

2.2 Modal Analysis Model

This part we suppress the Brake pads to find the natural frequency of the brake disc only. The Max Modes is set to 10. By deform the disc, we get the natural frequency is 1615.7 Hz shown in Figure 3.

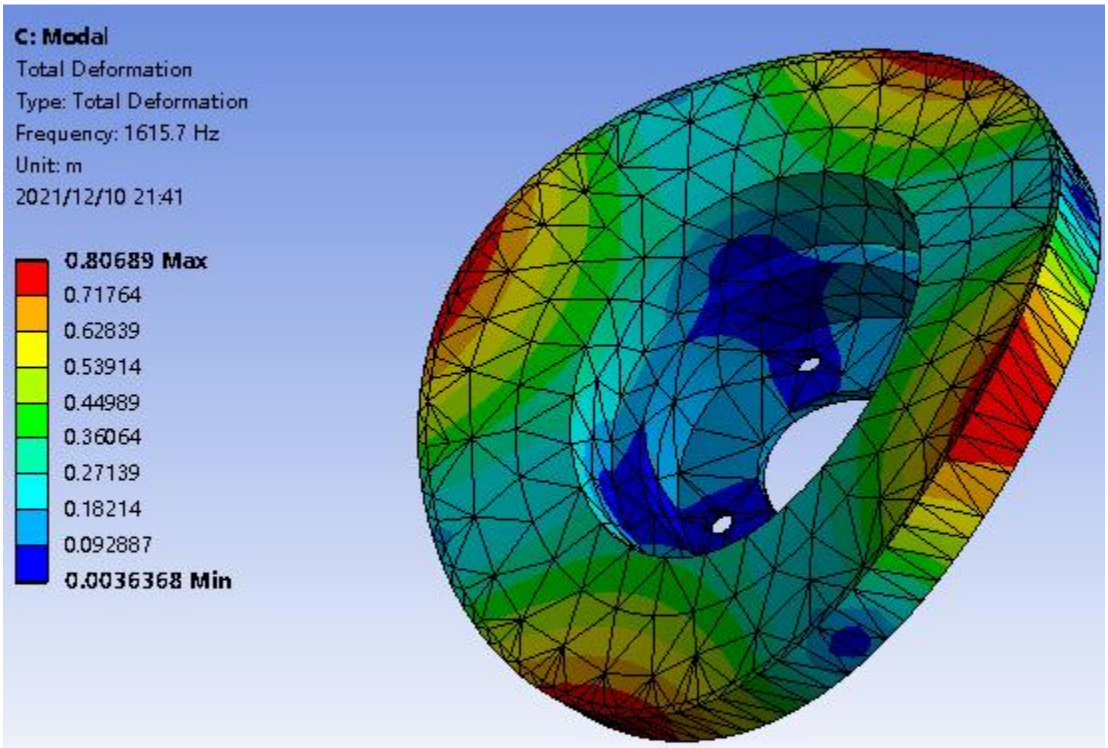

Figure 3 natural frequency of the brake disc

2.3 Thermal analysis model

The initial temperature is 35C. Convection happens for all the surface with coefficient =5w/m^2*C. Heat flux with 1.5395 W/m2 goes across the plate surface. The maximum temperature is 341 C

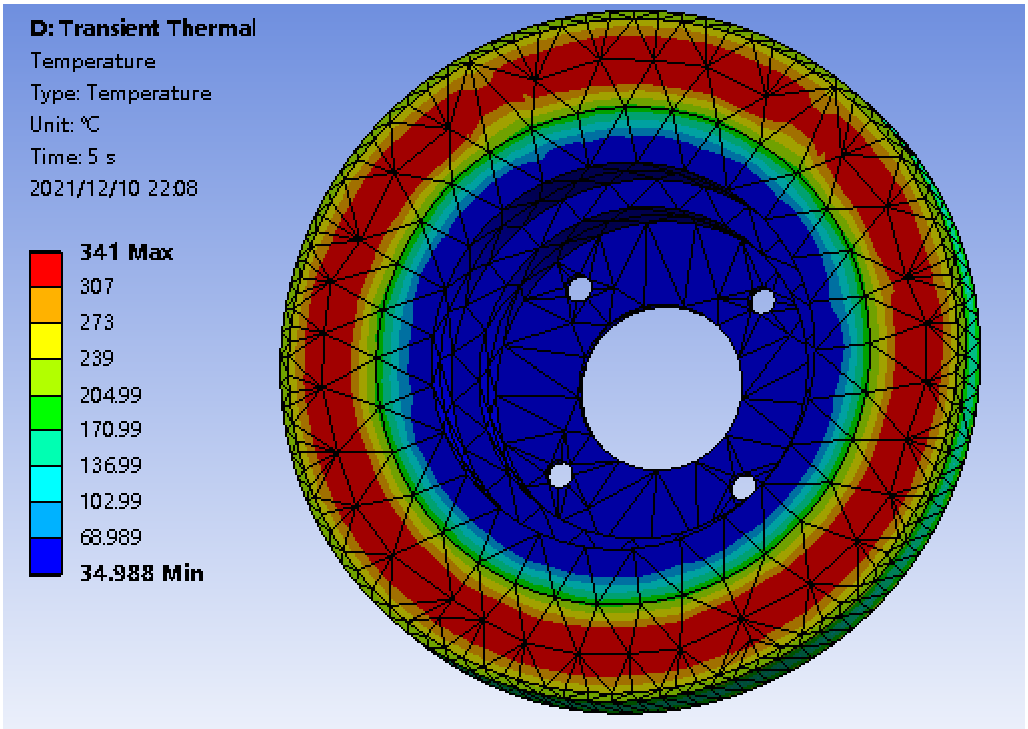

Figure 4 temperature

2.4 Design of Experiments

Latin Hypercube Sampling (LHS) method is used to run the experiments. 20 points are randomly picked with the input variables number selected in the fixed range. Figure 5 shows the results for the DOE.

Table 1 Design variables ranges

Design variables	Lower bound(mm)	Upper bound(mm)
thickness (P7)	20	30
outer diameter (P8)	125	140
inner diameter (P9)	70	82

Table of Outline A2: Design Points of Design of Experiments

	A	B	C	D	E	F	G	H
1	Name	P7 - rotor_thick... (mm)	P8 - rotor_OD (mm)	P9 - rotor_ID (mm)	P4 - Equivalent Stress Maximum (Pa)	P5 - Total Deformation Reported Frequency (Hz)	P6 - Temperature Maximum (C)	P10 - Disc Volume (m^3)
2	1	22.25	137.38	78.125	1.1511E+07	1341.5	350.75	0.0011148
3	2	20.25	135.13	71.375	1.0893E+07	1369.3	361.48	0.0010365
4	3	29.25	126.88	78.875	1.2196E+07	1575	335.08	0.0011324
5	4	27.25	139.63	80.375	1.1796E+07	1354.2	335.93	0.0013462
6	5	25.75	132.88	82.625	1.2117E+07	1381.4	343.07	0.0011146
7	6	21.25	131.38	81.875	1.1271E+07	1363.9	355.8	0.00094054
8	7	22.75	128.38	76.625	1.1447E+07	1516.4	347.74	0.00097516
9	8	26.25	134.38	72.125	1.1798E+07	1493.3	339.71	0.0012616
10	9	24.75	126.13	77.375	1.152E+07	1548.9	342.39	0.00099095
11	10	23.25	130.63	75.125	1.1532E+07	1495.7	346.57	0.0010458
12	11	23.75	135.88	74.375	1.1661E+07	1422.4	343.99	0.0011739
13	12	24.25	127.63	73.625	1.2675E+07	1591	343.66	0.0010345
14	13	29.75	129.13	69.875	1.2043E+07	1704.7	332.88	0.001296
15	14	25.25	129.88	72.875	1.1468E+07	1569.4	344.03	0.0011208
16	15	20.75	138.13	75.875	1.0902E+07	1323.5	359.75	0.0010827
17	16	21.75	125.38	69.125	1.1293E+07	1614.8	351.14	0.00093909
18	17	27.75	136.63	68.375	1.1785E+07	1499.4	338.15	0.0014088
19	18	28.25	138.88	70.625	1.2009E+07	1465.3	336.2	0.0014655
20	19	28.75	132.13	81.125	1.2409E+07	1463.4	336.48	0.0012153
21	20	26.75	133.63	79.625	1.2108E+07	1439.2	340.78	0.0011953

Figure 5 20 results for the DOE

2.4 Response surface

A response surface is generated for all the input and output values using **kriging**. The goodness of fit plots for all the subsystems are shown in Figure 6&7 with verification points. In this case the response function is linear, while it is not good matching the verification points.

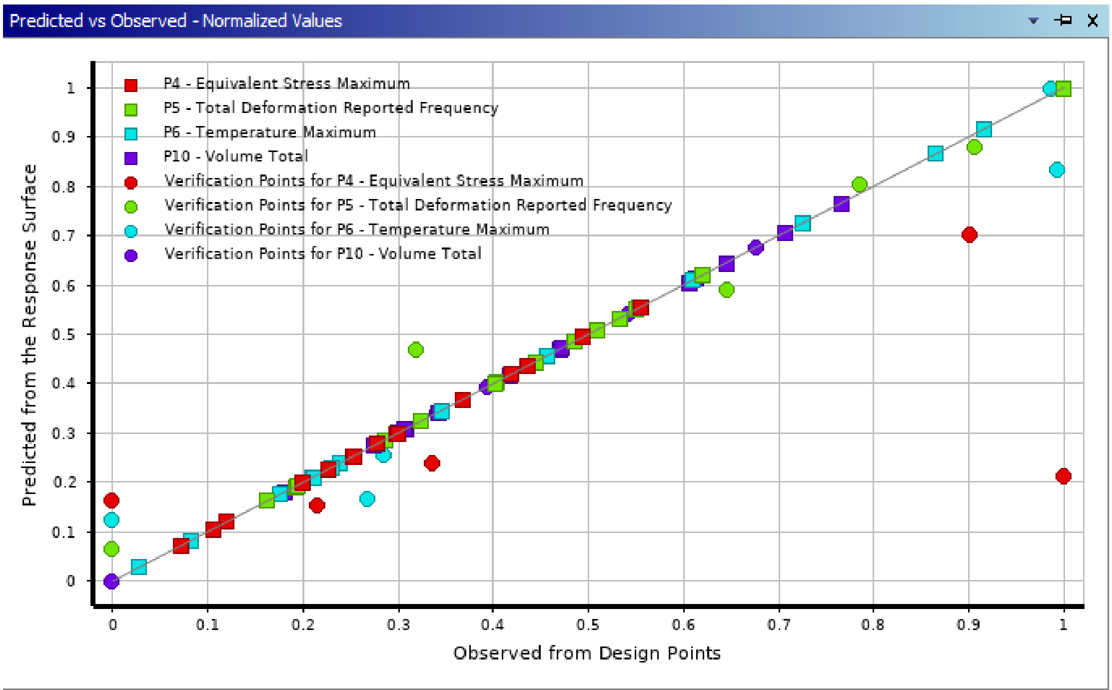

Figure 6 Response surface using Kriging

	A	B	C	D	E
1		P4 - Equivalent Stress Maximum	P5 - Total Deformation Reported Frequency	P6 - Temperature Maximum	P10 - Volume Total
2	Coefficient of Determination (Best Value = 1)				
3	Learning Points	1	1	1	1
4	Root Mean Square Error (Best Value = 0)				
5	Learning Points	0.0035292	1.4919E-07	2.5609E-08	2.3525E-15
6	Verification Points	1.1941E+06	35.987	3.0786	5.8298E-07
7	Relative Maximum Absolute Error (Best Value = 0%)				
8	Learning Points	0	0	0	0
9	Verification Points	312.87	60.047	49.839	0.57825
10	Relative Average Absolute Error (Best Value = 0%)				
11	Learning Points	0	0	0	0
12	Verification Points	104.15	25.402	26.629	0.30594

Figure 7 Response surface using Kriging

2.5 Sensitivity analysis

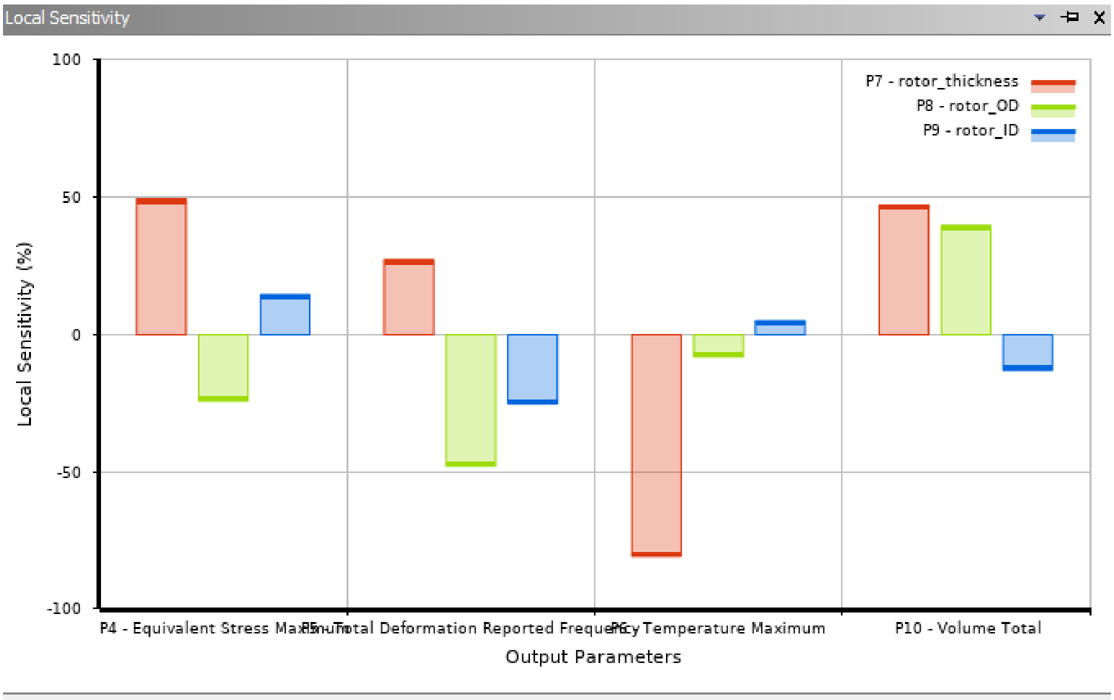

Figure 8 local sensitivity for each variables on 4 objective variables

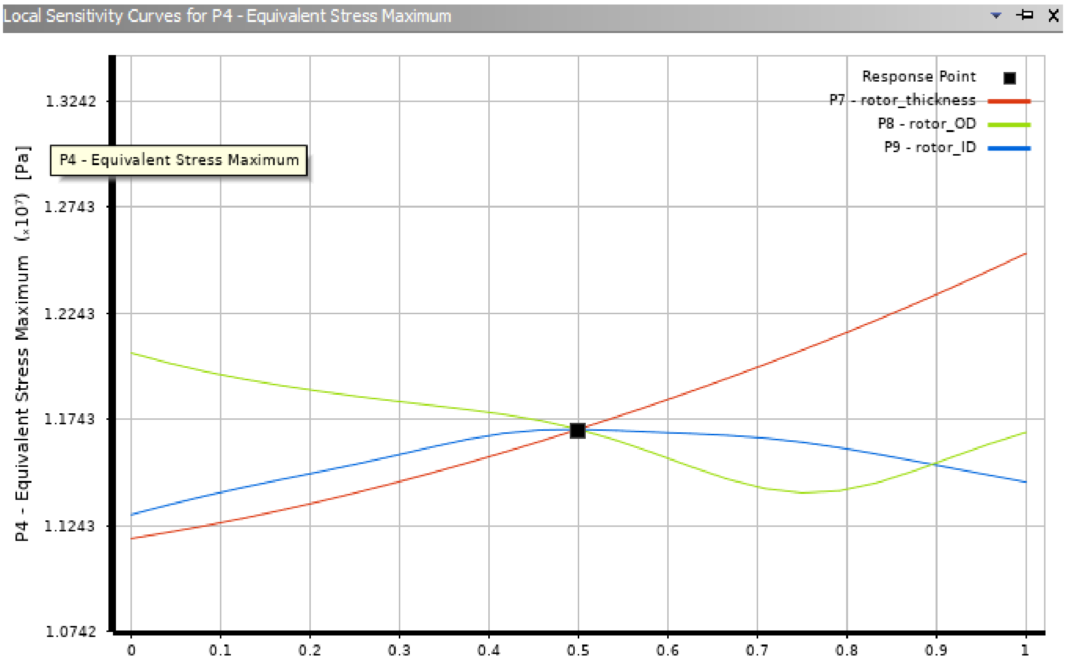

Figure 9 sensitivity of Max stress

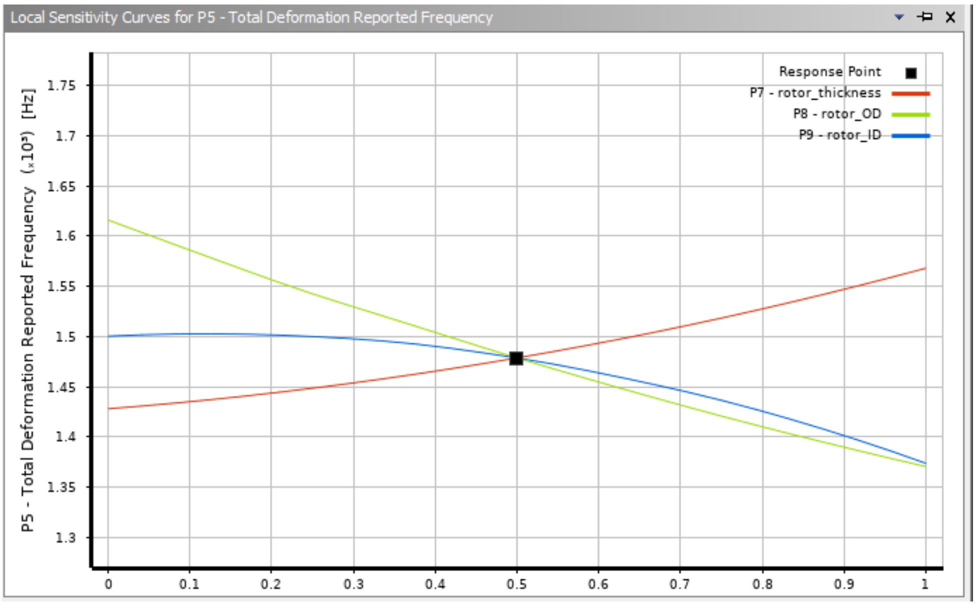

Figure 10 sensitivity of frequency

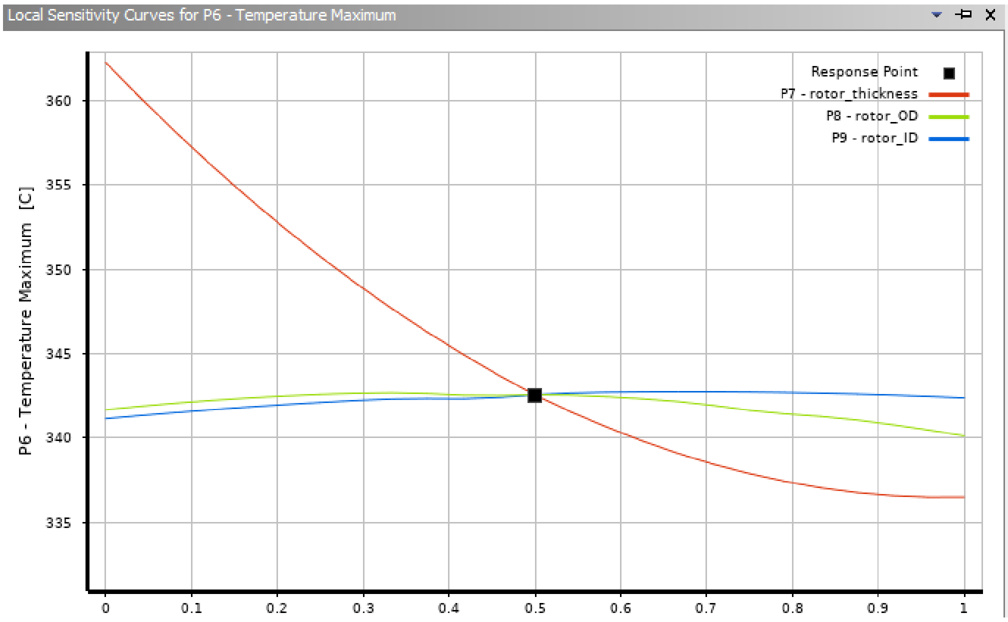

Figure 11 sensitivity of temperature

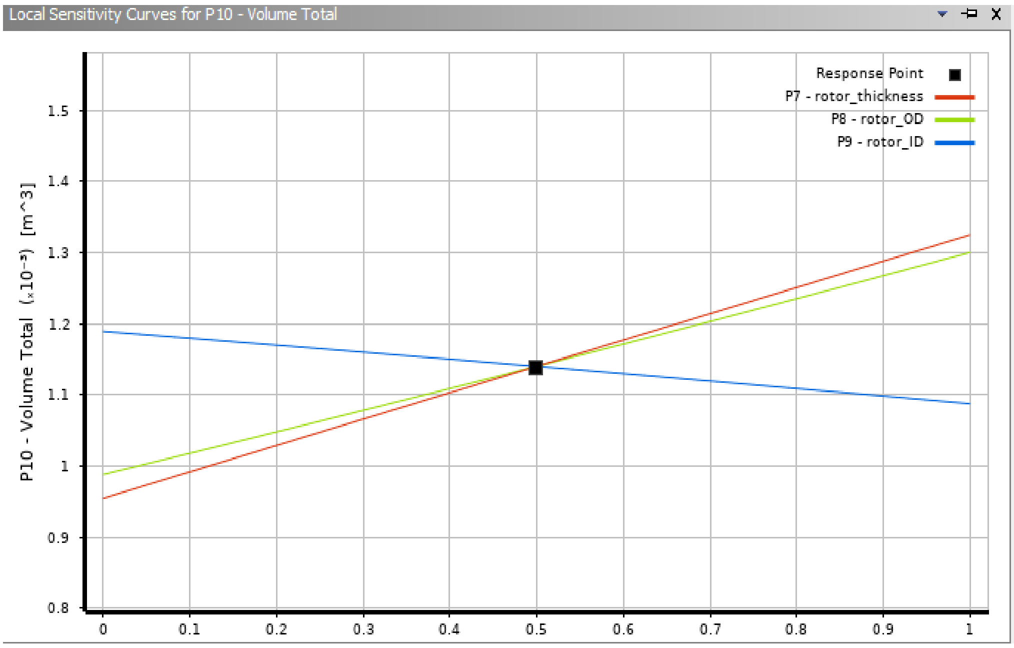

Figure 12 sensitivity of volume

3. Optimization

In this optimization problem, my design variables are outer diameter of the disc, inner diameter of the disc and the thickness of the disc. The constrains are the range for 3 variables and the stress, frequency and temperature has constraints too. The objectives are 1) min V 2) min max stress 3) min -natural frequency 4) min max temperature. All variables are continuous. Three best designs are selected.

3.1 Screening

Details are show in Figure 13.

Table of Schematic F4: Optimization

	A	B	C	D
1	Optimization Study			
2	Minimize P4; P4 <= 1.5E+07 Pa	Goal, Minimize P4 (Default importance); Strict Constraint, P4 values less than or equals to 1.5E+07 Pa (Default importance)		
3	Maximize P5; P5 >= 1200 Hz	Goal, Maximize P5 (Default importance); Strict Constraint, P5 values greater than or equals to 1200 Hz (Default importance)		
4	Minimize P6; P6 <= 400 C	Goal, Minimize P6 (Default importance); Strict Constraint, P6 values less than or equals to 400 C (Default importance)		
5	Minimize P10; P10 <= 0.002 m^3	Goal, Minimize P10 (Default importance); Strict Constraint, P10 values less than or equals to 0.002 m^3 (Default importance)		
6	Optimization Method			
7	Screening	The Screening optimization method uses a simple approach based on sampling and sorting. It supports multiple objectives and constraints as well as all types of input parameters. Usually it is used for preliminary design, which may lead you to apply other methods for more refined optimization results.		
8	Configuration	Generate 3000 samples and find 3 candidates.		
9	Status	Converged after 3000 evaluations.		
10	Candidate Points			
11		Candidate Point 1	Candidate Point 2	Candidate Point 3
12	P7 - rotor_thickness (mm)	21.442	21.168	21.802
13	P8 - rotor_OD (mm)	125.79	132.18	128.3
14	P9 - rotor_ID (mm)	70.265	81.623	70.331
15	P4 - Equivalent Stress Maximum (Pa)	★★★ 1.0994E+07	★★★ 1.096E+07	★★★ 1.1001E+07
16	P5 - Total Deformation Reported Frequency (Hz)	★★★ 1599.7	★★★ 1370.8	★★★ 1541.3
17	P6 - Temperature Maximum (C)	★★ 354.05	★★ 355.54	★★ 352.91
18	P10 - Volume Total (m^3)	★★ 0.0009291	★★ 0.00095343	★★ 0.00098448

Figure 13 summary of screening optimization

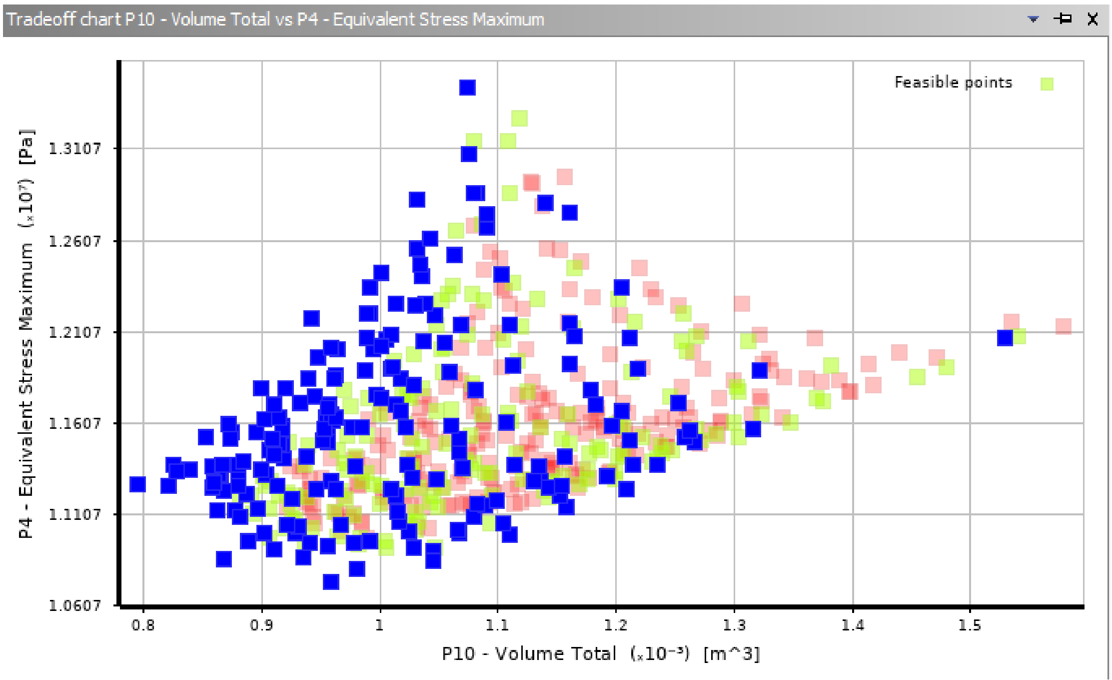

Figure 14(a) Trade off plot for stress and volume

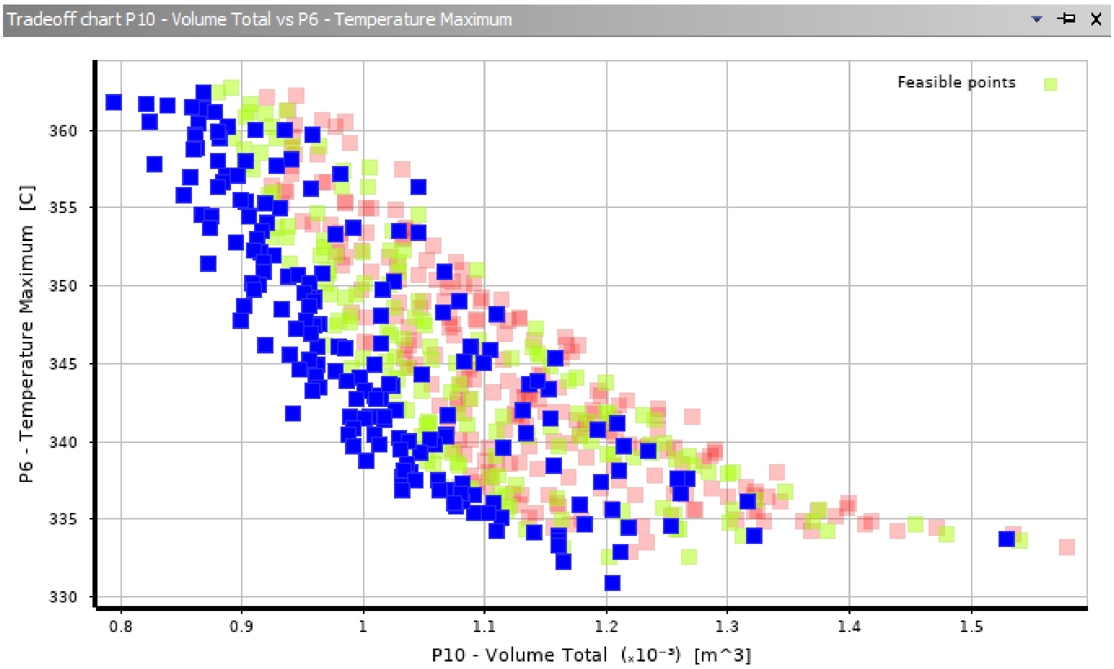

Figure 14(b) Trade off plot for temperature and volume

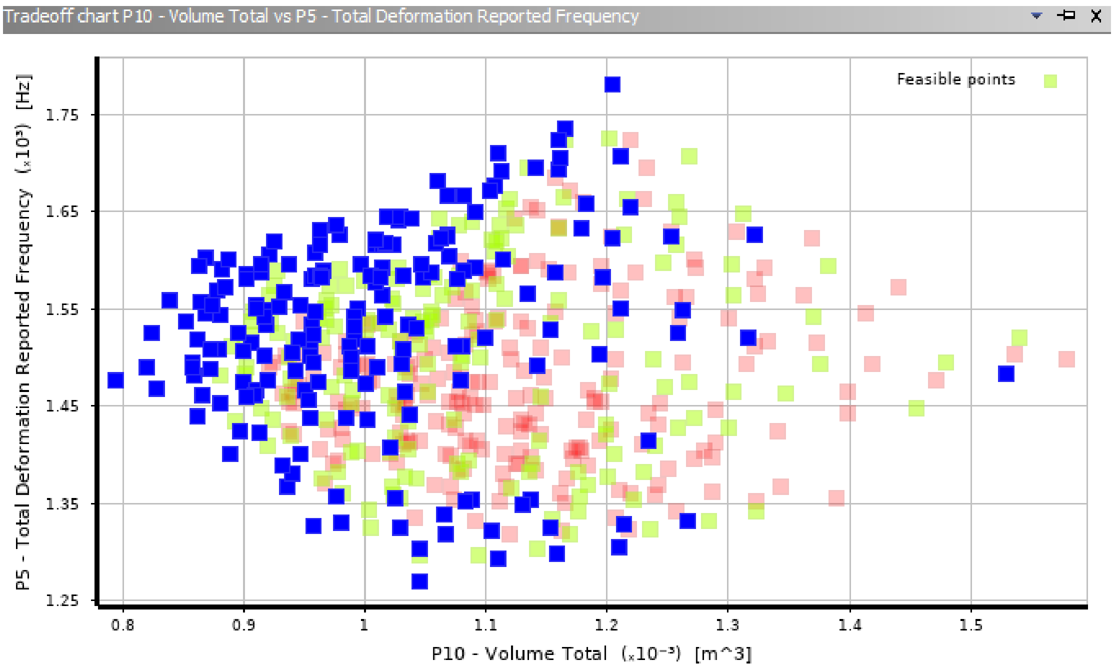

Figure 14(c) Trade off plot for frequency and volume

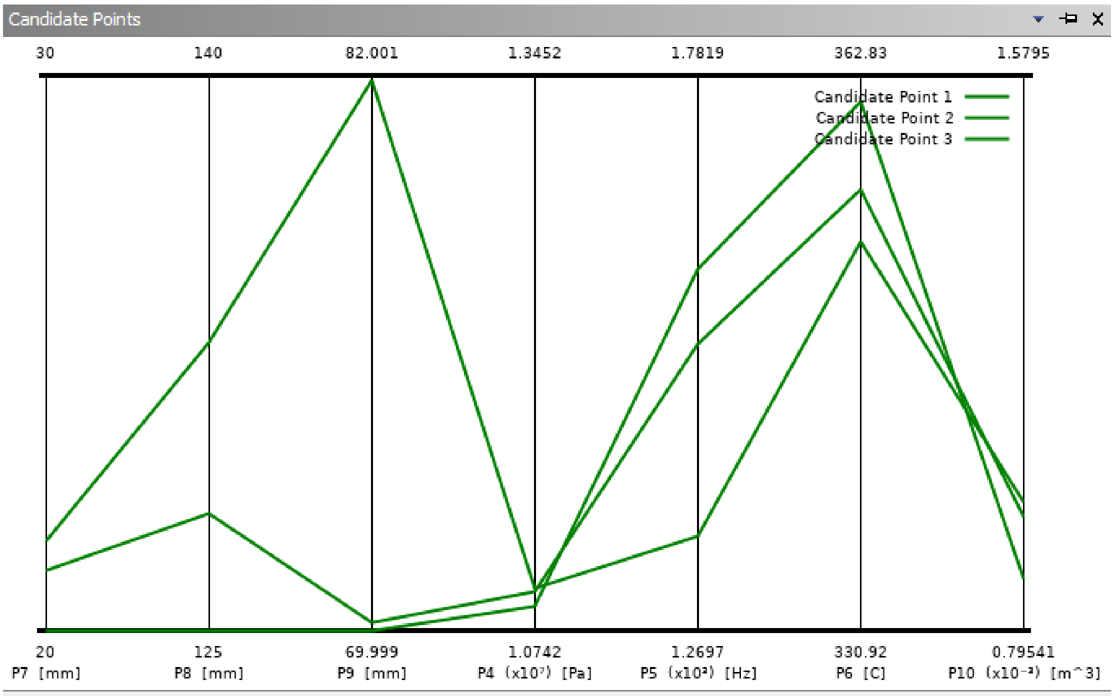

Figure 15 candidate points

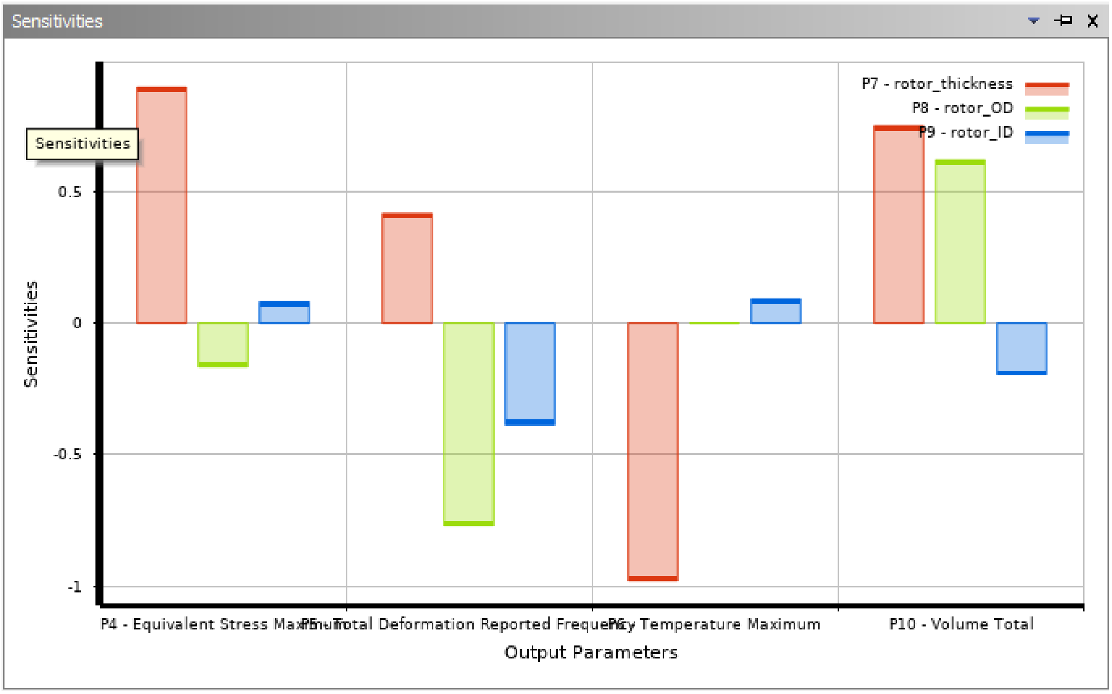

Figure 16 sensitivity for screening

3.2 MOGA

Details are show in Figure 17.

1.

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3	Maximize P5; P5 >= 1200 Hz	Goal, Maximize P5 (Default importance); Strict Constraint, P5 values greater than or equals to 1200 Hz (Default importance)		
4	Minimize P6; P6 <= 400 C	Goal, Minimize P6 (Default importance); Strict Constraint, P6 values less than or equals to 400 C (Default importance)		
5	Minimize P10; P10 <= 0.002 m^3	Goal, Minimize P10 (Default importance); Strict Constraint, P10 values less than or equals to 0.002 m^3 (Default importance)		
6	Optimization Method			
7	Screening	The Screening optimization method uses a simple approach based on sampling and sorting. It supports multiple objectives and constraints as well as all types of input parameters. Usually it is used for preliminary design, which may lead you to apply other methods for more refined optimization results.		
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Figure 17 summary of screening optimization

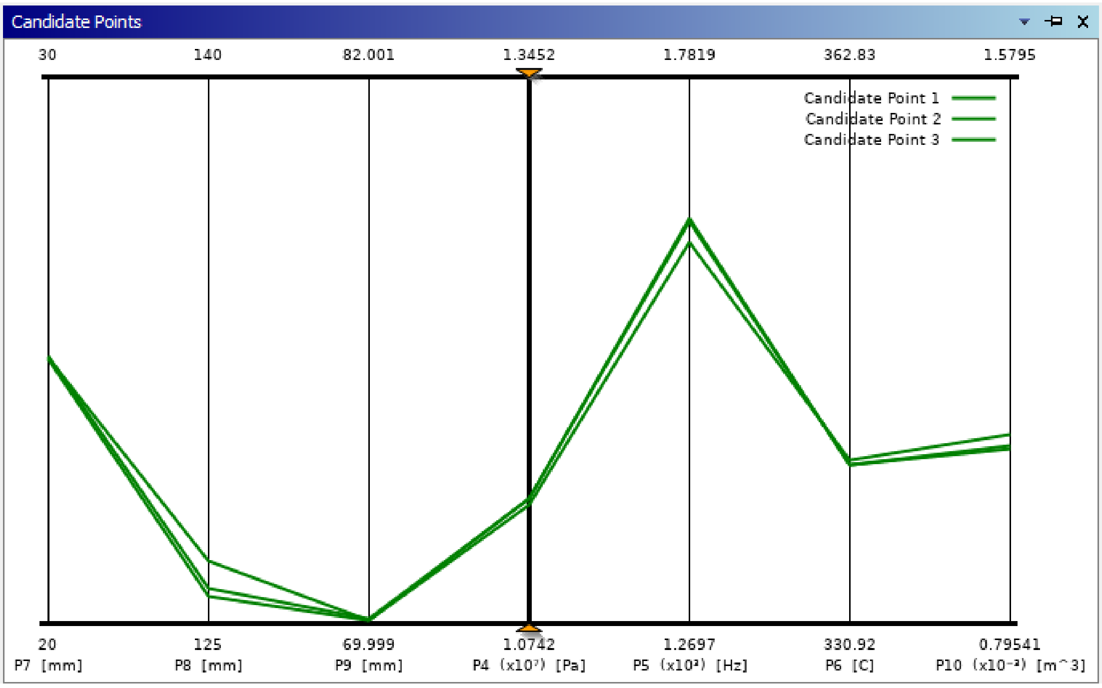

Figure 18 candidate points

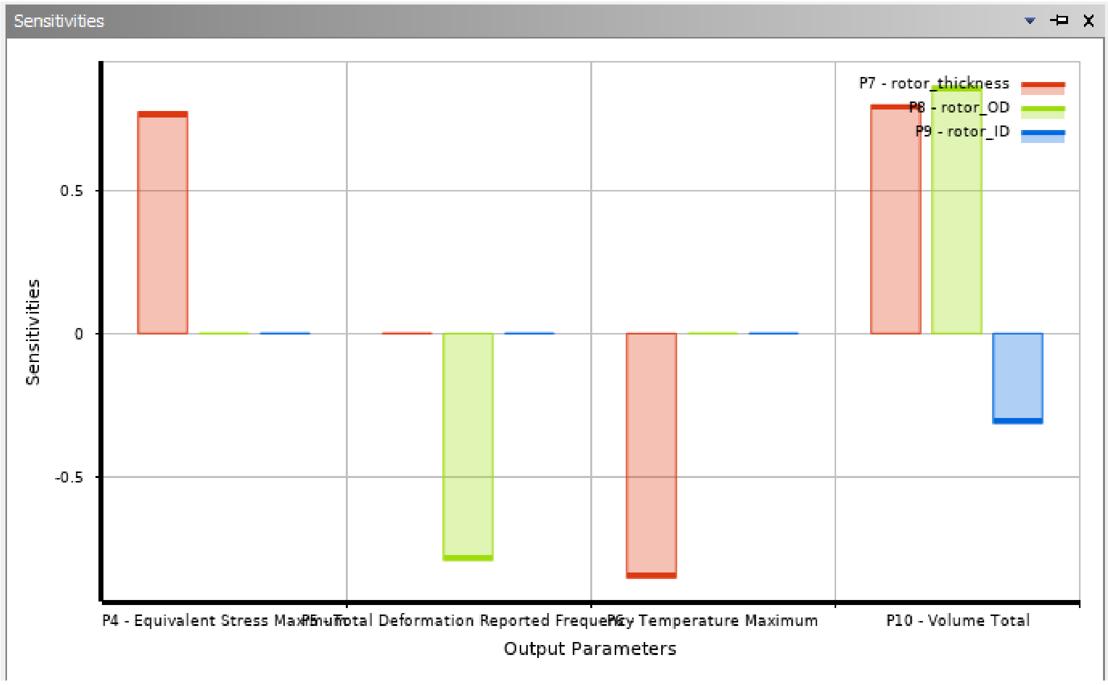

Figure 19 sensitivity of MOGA

By comparing two types of method, we found MORA performance better.