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Topology Optimization of Automotive Disc Brake using FEA-DOE Hybrid Modeling

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Abstract: *The objective of this Paper is to find the performance parameters of the disc brake system using experimental and statistical approach. A standard energy (DOE) design of experiments by Taguchi method is applied to study three performance parameters each with three levels. The Hole diameter, No. of pattern and Distance between hole becomes the design variables. The disc brake model is to be developed in creo 2.0 and analysed using ANSYS. The number of parameters and levels are more so probable models are too much and which consumes more time. To overcome this problem TAGUCHI method along with FEA is used. The reduction of temperature and weight is achieved by providing cross-drill hole. The orthogonal array is used by taking variable parameters. Then FEA is performed on those models to get the best solution.*

Keywords: *Parametric optimization, Disc brake, FE Analysis, FEA-Design of Experiments, Temperature reduction, Weight reduction*

I. Introduction

The most significant safety device in vehicle is its braking system, which slows down the vehicle very quickly. There are many types of brakes are used in automobile works on the same principle. Brakes are energy converting machine elements which converts braking energy into heat energy and this heat is dissipated into the surrounding. Using different numerical and experimental approaches the disc brake design is progressing. However, brake performance still needs much work to carry out. This is due to the fact that disc brake performance strong depending on many parameters including materials and geometry of brake components, component interaction, many operating and environmental conditions.

The main objective of the research is to reduce the weight of the disc brake and reduce the generated temperature. This optimized design is being constrained by the minimum stress. The disc brake is analysed using the finite element technique, appropriate model of the disc brake is to be developed. The high temperature generated in solid type disc brake is reduced by providing a cross drilled hole. Then FEA is performed on those models to get the best solution. The numbers and levels of parameters are more; the probable models are too many. So, to select optimum parameters among them large numbers of modelling and analysis work is involved which consumes more time. To overcome this problem, Design of Experiment technique is used along with FEA.

II. Literature review

In the past, several researchers have studied the optimization of performance of disc brake by the Taguchi's method of Design of experiments (DOE) to reduce the computational effort without affecting the final solution quality. **Mostafa et al.** (2013) analysed the disc brake using brake dynamometer and used Taguchi approach for DOE. The applied pressure, wedge angle inclination, speed of the vehicle was considered as control factors with three levels of each. By the S/N ratio graph and ANOVA analysis result the most effective parameter on brake performance were identified. The Taguchi method reduces time and experimental costs by minimizing the experiments. They concluded that by using Taguchi Approach the applied pressure and wedge angle were the most effective parameters for estimating the disc brake [1]. **Nouby et al.** (2013) evaluated disc brake experimentally using brake dynamometer and used Taguchi approach. For prediction of operation parameters which affect the performance of disc brake the Taguchi Method was utilized. An L16 orthogonal array was performed by taking applied pressure, speed of vehicle, angle inclination of wedge and water spraying as control factors with four levels. The important parameters to improve wedge type disc brake behaviour were defined by S/N ratio graph. The experimental results performed by dynamometer were compared with the predicted results using Taguchi approach [2]. **Patel et. al.** (2013) used Taguchi method to reduce the weight of the chassis frame of Eicher 11.10 chassis frame and FEA was performed to obtain the best solution for chassis frame [3]. **Singh et al.** (2014) identified three control factors were back plates thickness, slots width and slots angle, for each higher and lower levels and L8 orthogonal array was performed with the S/N ratio. ANOVA was utilized to analyse the effect of selected process parameters along with their levels of impact. They have concluded that the optimized process parameter slot width leads to minimize the defects of disc pads [4]. **Ghazaly et al.** (2014) proposed experimental and statistical studies to find out the optimal geometric parameters of the wedge disc brake performance. A typical response surface methodology called central composite design was applied to study four geometric parameters each with three levels [5].

III. Material of model

The material for disc brake is defined Grey cast iron, which is widely used material for disc brake. The material properties are as shown in table 1.

Table 1: Material Properties of Disc Brake [6]

Material	Grey Cast Iron
Density, kg/m^3	7100
Thermal conductivity, W/m.K	54
Young's Modulus, N/m^2	125
Poisson's Ratio	0.25
Specific Heat, J/kg.K	586

IV. Methodology

As an important subject in the statistical design of experiments, the Taguchi method is a collection of mathematical and statistical techniques useful for the parametric optimization and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response. Taguchi method is used to examine the relationship between a response and a set of quantitative experimental variables or factors [7].

Steps for the Experiment:

- Formulation of the problem – the success of any experiment is dependent on a full understanding of the nature of the problem.
- Selection of the output performance characteristics most relevant to the problem.
- Selection of parameters.
- Selection of factor levels.
- Design of an appropriate Orthogonal Array (OA).
- To Perform FEA with appropriate set of parameters.
- Thermal and Statistical analysis and interpretation of experimental results.
- Modeling and FEA with optimum parameter set for validation
  Flow chart of the experiment is given in figure 1.

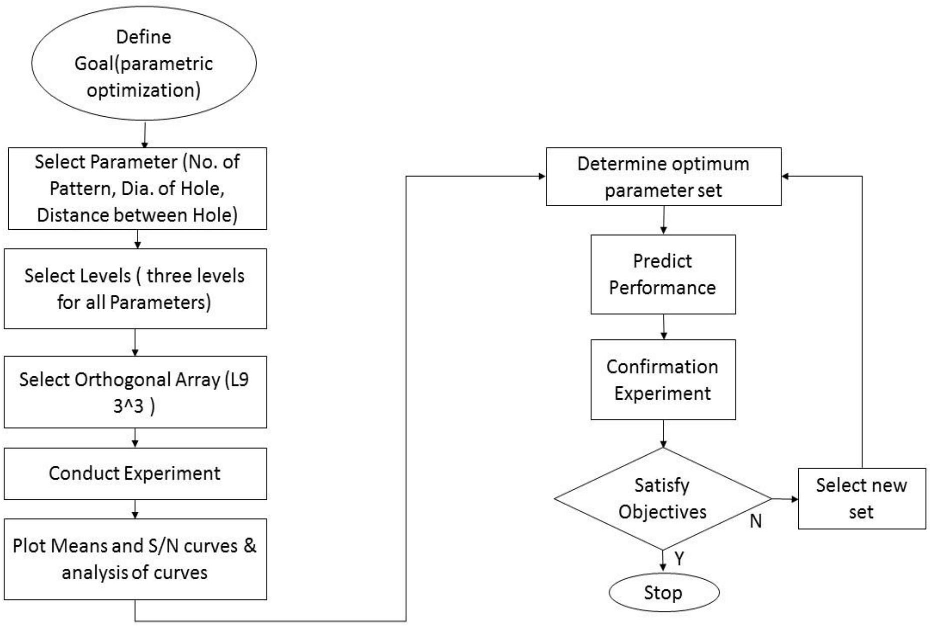

Fig. 1: Flow chart for experiment [3]

V. Experimental method

Experiments are planned according to Taguchi’s L9 orthogonal array for Hole Diameter, Distance between hole and Number of Pattern as shown in figure 1. It has 9 rows corresponding to the number of tests with 3 columns at three levels and 3 parameters as shown in Table 2. This orthogonal array is chosen due to its capability to check the interactions among factors.

The experimental results are then transferred into a Signal to Noise (S/N) ratio. There are three categories of quality characteristic in the analysis of the S/N ratio, (i) the-lower-the-better, (ii) the-higher-the-better and (iii) the-nominal-the better. Regardless of the category of the quality characteristic, process parameter settings with the highest S/N ratio always yield the optimum quality with minimum variance. The category the-lower-the-better was used to calculate the S/N ratio for quality characteristics Temperature, stress and deformation, according to below equation.

$$S/N = -10\log_{10}\left[\frac{1}{N}\sum_{i=1}^{n} Yi^2\right]$$

Table 2: Factors and their levels

Factor	Level 1	Level 2	Level 3
Number of Pattern	36	24	18
Hole Diameter (mm)	9	7	5
Distance between Hole (mm)	10	9	8

For finding out optimum Hole Diameter, Distance between hole, number of pattern the value of temperature, equivalent stress, deformation and weight is measured using ANSYS. Series of analysis is conducted to obtain minimum temperature rise for allowable stress and deformation condition. Taguchi method is being applied to select the control factors levels (Diameter of hole, Distance between hole, number of patterns) to come up with optimal response value (temperature, equivalent stress, deformation and weight).

VI. Result and discussion

The temperature, equivalent stress, deformation and weight are measured for each set of parameter using FEA in ANSYS, and the Results of FEA are analysed using Minitab 17. Minitab offers four types of designed experiments: factorial, response surface, mixture, and Taguchi (robust). The steps follow in Minitab to create, analyse, and graph an experimental design are similar for all design types. After conducting the analysis and entering the results, Minitab provides several analytical and graphing tools to help understand the results. Minitab version 17 is used for the analysis of results obtained by Finite element analysis. The S/N ratio for minimum temperature, equivalent stress, deformation and weight are coming under “Smaller-is-better” characteristic, which can be calculated as a logarithmic transformation of the loss function.

Taguchi designs experiments using especially constructed tables known as “orthogonal arrays” (OA). The use of these tables makes the design of experiments very easy and consistent.

Table 3: Experimental Results Table

Sr. No.	Number of Patterns	Diameter of Hole (mm)	Distance between Hole (mm)	Weight (kg)	Temperature (°C)	Equivalent Stress (MPa)	Deformation (mm)
1	36	9	10	2.599	205.14	130.60	0.21313
2	36	7	9	2.647	204.95	129.88	0.22001
3	36	5	8	2.718	204.48	141.17	0.22606
4	24	9	9	2.680	205.50	122.26	0.22265
5	24	7	8	2.712	205.08	152.12	0.22531
6	24	5	10	2.759	205.18	150.19	0.23005
7	18	9	8	2.680	205.06	119.95	0.22219
8	18	7	10	2.745	205.39	140.49	0.22924
9	18	5	9	2.780	205.18	157.97	0.23739

6.1 Taguchi Analysis for Temperature

From figure 3, mean value is maximum (205.25) for 24 pattern and minimum (204.85) for 36 pattern. Mean value is maximum (205.23) for 9 mm hole diameter and minimum (204.94) for 5 mm hole diameter. Mean value is maximum (205.23) for 10 mm distance between hole and minimum (204.87) for 8 mm distance between hole.

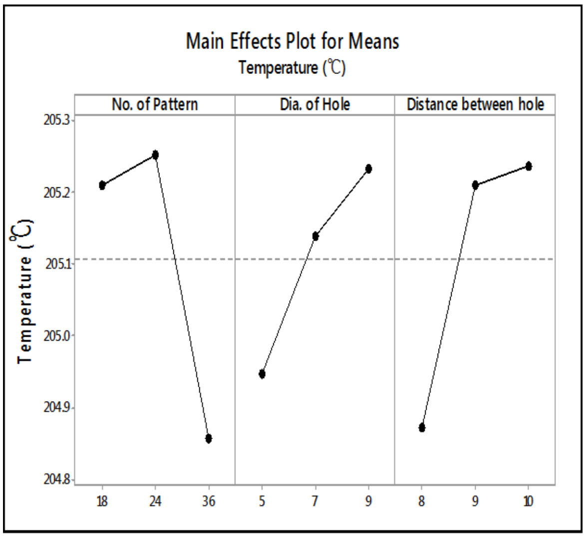

Fig. 3: Main Effects Plot for Mean data: Temperature

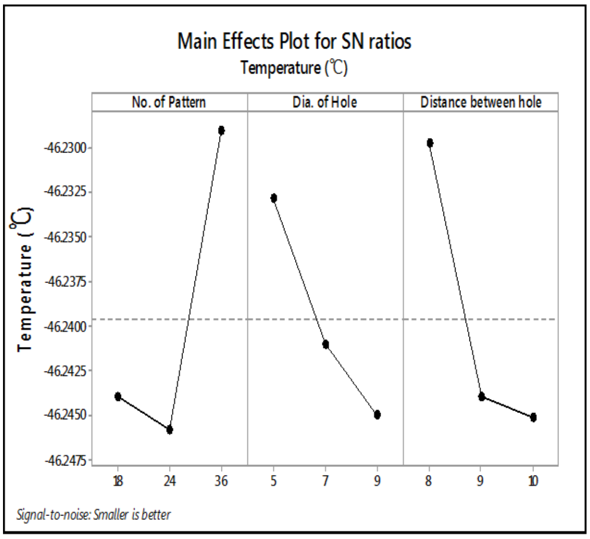

Fig. 4: Main Effects Plot for S/N Ratio data: Temperature

The S/N Ratio for different performance response were calculated at each factor level and the average effect was determined by taking the total of each factor level and divided by the number of data points in the total. The greater difference between S/N ratio values the levels, the parametric influence will be much. The parameter level having the highest S/N ratio corresponds to the sets of parameters indicates highest performance.

The optimum set is determined by choosing the level with the highest S/N ratio. Referring (figure 4) the response curve for S/N ratio, the highest S/N ratio was observed at No. of pattern (36), dia. of hole (5) and distance between hole (8) which are optimum parameter set for temperature as shown in table 4.

Table 4: Optimize set of parameter for Temperature

No. of Pattern	Diameter of Hole	Distance between Hole
36	5	8

FEA of Optimize set of Parameter for Temperature:

Experiment has been carried out using optimum set of parameter. Experimental Temperature for optimum set of parameter is 204.48 ºC. This experimental value is nearer the predicted value 204.46 ºC.

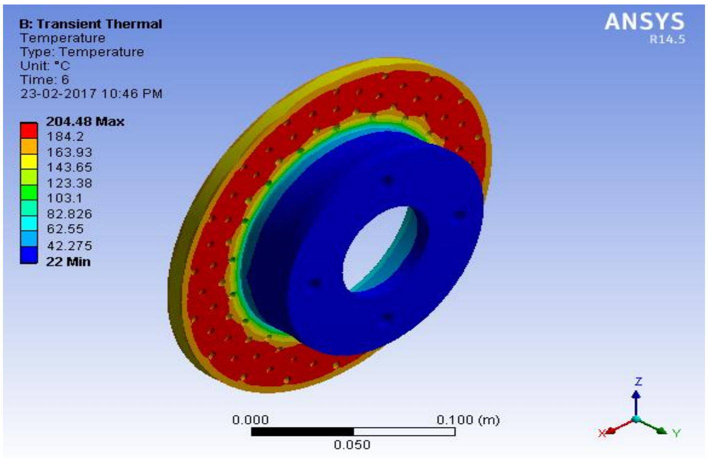

Fig. 5: Temperature Distribution of Optimize set of Parameter

6.2 Taguchi Analysis for Equivalent Stress

From figure 6, mean value is maximum (141.52) for 24 pattern and minimum (133.88) for 36 pattern. Mean value is maximum (149.77) for 5 mm hole diameter and minimum (124.27) for 9 mm hole diameter. Mean value is maximum (140.42) for 10 mm distance between hole and minimum (136.70) for 9 mm distance between hole.

The optimum set is determined by choosing the level with the highest S/N ratio. Referring (figure 7) the response curve for S/N ratio, the highest S/N ratio was observed at No. of pattern (36), dia. of hole (9) and distance between hole (9) which are optimum parameter set for Equivalent Stress as shown in table 5.

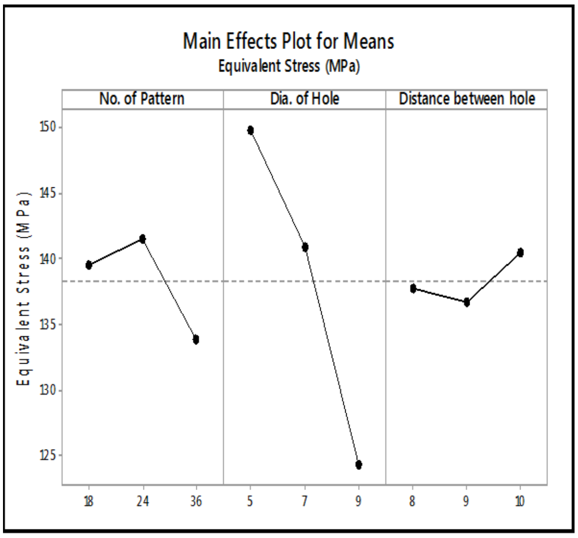

Fig. 6: Main Effects Plot for Mean data: Equivalent Stress

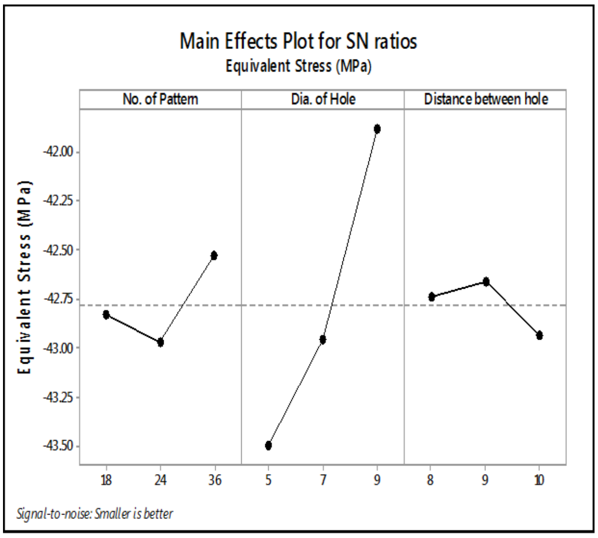

Fig. 7: Main Effects Plot for S/N Ratio data: Equivalent Stress

Table 5: Optimize set of parameter for Equivalent Stress

No. of Pattern	Diameter of Hole	Distance between Hole
36	9	9

Experiment has been carried out using optimum set of parameter. Experimental Equivalent Stress for optimum set of parameter is 109.47 MPa. This experimental value is nearer the predicted 113.81 MPa.

FEA of Optimize set of Parameter for Equivalent stress:

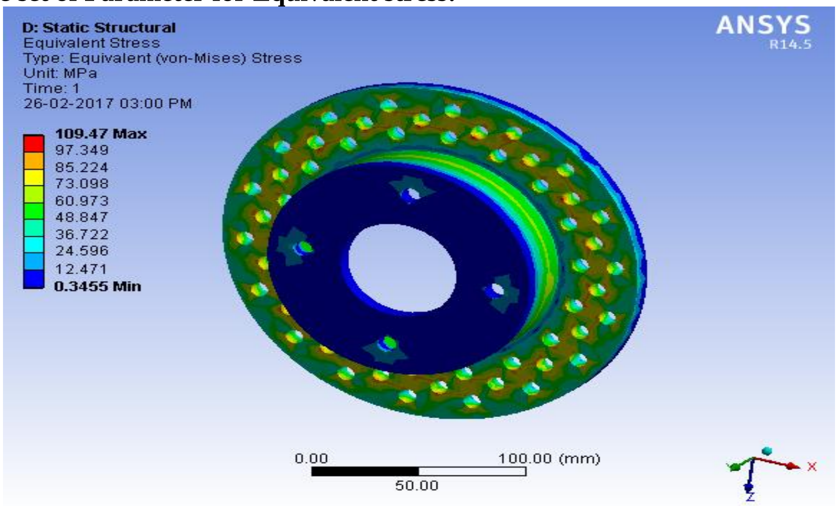

Fig. 8: Equivalent stress Distribution of Optimize set of Parameter

6.3 Taguchi Analysis for Deformation

From figure 9, mean value is maximum (0.2296) for 18 pattern and minimum (0.2197) for 36 pattern. Mean value is maximum (0.2311) for 5 mm hole diameter and minimum (0.2193) for 9 mm hole diameter. The mean value is maximum (0.2266) for 9 mm distance between hole and minimum (0.2241) for 10 mm distance between hole.

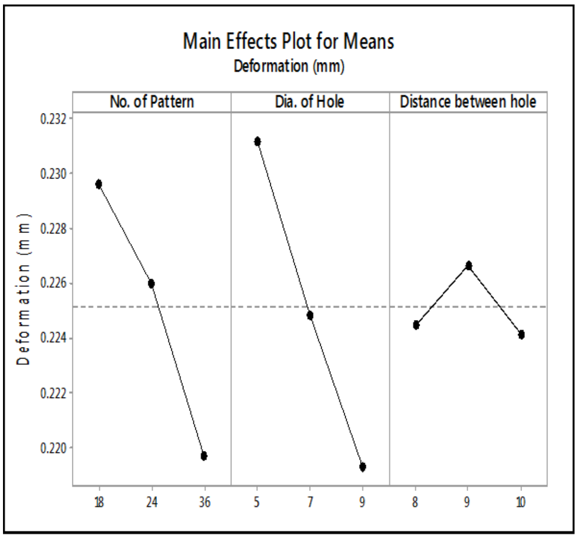

Fig. 9: Main Effects Plot for Mean data: Deformation

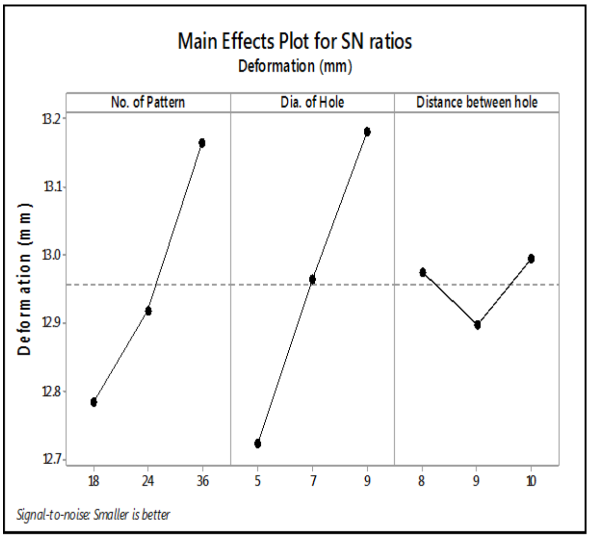

Fig. 10: Main Effects Plot for S/N Ratio data: Deformation

The optimum set is determined by choosing the level with the highest S/N ratio. Referring (figure 10) the response curve for S/N ratio, the highest S/N ratio was observed at No. of pattern (36), dia. of hole (9) and distance between hole (10) which are optimum parameter set for deformation as shown in table 6.

Table 6: Optimize set of parameter for Deformation

No. of Pattern	Diameter of Hole	Distance between Hole
36	9	10

Experiment has been carried out using optimum set of parameter. Experimental Deformation for optimum set of parameter is 0.2131 mm. This experimental value is nearer the predicted value 0.2129 mm.

FEA of Optimize set of Parameter for Deformation:

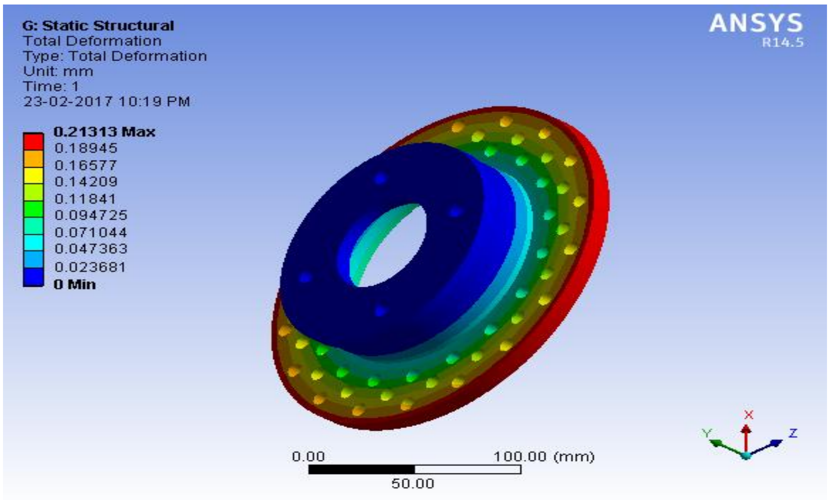

Fig. 11: Deformation distribution of Optimize set of Parameter

6.4 Taguchi Analysis for Weight

From figure 12, mean value is maximum (2.73) for 18 pattern and minimum (2.65) for 36 pattern. Mean value is maximum (2.75) for 5 mm hole diameter and minimum (2.65) for 9 mm hole diameter. Mean value is maximum (2.703) for 8 mm distance between hole and minimum (2.701) for 10 mm distance between hole.

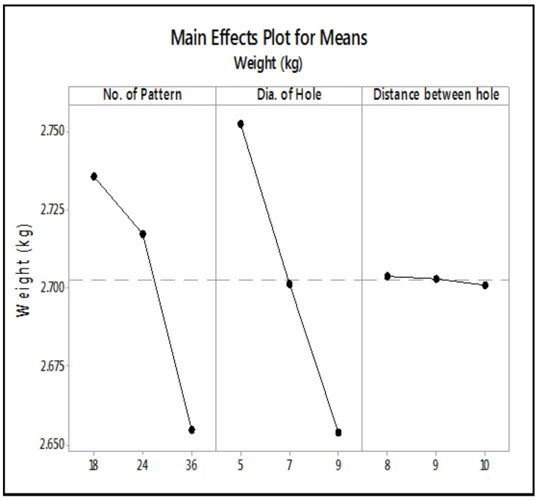

Fig. 12: Main Effects Plot for Mean data: Weight

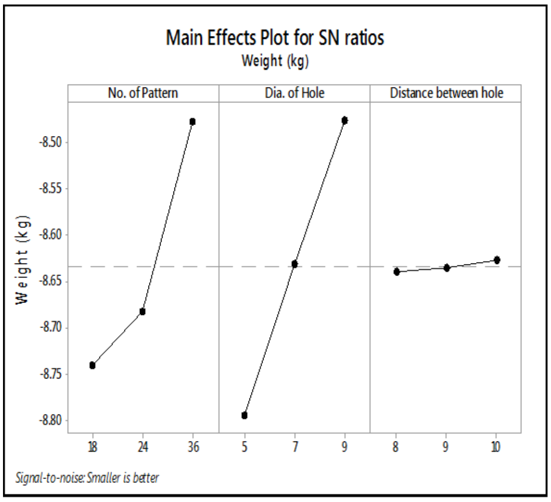

Fig. 13: Main Effects Plot for S/N Ratio data: Weight

The optimum set is determined by choosing the level with the highest S/N ratio. Referring (figure 13) the response curve for S/N ratio, the highest S/N ratio was observed at No. of pattern (36), dia. of hole (9) and distance between hole (10) which are optimum parameter set for weight as shown in table 7.

Table 7: Optimize set of parameter for Weight

No. of Pattern	Diameter of Hole	Distance between Hole
36	9	10

The experiment has been carried out using optimum set of parameter. Experimental Weight for optimum set of parameter is 2.599 kg. This experimental value is nearer the predicted value 2.604 kg.

VII. Validation of Taguchi Result

Table 8: Optimum set of parameter and Predicted Value

Response	Optimum Set of Parameter			Predicted Value	Experiment Value	% Variation
	No. of Pattern	Dia. of Hole	Distance between hole			
Temperature (°C)	36	5	8	204.46	204.48	0.48
Equivalent stress (MPa)	36	9	9	113.81	109.47	3.97
Deformation (mm)	36	9	10	0.2129	0.21313	0.10
Weight (kg)	36	9	10	2.604	2.599	0.19

From the Table 8, based on Equivalent stress the optimum set is No. of Pattern (36), Dia. of Hole (9), Distance between Hole (9). The weight value for this set is same as the weight value of the above set in table 8. The Deformation and Temperature value is near to the other set parameter in the Table 8. So, the optimum set of parameter of the disc brake for lower weight and lower Equivalent stress is No. of Pattern (36), Dia. of Hole (9), Distance between Hole (9) considered.

The model of optimized disc brake as per dimension given in Table 9 is created in Creo Parametric 2.0 as shown in figure 14. The model is then saved in IGES format which can be directly imported into ANSYS workbench.

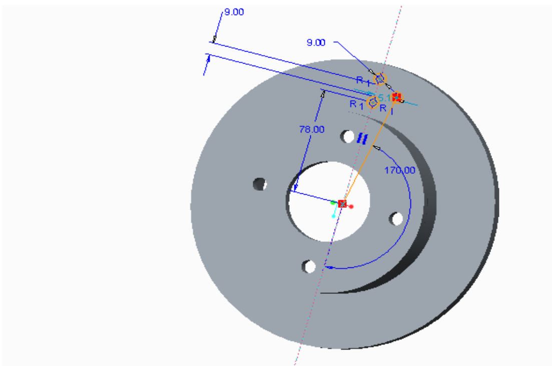

Fig. 14: Modeling of optimized disc brake

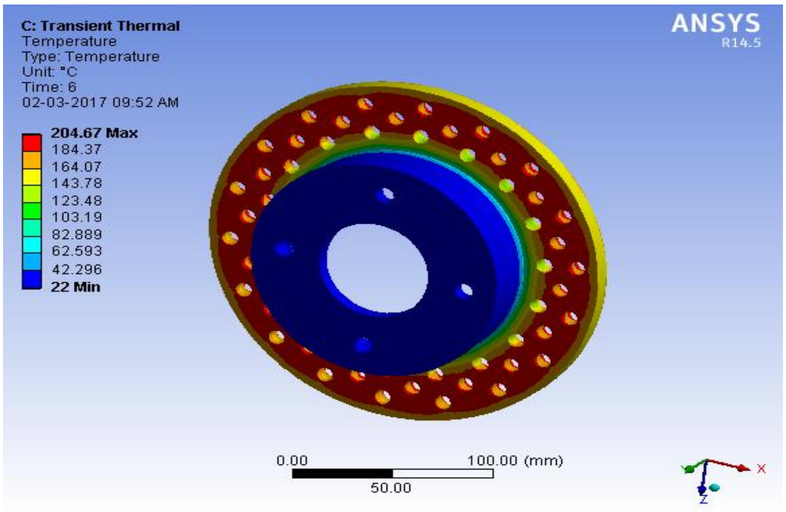

Fig. 15: Temperature in optimized disc brake

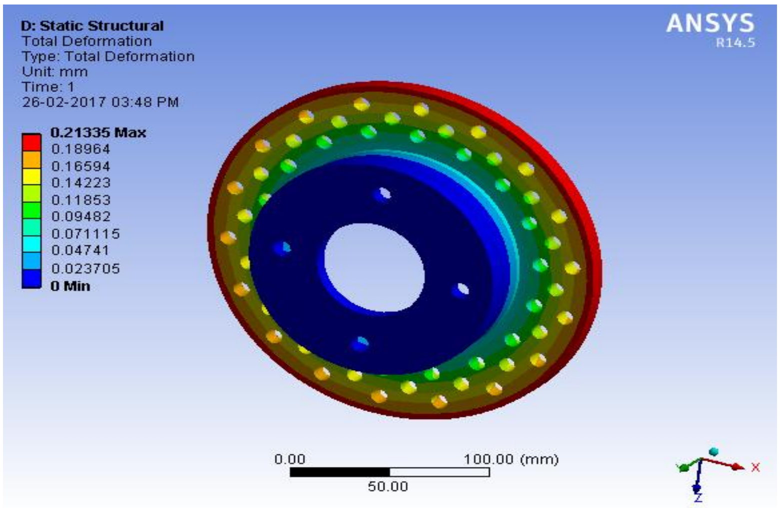

Fig. 16: Deformation in optimized disc brake

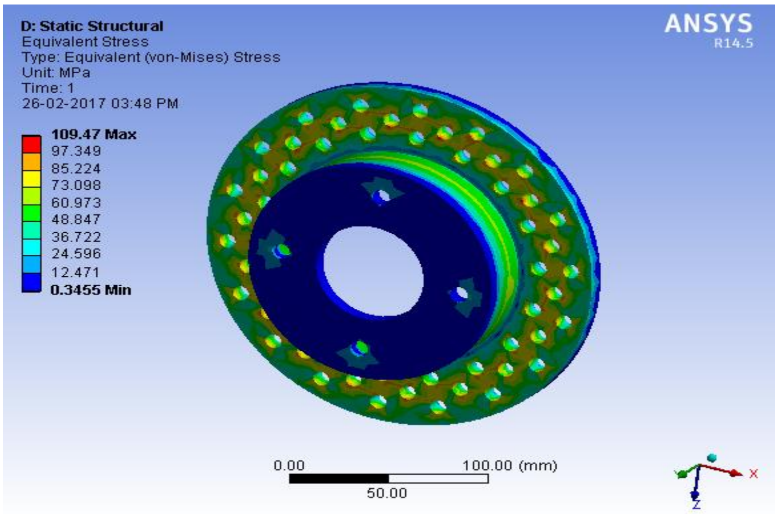

Fig. 17: Equivalent stress in optimized disc brake

The generated stress (109.47 MPa) is less than the permissible value so the design is safe based on rigidity criteria. The stress is as shown in figure 17.

Table 9: Optimum set of parameter and Predicted Value

Response	Optimum Set of Parameter			Predicted Value	Experiment Value	% Variation
	No. of Pattern	Dia. of Hole	Distance between hole			
Equivalent Stress	36	9	9	113.81	109.47	3.97
Weight	36	9	9	2.604	2.599	0.19

This percentage variation is caused by the uncertainties of Taguchi Prediction and accuracy of FEA.

VIII. Conclusion

The FEM-based Taguchi methods have efficiently reduced the time and efforts essential for estimating the design variables of implants. The optimal parameter combination for the minimum weight with permissible value of stress is obtained by using the analysis of S/N ratio. According to the results 36 No. of Pattern, 9 mm Hole diameter and 9 mm distance between hole are the optimal parameters for permissible stress and weight. Weight reduction achieved by FEA-DOE modelling is 0.19 % and Equivalent Stress is 3.97 % as shown in Table. 9.

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