Optimization of Geometric Parameters of a New Wedge Brake Using Taguchi Approach

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Abstract. The main objective of the present study is to optimize the geometric parameters of wedge disc brake for improving brake performance by applying the Taguchi method with orthogonal array robust design. The experimental tests using brake dynamometers are integrated with Taguchi method to find out the significant contributions of different types of geometric parameters for effective increasing of the brake performance. From Taguchi method results, the effective geometric parameters to improve the performance of wedge brake are obtained. Results of this work show that the most significant geometric parameters on wedge brake performance can be achieved through combination of the friction material thickness and friction material length.

Keywords: geometric parameters; wedge disc brake; Taguchi method.

1 Introduction

Optimization approach is an engineering methodology for improving productivity during research and development. It helps to achieve high-quality products quickly and with low cost. According to Dr. Taguchi [1,2], optimized method is one that is created with a system of design tools to reduce variability in product or process, while simultaneously guiding the performance towards an optimal setting. A product that is robustly designed will provide customer satisfaction even when subjected to extreme conditions on the manufacturing floor or in the service environment.

The brake performance has been measured during the braking process in many experimental investigations. Experimental investigations widely used brake dynamometers to study the brake performance at different operation and geometric design parameters. The experimental researches measure the influence of temperature, pressure, and temperature on friction by external control of the parameters [3, 4]. Many researchers used the brake dynamometer to investigate the brake system at different

design stages to optimize the performance. There are two basic types of brake dynamometer. These types are; inertia dynamometer that has attached flywheel [5,6] and drag dynamometer that has the ability to test the brake system at constant speeds [7-11]. Despite the large research efforts that have been carried out to evaluate the brake systems during the last years, still many challenges ahead and evaluation brake performance is still a complex phenomenon. This may be due to the fact that brake system is influenced by a large number of variables including materials of brake components, geometry of components, component interaction, many operating and environmental condition [12].

In order to find an optimum manufacturing condition of brake systems, a large number of experiments are required to prepare test specimens and also to carry out experimental tests using brake dynamometer. To reduce the number of experiments, several experimental designs have been suggested [13,14]. Among several experimental design techniques, the Taguchi method has been successfully applied for a systematic approach to optimize designs and to achieve manufacturing parameters [15]. It is designed to minimize the number of experiments and to analyze the specific interactions between control factors and noise factors using an orthogonal array [16, 17].

Taguchi techniques were developed by Taguchi in the late 1940's. Taguchi developed the foundations of robust design and validated its basic philosophies by applying them in the development of many products [18]. Taguchi method can be used for optimization methodology that improves the quality of existing products and processes and simultaneously reduces their costs very rapidly, with minimum engineering resources and development man-hours. It achieves this objective by making the product or process performance "insensitive" to variations in factors such as materials, manufacturing equipment, workmanship and operating conditions. It also makes the product or process robust and therefore it is called as robust design [19]. The Taguchi method is a systematic application of design and analysis of experiments for the purpose of designing and improving product quality. It can reveal an optimal setting after a limited number of experiments have been conducted [20-22].

According to Taguchi's quality engineering philosophy and methodology, there are three important steps in designing a product or process: system design, parameter design and tolerance design [23-26]. In this research, the investigation carried out is to better understand the effect of friction material thickness, friction material length, number friction material slots and number of rotor disc holes on the performance of a new wedge disc brake. Statistical study using the Taguchi method is conducted to give the optimum working conditions of the parameter that affects the performance of wedge disc brake. Four control factors are defined as friction material thickness, friction material length, number friction material slots and number of rotor disc holes each, at three levels are selected and an orthogonal array layout of L9 (3^4) are performed. From the signal-to-noise (S/N) ratio of the test results, the significant parameters to improve wedge disc brake behavior are suggested.

2 Description of Taguchi Method

Taguchi method is one of the most popular methods for optimizing the design parameters. This method improves product quality based on the concepts of statistics and engineering [27]. The method is capable of establishing an optimal design configuration even when interactions exist among the control variables. Basically, the Taguchi method is a powerful tool for the design of high quality systems. It provides a simple, efficient and systematic approach to optimize designs for performance, quality, and cost. The methodology is valuable when the design parameters are qualitative and discrete. Taguchi parameter design can optimize the performance characteristics through the settings of design parameters and reduce the sensitivity of the system performance to sources of variation. In recent years, the rapid growth of interest in the Taguchi method has led to numerous applications of the method in a world-wide range of industries and nations [28].

Recently, Taguchi method has become a well-recognized approach for analyzing the interaction effects while performing ranking and screening of various controllable factors. Moreover, this method is proven to be capable of solving a variety of problems involving continuous, discrete and qualitative design variables. According to Taguchi method for optimization systems, all machines or set-up are classified as engineering systems (if it produces a set of responses for a given set of inputs). Those systems can be classified in to two categories. They are: i) Static system and ii) Dynamic system.

i) The static system to be optimized has several control factors which directly decide the target or desired value of the output. The optimization then involves determining the best control factor levels so that the output is at the target value. This is the primary aim of the Taguchi experiments to minimize variations in output even though noise is present in the process. The process is then said to have become optimized.

ii) The dynamic system has signal factors (input from the end user) in addition to control and noise factors. If the product to be optimized has a signal input that directly decides the output; the optimization involves determining the best control factor levels so that the "input signal / output" ratio is closest to the desired relationship. Systems like disc brake system produce outputs namely brake performance for a set of inputs parameters. The present study is aimed at establishing the input-output relationships for prediction of brake performance. Optimization of the performance of disc brake is considered a static system shown in Fig. 1.
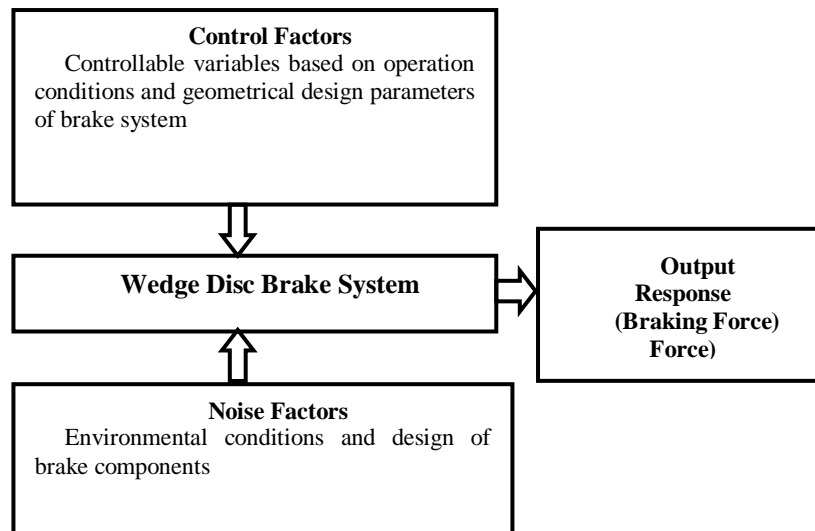
Fig. 1 P-diagram of wedge disc brake performance system

3   Taguchi Method Optimization

In this section, parameter design is used to select optimal or sub-optimal levels for types of required parameters. According to Taguchi, The overall framework is shown in Fig. 2. To summarize, the parameter design of the Taguchi method includes the following steps:

Step1. Planning of the experiment

    a) Defining the control factors, noise factors and quality responses for the product or process.
    b) Determining the levels of each factor.
    c) Selecting an appropriate orthogonal array (OA) table. The selection of the most appropriate OA depends on the number of factors and interactions, and the number of levels for the factors.
    d) Transforming the data from the experiments into a proper S/N ratio.

Step2. Carrying out the experiments

Step3. Analyzing and examining the results

    a) Executing an ANOVA analysis to determine the significant parameters.
    b) Conducting a main effect plot analysis to determine the optimal levels of the control factors.
    c) Executing a factor contribution rate analysis.
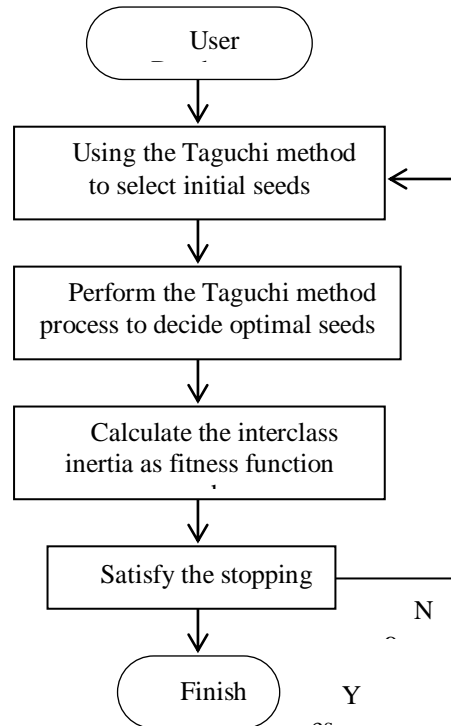   d) Confirming the optimal process parameters through the confirmation experiment.

Fig. 2 overall framework of the Taguchi method

4   Orthogonal Array

The effect of many different parameters on the performance characteristic in a condensed set of experiments can be examined by using the orthogonal array experimental design proposed by Taguchi. Once the parameters affecting a process that can be controlled have been determined, the levels at which these parameters should be varied must be determined. Determining what levels of a variable to test requires an in-depth understanding of the process, including the minimum, maximum, and current value of the parameter. If the difference between the minimum and maximum value of a parameter is large, the values being tested can be further apart or more values can be tested. If the range of a parameter is small, then less value can be tested or the values tested can be closer together.

While there are many standard orthogonal arrays available, each of the arrays is meant for a specific number of independent design variables and levels. For example, if one wants to conduct an experiment to understand the influence of 4 different independent variables with each variable having 3 set values (level values), then an L9 orthogonal

array might be the right choice. The L9 orthogonal array is meant for understanding the effect of 4 independent factors each having 3 factor level values. This array assumes that there is no interaction between any two factors. While in many cases, no interaction model assumption is valid, there are some cases where there is a clear evidence of interaction. A typical case of interaction would be the interaction between the material properties and temperature.

4.1 Analyzing Experimental Data

Once the experimental design has been determined and the OA has been selected, the measured performance characteristic can be used to analyze the relative effect of the different parameters. To determine the effect each variable has on the output, the signal-to-noise ratio, or the S/N number, needs to be calculated for each experiment conducted.

4.2 Signal-to-Noise Ratio

In the Taguchi method, the Signal-to-Noise Ratio (S/N ratio) is computed to analyze the deviation between the experimental value and the desired value. Usually, there are three types of quality characteristic in the analysis of the signal-to-noise ratio, (i.e. the lower-the-better, the higher-the-better, and nominal-the-better). Since, the requirement is to maximize the brake performance through selection a proper parameters; higher-the-better quality characteristic is employed.

The S/N ratio η is given by:

$$\eta = -10\log(MSD) \tag{1}$$

where *MSD* is the mean-square deviation for the output characteristic. *MSD* for the smaller-the-better quality characteristic is calculated by the following equation,

Larger the better (for making the system response as large as possible):

$$MSD = \frac{1}{N}\left[\sum_{i=1}^{n}\frac{1}{Y_i^2}\right] \tag{2}$$

Smaller the better (for making the system response as small as possible):

$$MSD = \frac{1}{N}\left[\sum_{i=1}^{n}Y_i^2\right] \tag{3}$$

Nominal the best (for reducing variability around a target):

$$MSD = \left[\frac{Y^-}{s_{\bar{y}}^2}\right] \tag{4}$$

Where Y_i is the squeal response for the i_{th} test, n denotes the number of tests and N is the total number of data points, y^- is the mean of observed data, $S_y{}^2$ is the variance of y,

and y is the observed data. The function '-log' is a monotonically decreasing one, it means that we should maximize the S/N value. The S/N values are calculated using Equations.1 and 4. Table 3, shows the response table for S/N ratios using smaller-the-better approach.

These S/N ratios are derived from the quadratic loss function and are expressed in a decibel scale. Once all of the S/N ratios have been computed for each run of an experiment, Taguchi advocates a graphical approach to analyze the data. In the graphical approach, the S/N ratios and average responses are plotted for each factor against each of its levels. The graphs are then examined to "pick the winner," i.e., pick the factor level which (1) best maximize S/N and (2) bring the mean on target (or maximize or minimize the mean, as the case may be). Using this information, the control factors can also be grouped as follows.

1. Factors that affect both the variation and the average performance of the product.
2. Factors that affect the variation only.
3. Factors that affect the average only.
4. Factors that do not affect either the variance or the average.

Factors in the first and second groups can be utilized to reduce the variations in the system, making it more robust. Factors in the third group are then used to adjust the average to the target value. Lastly, factors in the fourth group are set to the most economical level. Finally, confirmation tests should be run at the "optimal" product settings to verify that the predicted performance is actually realized. A demonstration of Taguchi's approach to parameter design serves as our case study in the next section.

4.3   Optimization Of Geometric Parameters Using Taguchi Methods

Four control factors are defined as number of rotor holes, friction material thickness, friction material length, friction material slots each at three levels are selected and an orthogonal array layout of L9 (3^4) are performed. From the signal-to-noise (S/N) ratio of the test results, the significant parameters to improve wedge disc brake behavior are suggested. The wedge brake performance based on the experimental results is compared with the predicted results using Taguchi approach. The details of this analysis as following subsections:

Based on the detailed literature survey, the wedge disc brake performance influences by number of rotor holes, friction material thickness, friction material length, friction material slots that are important and their design have effects on the performance. To select the optimum values for the each parameter for effective increasing brake performance, the following parameters are considered for the experiments, as listed in Table 1.

Table 1 Parameters and their levels for Taguchi method

Test	No. of hole	slots	length	thickness	Results
1	0	1	11	10.0	3293.00
2	0	2	9	7.5	2539.00
3	0	3	7	5.0	2103.00
4	64	1	9	5.0	2213.83
5	64	2	7	10.0	2609.63
6	64	3	11	7.5	2544.00
7	32	1	7	7.5	2386.14
8	32	2	11	5.0	2385.00
9	32	3	9	10.0	2765.00

While there are many standard orthogonal arrays available, each of the arrays is meant for a specific number of independent design variables and levels. For example, if one wants to conduct an experiment to understand the influence of 4 different independent variables with each variable having 3 set values (level values), then an L9 orthogonal array might be the right choice. The L9 orthogonal array is meant for understanding the effect of 4 independent factors each having 3 factor level values. This array assumes that there is no interaction between any two factors. While in many cases, no interaction model assumption is valid, there are some cases where there is a clear evidence of interaction.

In this study, if there is an experiment having 4 factors which have three values, then total number of experiment is 81. The Taguchi orthogonal array make list of nine experiments in a particular order which cover all factors. By using this method number of experiments reduced to 9 instead of 81 with almost same accuracy. The present set of excremental tests is conducted as per the Taguchi L9 (3^4) orthogonal design array to identify the "most significant" variables by ranking with respect to their relative impact on the brake performance. The L_9 orthogonal array consists of four control parameters at three levels, as shown in Table 2.

The S/N values are calculated using Equations.1 and 2. Table 3, shows the response table for S/N ratios using larger-the-better approach.

Table 2 Design layout using Taguchi L9 array

Factors	Levels		
	1	**2**	**3**
A:No. of rotor disc holes	0	32	64
B:No. of friction material slots	1	2	3
C:friction material length (cm)	11	9	7
D: Friction material thickness (mm)	10	7.5	5

Table 3 Response table for S/N ratios using larger-the-better

Level	A	B	C	D
1	68.16	68.27	67.31	66.83
2	67.98	67.99	67.94	67.92
3	67.78	67.66	68.67	69.17
Delta	0.38	0.61	1.36	2.34
Rank	4	3	2	1

5 Results of Taguchi Method

From the Fig. 3 of main effects plot and from Table 4 of S/N ratio, it is observed that A1-B1-C4-D4 is the optimum combination for maximum brake force. Similarly, A4-B4-C1-D1 is the combination for minimum brake force. In this study, the brake force is considered an indication for brake performance (as the brake force increase the brake performance increase). It is observed that these combinations of parameters are not included in the experimental runs. Hence, an additional two confirmation tests are run at these combinations. The experimental and predicted results are shown in Table 4
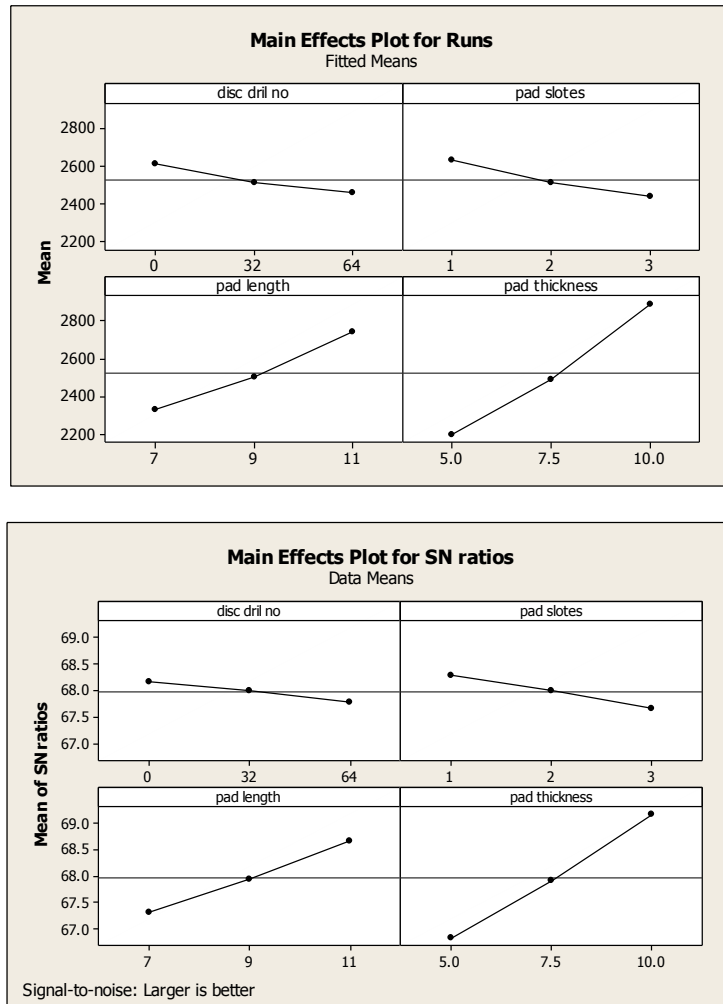
Fig. 3 Main effects plot of the variables on the brake performance

6   Confirmation Test

Furthermore, the confirmation test is conducted to verify the improvement of results and to predict the optimum performance at the selected levels of significant parameters. The confirmation experiment is highly recommended by Taguchi to verify experimental conclusions. The most optimal set of combination of parameter was performed with

combination of the optimum levels to compare the results with the predicted performance. The predicted mean of the response characteristic of Taguchi can be expressed as shown in Table 4 and Fig. 3.

Table 4 Verification Experimental results

Difference	Exp.	Predicted	S/N Ratio	thickness	Length	slots	holes	Run
5.90%	3097	3293	70.35	10	11	1	0	1
8.50%	1689	1847	65.65	5	7	3	64	2

As is seen from the Table 4, the predicted results of brake performance using Taguchi method and experimental results from brake test rig found to be in good agreement. It shows the adequacy of the Taguchi approach in prediction of the brake performance. It can be concluded that the optimal value of braking force is 3293 N, at number of rotor disc holes, one friction material slot, friction material length 11 cm, and friction material thickness 10 mm. Fig. 4 shows the statistics deviation of the performance in the disc brake system.
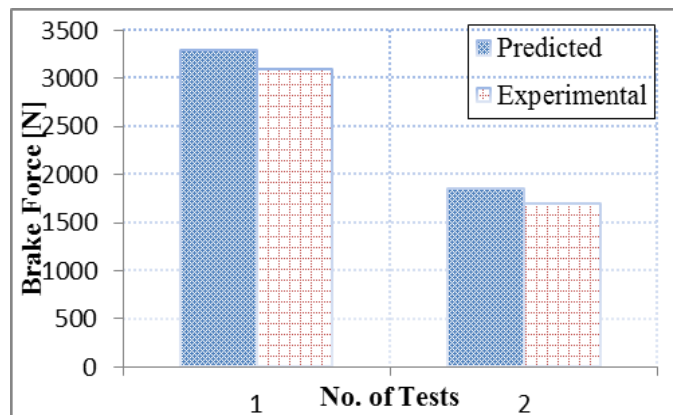
Fig. 4 Comparison between predicted by Taguchi and Experimental results

7 Conclusion

In this paper, a new methodology for evaluation of different types of parameters used in practice for evaluation the new wedge disc brake components are examined to increase braking force generation. The experimental tests using brake dynamometers is integrated with Taguchi method to find out the contributions of several types of

geometric design parameters and its effects for effective increasing of brake performance. The results revealed that the friction material thickness contributes 49.9 % of the total brake performance. It is followed by the friction material length, which contributes 29 % of the system performance. In addition, the number of friction material slots contributes a percentage of 13 % . finaly, the number of rotor disc holes contributes 8.1% of the total brake performance. It is also seen that friction material thickness, and friction material length are the most significant parameters that have a significant effect on wedge brake performance. Finally it can be reported that, Taguchi method can simplify the test protocol required to optimize wedge disc brake by reducing the number of trial batches.

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