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Optimization of Operation Parameters on a Novel Wedge Disc Brake by Taguchi Method

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Abstract In this paper, a novel wedge disc brake is evaluated experimentally using brake dynamometer and Taguchi approach. The main purpose of Taguchi method is to assess the significant of different operation parameters that effect of wedge brake performance. This approach facilitated the study factors and their settings with a small number of experimental runs leading to considerable economy in time and cost for the process optimization. Four control factors are defined as applied pressure, vehicle speed, wedge angle inclination and water spraying, each at four levels are selected and an orthogonal array layout of L16 (4^4) 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 Taguchiapproach and they are found to be in good agreement.

Keywords: *Taguchi approach, wedge disc brake, applied pressure, sliding speed, water spraying*

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1. Introduction

There are many types of brake systems that have been used since the inception of the motor car, but in principle they are all similar. The main function of brake system is to retard the vehicle by transforming the kinetic energy of the vehicle into heat by the process of friction, and this heat must be effectively and efficiently dissipating to the surroundings by the brake components. Experimental approaches using brake dynamometers or on-road tests have been widely used to examine the brake performance to investigate the effects of different parameters and operating conditions. There are two designs for the brake dynamometer. The first design is an inertia-type brake dynamometer that has flywheel attached to it [1]. The second design is a drag-type brake dynamometer that can only test brake at a constant speed [2]. The advantage of brake dynamometer is that it provided a means of tight experimental control. Pad or rotor temperature, brake pressure, rotational speed, and their associated ramp rates are all parameters that can be monitored precisely [3].

In order to find an optimum manufacturing condition of brake pads, 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 [4,5]. Among several experimental design techniques, the Taguchi method has been successfully applied for a systematic approach to optimize designs and to achieve manufacturing parameters [6]. 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 [7,8].

Taguchi techniques were developed by Dr. Genichi 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 [9]. 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 [10]. 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 [11,12,13]. Taguchi method based design of experiment is conducted to better assess the contributions of different materials and its interaction effects for effective reduction of brake vibration. The results concluded that the pad friction material contributes 56% to the total system instability [14].

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 [15,16,17,18]. In the system design, a basic functional prototype design is produced depending on engineering knowledge. Since the system design is an initial functional design, it may be far from optimum in terms of quality and cost. Then, the role of parameter design is coming to optimise the settings of the parameter values in order to improve quality characteristics and to identify the product parameter values under the optimal condition. In addition, it is intended that the optimal parameter values obtained from the parameter design are insensitive to the variation of environmental conditions and other noise factors. Finally, the tolerance design is used to determine and analyse tolerances around the optimal settings recommended by the parameter design. The tolerance design is required if the reduced variation obtained by the parameter design does not meet the required product performance [19].

In this research, the investigation carried out is to better understand the effect of the applied pressure, rotational speed, angle and waters praying 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 applied pressure, sliding speed, angle inclination and water spraying, each at four levels are selected and an orthogonal array layout ofL16 (4^4) 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. Experimental Method

The main objective of the current test rig (simplified dynamometer) is to enable the measurement of performance of the new wedge disc brake system. A dynamometer is designed to provide the necessary disc rotation speed, applied pressure; wedge angle and water spray to the new wedge brake. It can be divided into three main groups: the driving unit, the braking unit and the measurement facilities. Figure 1 shows a photo of the test rig with its different units.

The driving unit consists of anA.C. motor of 18.56 KW and 1500 rpm, that rotates the driving shaft at different rotating speeds. This is achieved with the help of a two manual gearboxes. The braking unit comprises the new wedge disc brake assembly, as shown in Figure 2. Brake master cylinder is used to apply an adequate pressure. Approximately 10 bar of hydraulic pressure is sufficient to produce the maximum brake force. The measurement facilities including suitable instruments to measure the following: Rotating speed (tachometer), Actuating pressure (a pressure gauge), temperature (thermocouple) and tangential force (load cell).

Brake performance are recorded at four vehicle speeds 6, 11.6, 22.6 and 36.3 km/hr. Equivalent to (54, 105, 205 and 329 rpm.), that is obtained from the gearboxes reduction ratios and measured by speed tachometer. Different brake pressure in the range 2.5 to 10 bar is controlled and wedge angle is adjustedmanually between 15° to 45°, water spray is controlled up to 240 mm3through all vibration tests. Four-channel data acquisition system is used to monitor braking force. The acquired signals are transferred to a computer in digital form for storage and further analysis. For more details on experimental work see reference [20].

Figure 1. Main components of the brake dynamometer

Figure 2. Modified (wedge) disc brake

3. Taguchi Method

In the present work, Taguchi method is integrated to find out the significant contributions of the different operation variables with other design parameters. According to Taguchi, 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 and ii) Dynamic. The dynamic system has signal factors (input from the end user) in addition to control and noise factors, whereas in static system signal factors are not present. Optimization of performance of disc brake is a static system. The parameter design of the Taguchi method includes the following steps:

1. Identify the quality characteristics and parameters to be evaluated.
2. Determine the number of levels for the parameters and possible interactions between the parameters.
3. Select the appropriate orthogonal array and assign the parameters to the orthogonal array.
4. Conduct the experiments based on the arrangement of the orthogonal array.
5. Analyse the experimental results using the signal-to-noise ratio and statistical analysis of variance.
6. Select the optimal levels of parameters.
7. Verify the optimal parameters through the confirmation experiment.

3.1. Selection of Variables and Their Levels

Based on the detailed literature survey, the wedge disc brake performance influences by applied pressure, rotational speed, angle and water spraying 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. Operation Parameters and Their Levels for Taguchi Method

Factors	Levels			
	1	2	3	4
A: Applied pressure (bar)	2.5	5	7.5	10
B: Rotational speed (rpm)	54	105	205	329
C: Wedge angle (degree)	15	25	35	45
D: Water spray (mm^3)	0	80	160	240

3.2. Taguchi Orthogonal Arrays

While there are many standard orthogonal arrays available, each of the arrays is meant for a specific number of independent design variables and levels. In this research,If there is an experiment having 4 factors which have four values, then total number of experiment is 256. Then results of all experiments will give 100 accurate results. In comparison to above method the Taguchi orthogonal array make list of sixteen experiments in a particular order which cover all factors. Those sixteen experiments will give 99.96% accurate result. By using this method number of experiments reduced to 16 instead of 256 with almost same accuracy. The present set of experimental tests is conducted as per the Taguchi L_{16} (4^4) orthogonal design array to identify the "most significant" variables by ranking with respect to their relative impact on the brake performance. The L_{16} orthogonal array consists of four control parameters at four levels, as shown in Table 2. The experimental tests are carried out for sixteen row and the results are recorded in the Table 2.

Table 2. Design Layout Using Taguchi L_{16}Array

Test no.	Pressure	Speed	Angle	Water	Results
1	2.5	54	45	0	873
2	2.5	105	35	80	918
3	2.5	205	25	160	1089
4	2.5	329	15	240	1420
5	5	54	35	160	1754
6	5	105	45	240	1242
7	5	205	15	0	2483
8	5	329	25	80	1767
9	7.5	54	25	240	2782
10	7.5	105	15	160	3255
11	7.5	205	45	80	2102
12	7.5	329	35	0	2145
13	10	54	15	80	4298
14	10	105	25	0	4099
15	10	205	35	240	3016
16	10	329	45	160	2497

3.3. Signal-to-Noise Ratio

In the Taguchi method, the S/N ratio is computed to analyze the deviation between the simulated 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 larger-the-better, and nominal-the-better). Since, the requirement is to maximize the brake performance through selection a proper parameters; larger-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 larger-the-better quality characteristic is calculated by the following equation,

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

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. 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 "equation 1" and "equation 2". Table 3, shows the response table for S/N ratios using larger-the-better approach.

Table 3. Response Table for S/N Ratios Using Larger-The-Better

Level	Pressure	Speed	Angle	Water
1	60.47	66.31	68.47	66.40
2	64.90	65.91	66.71	65.83
3	68.05	66.17	65.09	65.96
4	70.61	65.64	63.78	65.85
Delta	10.15	0.67	4.69	0.57
Rank	1	3	2	4

4. Results and Discussion

From Figure 3 of main effects plot and from Table 3 of S/N ratio, it is observed thatA4-B1-C1-D1 and A4-B2-C1-D1 are the optimum combination for maximumbrake force. Similarly, A1-B4-C4-D4is the combination for minimumbrake 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 three confirmation tests are run at these combinations. The experimental and predicted results are shown in Table 4.

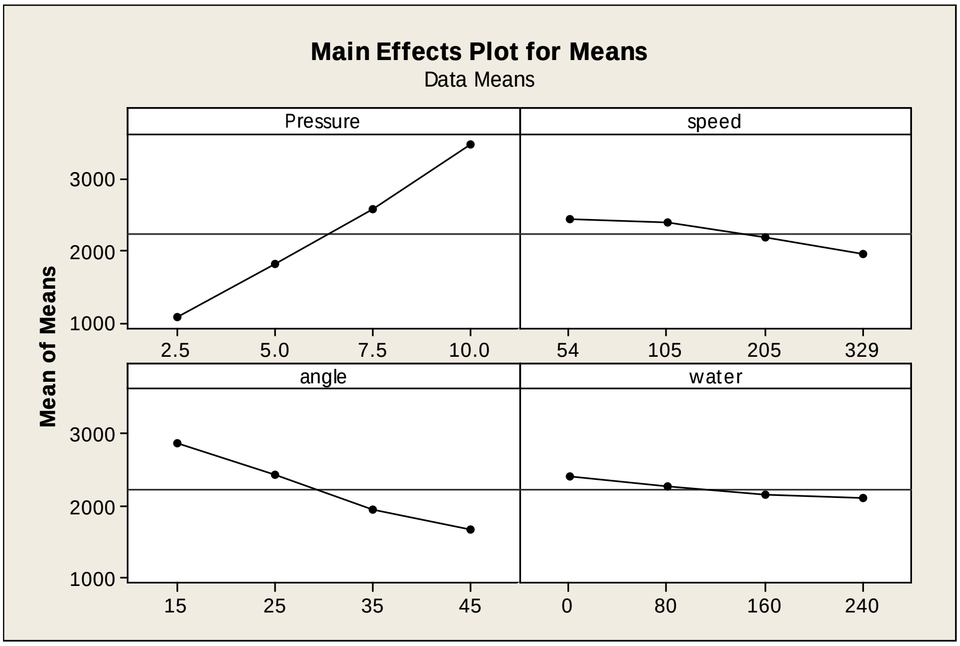

Figure 3. Main effects plot of the variables on the brake performance

5. 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 Figure 3.

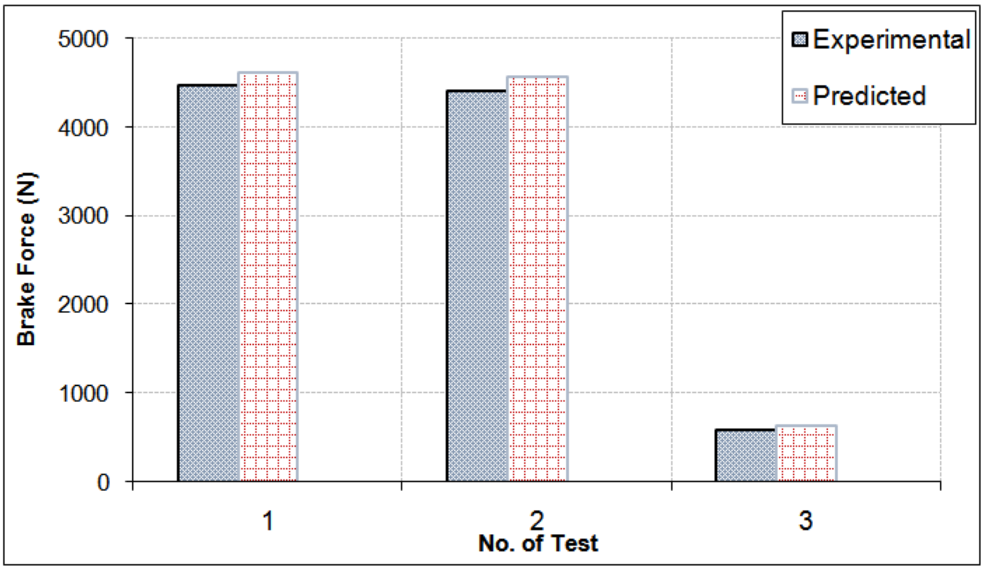

Figure 4. Comparison between predicted by Taguchi and Experimental results

Table 4. Verification Experimental Results

Run	Pressure	Speed	Angle	Water	S/N Ratio	Predicted	Experimental	Difference
1	10	54	15	0	78.76	4467	4610	3.10%
2	10	105	15	0	73.32	4418	4565	3.20%
3	2.5	329	45	240	59.77	589	635	7.20%

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 4610 N, at pressure value 10 bar, speed 54 rpm., wedge angle 15 degree and with dry conditions. Figure 4 shows the statistics deviation of the performance in the disc brake system.

6. Contributions of Parameters

Based on the Taguchi method and S/N ratio, contributions of parameters are computed and plotted, as shown in Figure 5. It is found that the applied pressure contributes 63.1% of the total brake performance. It is followed by the angle, which contributes 29.2 % of the system performance. Rotational speed and water spraying contribute 4.1 and 3.6 % respectively.

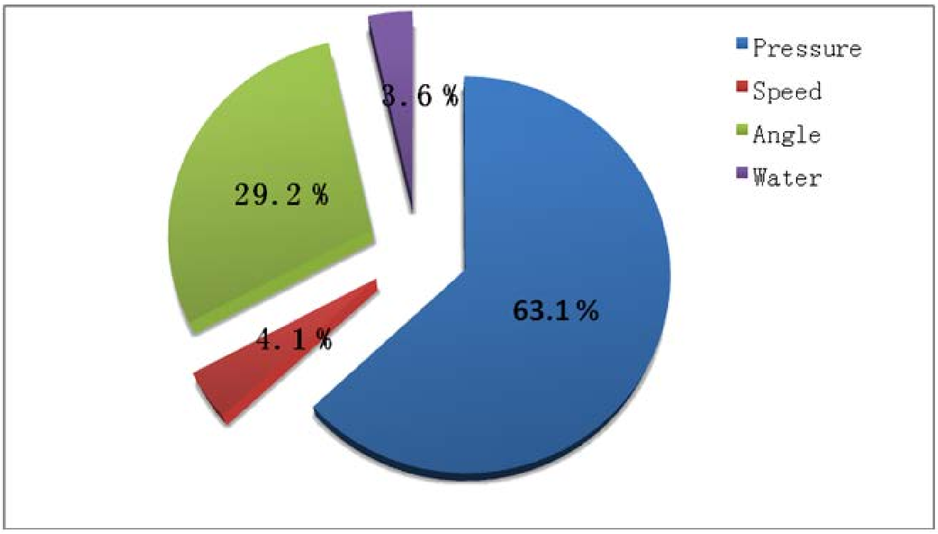

Figure 5. Contribution of different parameterson the wedge brake performance

7. Conclusions

A new method is established using Taguchi method for evaluation of the optimum parameters and their setting on the wedge brake performance. Taguchi method with L16 (4^4) orthogonal array is used in this study to investigate ranking of the effective parameters namely; the applied pressure, rotational speed, wedge angle and water spraying on the performance of wedge disc brake. The results showed that the applied braking pressure contributes 63.1 % of the total brake performance of wedge brake. It is followed by the wedge angle, which contributes 29.2 % of the system performance. Rotational speed and water spraying contribute 4.1 and 3.6 % respectively. It can be observed that the most significant parameters in this research are applied pressure and wedge angle. At the end of this research, it is seen 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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