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Operation Parameters Optimization on a New Wedge Disc Brake by Taguchi Method

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Abstract: *The aim of this research is to investigate Optimization of Operation Parameters on a new disc brake 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. Fife control factors are defined as applied pressure, vehicle speed, wedge angle inclination, sand, and oil, each at four levels are selected and an orthogonal array layout of L16 (4^5) 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 and they are found to be in good agreement.*

Keywords— Wedge disc brake; Taguchi approach; applied force; wedge inclination angle; brake force

INTRODUCTION

There are many types of brake systems that have been used since inception of the motor car and it is a tool to slow or stop the turning motion of the vehicle wheels through transforming kinetic energy to heat [1]. The drum brake and disc brake are the main two types of friction brake. Disc brake have many advantages than drum brake of that: fade resistance, self-adjustment, and freedom of pull. Therefore, drum brake systems for vehicles are being replaced with disc brake systems. It should be noted that the main disadvantage of disc brake system is non-occurrence of the self-energizing phenomenon [2]. Hence, so there were many efforts to modify the disc brake system that could be self-amplified. In wedge disc brake system, a great brake force can be achieved with small-applied force. There were many models of wedge disc brake systems according to applied force direction whether, is normal or tangential. It has different advantages such as improved ABS performance especially on slippery roads, continuous brake power distribution, shorter stopping distance, and environmentally friendly brake system [2]. Therefor new wedge disc brake will be investigated in this study. Coefficient of friction μ, which is between pads and rotor disc that presented by Coulomb's law, is defined as the ratio of brake force to the applied force. Many efforts were done to determine it accurately, for example, Blau [3], and Serverin and Dörsch [4], presented a friction law depending based on many parameters such as normal force, sliding speed, contact temperature and number of brakes. However, it has no exact trend with these working parameters. The ratio of the total brake force to the applied force is called as the characteristic brake factor C* which is considered as the main performance of the vehicle braking system [5]. It depends basically on the value of friction coefficient. Serverin and Dörsch [4] have presented the variation in the characteristic brake factor C* with different friction coefficients. They found that the characteristic brake factor is affected by friction coefficient μ variations with uneven impact, where the degree of influence of the friction coefficient μ on the characteristic brake factor C* is higher with the self-amplified brakes (drum and wedge) than with the conventional disc brakes. Wedge disc brake, which its mechanical model shown in Fig. 1, is an application of mechatronics in a new disc brake system. The concept of Roberts [6] was based upon the application of self-amplification action in the disc brake system by using a wedge mechanism. This mechanism is similar to the patent presented by Dietrich [7]. In this work, the researcher tries to find the optimal operating point. The characteristic brake factor C* is:

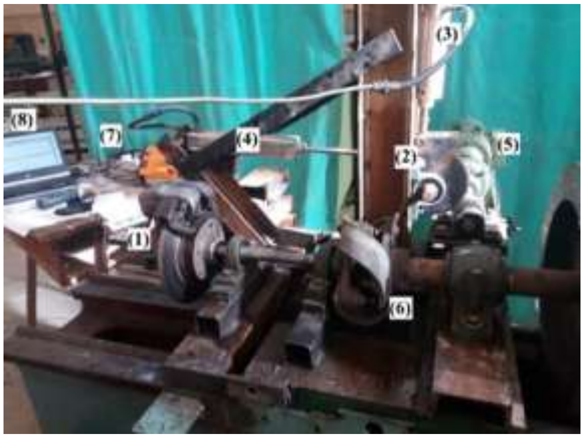
$$c^* = \frac{2\mu}{\tan(\alpha) - \mu}$$

Where, α is wedge inclination angle. They even considered using the operating point when the characteristic brake factor C* is infinity, i.e., the term tan (α) – μ becomes zero.

DESCRIPTION OF TEST-RIG

The test rig was built in order to generate the kinetic energy required for the system and then brake this energy by the brake wedge mechanism and measure the brake force at different speeds, applied forces, and different wedge inclination angles. The test rig consists of driving mechanism, flexible coupling, brake rotor disc, brake wedge mechanism, hydraulic connections for the brake fluid, and a measuring system for the brake force. The test rig is shown in Fig. 1.

The driving mechanism is mainly the gear box of the lathe machine to give the system the ability of working with different speeds. The driving mechanism is also having a flywheel to give the required inertia force for the braking system. The lathe itself is driven by an AC electric motor characterized by a constant rotational speed with maximum power of 10 hp (7.46 kW) at 1450 rpm.



(1)	Rotor disc	(5)	Inclination angle Control
(2)	New wedge disc brake	(6)	Coupling
(3),	Hydraulic press (a)	(7)	Measuring system
(4)	Hydraulic press (b)	(8)	Computer

Fig. 1. *Experimental test rig*

The brake rotor disc is the element for testing the brake force on it and it has a brake pads installed on it and connected with the brake wedge mechanism by the hydraulic connections. The new wedge mechanism is shown in Fig. 2.

The wedge mechanism is the most important part in the system, which consists of: two metallic parts have an inclined sliding surface between them has an inclination of 45^{o}, the lower part is connected to a gear driving mechanism to control the inclination of this part, the upper part is the wedge which is connected to the hydraulic connections from the applied force source and to the normal force on the brake pads which installed on the rotor disc.

The lower gear controlling the inclination angle of the wedge mechanism is driven by an electric motor with brake to adjust the inclination of the lower part of the mechanism as shown in Fig. 2. The sliding surface between the two parts of the wedge has a ladder bearing to prevent the friction between these two parts.

The hydraulic connection is the main part transferring the pressure from the hydraulic pedal to the brake pads. These connections take the pressure from the hydraulic pedal by means of a hydraulic press, this pressure is transferred to the wedge by another hydraulic press numbered 3 in Fig.2. After the wedge there are other hydraulic connections transferring the pressure from the wedge to the brake pads as shown in Fig.2.

After conducting the test and applying the brake force on the rotor disc, a measuring system for the disc braking force is installed to measure and record the brake force.

The applied force from the hydraulic pedal to the hydraulic press (a) at fig. (1) can be adjusted by using a pressure gauge with a control valve. The applied force acting from the hydraulic press (a) to the wedge moving it to force the hydraulic press (b) which generates the normal force at the hydraulic connection from press (b) to the brake pads. The normal force from the wedge is measured by a hydraulic gauge and recorded during the test

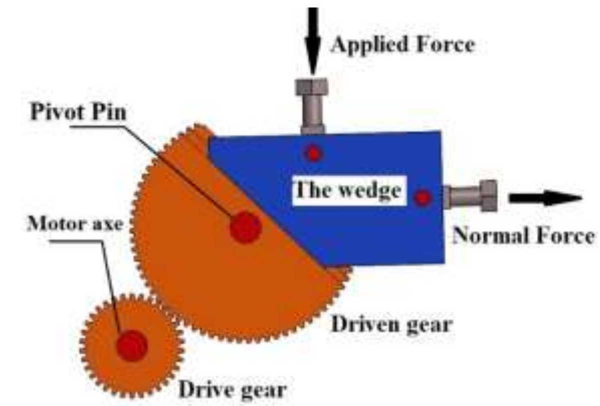


Fig. 2. *New wedge mechanism*

Measurement Instrumentation

The designed test rig with the measurement instrumentation is shown schematically in Fig. 3.

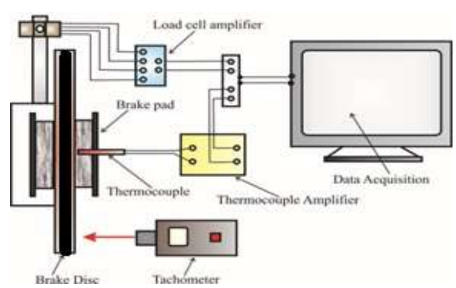


Fig. 3. *Schematic sketch of brake force, temperature and speed measurement instrumentations*

The instrumentation includes:

- Applied force measurement.
- Rotational speed measurement.
- Brake force measurement.
- Friction temperature measurement.

The applied force can be measured by a pressure gauge installed in the hydraulic line after the pedal. The hydraulic pressure of the brake fluid in the line can be multiplied by the area of the press (a) to obtain the applied force. The hydraulic press (a) and (b) pistons have a diameter of 40 mm. The applied force is adjusted to the required value by using a control valve.

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The rotational speed of the lathe machine is adjusted to the required rpm and was checked also by the use of a digital photo tachometer.

The brake force is measured by a load cell (tension-compression load cell with 400 kg maximum load) which was installed beside the rotor disc and the force transmitted to it by means of a metallic connection was tightened to the rotor disc.

The temperature due to the friction was measured by a thermocouple mounted on the rotor disc above the brake pads.

The brake force and the temperature of the friction were recorded using a data logger transferring these readings to the computer to record it as shown in figure 4.

EXPERIMENTAL WORK

The experiments were conducted to check the new wedge mechanism effect and to decide the optimum inclination angle for the wedge.

The selected parameters for the experiments were as follows:

The rotational speed (N) of 76, 150, 230, and 305 rpm.

The applied pressure (P_{app}) of 5, 7.5, 10, and 12.5 bar these values of pressure equals applied forces (F_{app}) of 628.572, 942.857, 1257.143, and 1571.43N respectively.

Inclination angle (α) of 45, 35, 25, 15, 12, and 10 degrees.

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. Analyses 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.

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]	5	7.5	10	12.5
B:Rotational speed [rpm]	76	150	230	305
C:Wedge angle [degree]	45	35	25	12
D: Sand diameter [µm]	150	300	450	600
E: Oil volume [mm3]	5	10	15	20

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 5 factors which have four values, then total number of experiment is 1024. Then results of all experiments will give 600 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 99.95% accurate result. By using this method number of experiments reduced to 16 instead of 1024 with almost same accuracy. The present set of experimental tests is conducted as per the Taguchi L_{16} (4^5) 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 fife 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*

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Tests	pressure	speed	angle	sand	oil
1	5	76	45	150	5
2	5	150	35	300	10
3	5	230	25	450	15
4	5	305	12	600	20
5	7.5	76	35	450	20
6	7.5	150	45	600	15
7	7.5	230	12	150	10
8	7.5	305	25	300	5
9	10	76	25	600	10
10	10	150	12	450	5
11	10	230	45	300	20
12	10	305	35	150	15
13	12.5	76	12	300	15
14	12.5	150	25	150	20
15	12.5	230	35	600	5
16	12.5	305	45	450	10

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:

$$\eta = -10 \log (MSD) \qquad (1)$$

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,

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

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	A	B	C	D	E
1	72.42	75.01	75.99	73.81	73.90
2	73.46	73.64	75.47	73.82	73.87
3	74.34	73.60	73.16	74.02	73.85
4	75.33	73.30	70.92	73.90	73.93
Delta	2.91	1.71	5.07	0.02	0.08
Rank	2	3	1	4	5

RESULTS AND DISCUSSION

From Figure 4 of main effects plot and from Table 3 of S/N ratio, it is observed that A4-B1-C1-D3-E4 are the optimum combination for maximum brake force. Similarly, A1-B4-C4-D1-E3 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 three confirmation tests are run at these combinations.

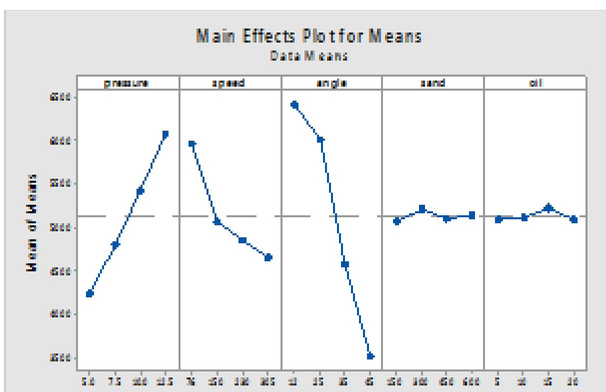

Fig. 4. *Main effects plot of the variables on the brake performance*

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 Figure 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 6762 N, at pressure value 12 bar, speed 76 rpm, wedge angle 12 degree. Figure 5. shows the statistics deviation of the performance in the wedge disc brake system

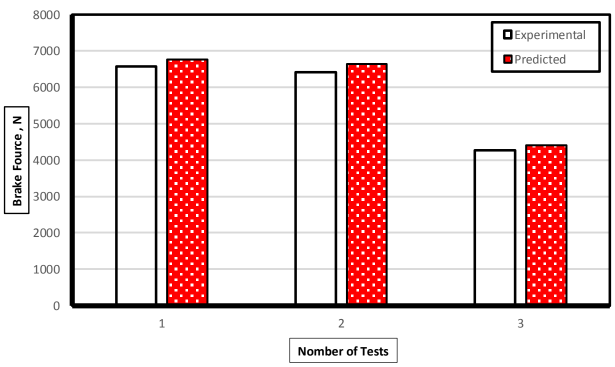

Fig. 5. *Comparison between predicted by Taguchi and experimental results*

Based on Taguchi method and S/N ratio, contributions of parameters are computed and plotted, as shown in Figure 6 it is found that the angle contributes 45.84 % of the system performance. It is followed by applied pressure, which contributes 29.01 % of the total brake performance. Rotational speed contribute 20.76 % but sand and oil contributes 2.23 and 2.15 % respectively

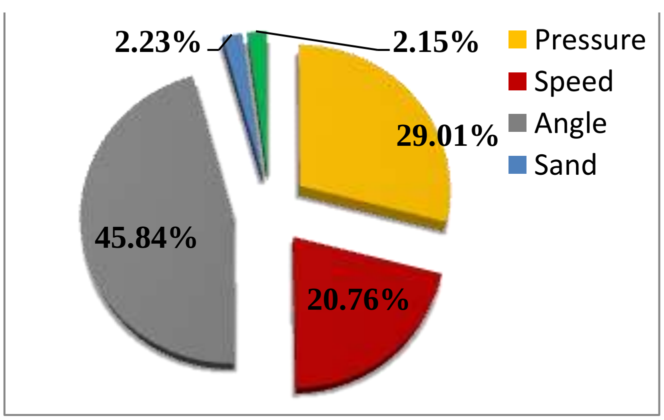

Fig. 6. *Contribution of operation parameters*

CONCLUSION

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 L_{16} (4^5) orthogonal array is used in this study to investigate ranking of the effective parameters namely; the applied pressure, rotational speed, wedge angle, sand and oil on the performance of wedge disc brake. The results showed that the angle contributes 45.84 % of the system performance. It is followed by applied pressure, which contributes 29.01 % of the total brake performance. Rotational speed contribute 20.76 % but sand and oil contributes 2.23 and 2.15 % respectively. It can be observed that the most significant parameters in this research are wedge angle and applied pressure. 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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