Optimization of a New Wedge Disc Brake Using Taguchi Approach

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ABSTRACT: *In this study, a new wedge disc brake performance is assessed using brake dynamometer and Taguchi approach. The Taguchi method is widely used in the industry for optimizing the product and the process conditions. Taguchi orthogonal design method is used to gain better understanding about the factors that effect of wedge brake performance using L9 orthogonal array. Three control factors were considered as applied pressure, vehicle speed and wedge angle inclination, each at three levels is selected. The most affects parameters on brake performance were performed using the analysis of signal-to-noise (S/N) ratio and ANOVA analysis, respectively. It can be concluded that Taguchi method is reliable and reduce the time and experimental costs. In addition, the results indicated that the applied pressure and wedge angle are the most significant parameters for evaluation the wedge disc brake.*

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

I. INTRODUCTION

In spite of the extensive research efforts that have been carried out to evaluate the brake systems during the last decades, 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. Friction behavior is the most critical factor in brake system design and performance. For up-front design and system modeling it is desirable to describe the frictional behavior of a brake lining as a function of the local conditions such as contact pressure, temperature, and sliding speed. Typically, frictional performance is assessed using brake dynamometer testing of full-scale hardware, and the average friction value is then used for the remaining brake system development [1].

There are many research papers on investigation of the brake systems has been conducted using theoretical, numerical and experimental approaches. The experimental approaches have been used to measure the brake performance for the system during braking event. Experimental approaches using brake dynamometers have been widely used to study the brake performance at different design parameters and operating conditions. Moreover, Experimental approaches used to measure friction as a function of temperature, pressure, and temperature by external control of these variables [2, 3]. Many researchers used the brake dynamometer to examine the brake system during different design stages to optimize its performance. Iijima et al. [4] used a brake dynamometer to measure brake dust from three types of NAO pads. Pad or rotor temperature, brake pressure, rotational speed, and their associated ramp rates are all parameters that can be monitored precisely [5]. Actually, there are two basic designs for the brake dynamometer. The first design is an inertia dynamometer that has flywheel attached to it [6, 7]. The second design is a drag dynamometer that can only test the brake system at a constant speed [8-12].

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. The method is capable of establishing an optimal design configuration even when interactions exist among the control variables. Among several optimization techniques, the Taguchi method has been successfully applied for a systematic approach to optimize designs and to achieve manufacturing parameters [13]. The method can be used for improving the quality of existing products and processes and simultaneously reducing their costs very rapidly. Taguchi method is designed to minimize the number of experiments and to analyze the specific interactions between control factors and noise factors using an orthogonal array [14-15].Lately, 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 [16]. 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. Recently, Nouby et al. [17] used Taguchi method based design of experiment to evaluate the contributions of different materials of disc brake components and its interaction effects for effective reduction of disc brake noise and vibration. Their results concluded that the friction material of the brake system contributes approximately 56% to the total system instability.

In this study, the modeling and optimization of different parameters on wedge disc brake performance were investigated by using the Taguchi design method. 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. An L9 orthogonal array of the Taguchi method was implemented to investigate the effects of brake performance. The most affects parameters on brake performance were performed by using the analysis of signal-to-noise (S/N) ratio and ANOVA analysis, respectively. And also, the braking force results obtained as experimental and the results of the regression analysis obtained empirical equations are compared.

II. EXPERIMENTAL SETUP

The primary goal in the development of the current simplified dynamometer is to generate accurate braking forces data for use in evaluating the new wedge disc brake system. The dynamometer designed to study the effect of many operation and design parameters on the performance of the novel wedge disc brake. The operating parameters such as applied force, wedge inclination angle, sliding speed, and water spray as function of time. In addition, design parameters namely; friction material slots, different brake pad thickness and length, and different types of brake rotor. Moreover, the brake dynamometer can be used to study the noise and vibration of the brake systems.

In this study, the brake dynamometer is designed to provide the necessary disc rotation speed, applied pressure and wedge angle for investigating the new wedge brake mechanism. It can be divided into three main subsystems: the driving system, the braking system and the measurement facilities. Fig. 1 shows a photo of the test rig with its different systems.The driving system consists of an A.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 system contains the new wedge disc brake assembly which used in this study to increase the braking force, as shown in Fig. 2. Brake master cylinder is used to apply required pressure. 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 performances are recorded at different vehicle speeds ranged from 6 to 36.3 km/hr., set from the gearboxes reduction ratio and measured by speed tachometer. Different brake pressure in the range of 2.5 to 10 bars is controlled and wedge angle is adjusted manually between 15˚ to 45˚. 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 details, see reference [18].

Fig. 1 Main components of the brake dynamometer.

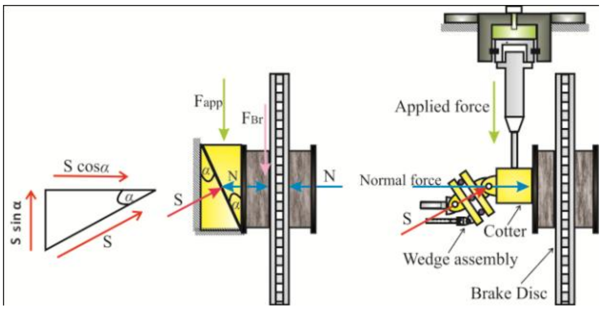

Fig. 2 Wedge disc brake.

III. TAGUCHI APPROACH

Despite of huge number of studies has been made on brake system; there is no general agreement about the effect of some parameters on the final product. In addition, the interrelationships between the effecting parameters involve complex processes. The study of factors influencing the final products phase is also a time consuming task. Hence, the analysis using conventional experimental methods is inefficient and expensive. Therefore for the present study, Taguchi orthogonal design method was used to gain better understanding and find out the significant contributions of the different operation variables with other design parameters. Taguchi method is a combination of mathematical and statistical techniques used in an empirical study, which is economical for optimization of complicated processes [19-20]. By application of this method, less experimental work is required in order to study multiple levels of all input parameters and some effects due to statistical variations are filtered out. The main steps of Taguchi method as follows:

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.

The wedge disc brake force as output response is tested through the dynamometer considering three factors namely; applied pressure, rotational speed andwedge angle. The levels of each factor are selected to further investigations using Taguchi approach.The factors and levels are shown in Table 1.

Table 1 Assignment of the levels to the factors

Symbol	**Factors**	**Levels**		
		1	**2**	**3**
A	Applied pressure (bar)	2.5	6.25	10
B	Rotational speed (rpm)	54	205	329
C	Wedge angle (degree)	15	30	45

3.1 Orthogonal Arrays

One of the major tools in the Taguchi method is called the orthogonal array. Orthogonal design is one of the most effective and time-saving methods for the studies involving multiple variables in order to find out which factors (or variables) influence to the most extent properties of the target product. An array is called orthogonal due to that each column indicates a value of a considered factor, and the factors listed in the orthogonal array can be evaluated independently. Every row in an orthogonal array represents a set of parameters for one run of the experiment. The L9 orthogonal array of the Taguchi method was chosen in our studies. The selection of the orthogonal array is based on the condition that the degrees of freedom for the orthogonal array should be greater than or at least equals sum of those of parameters. The factors (variables) and levels for L9 (3^3) orthogonal array design are listed in Table 1. Three factors were considered namely;applied pressure (bar), rotational speed (rpm) and wedge angle (degree). For each factor, three levels were selected in order to eliminate the influence and validate the results. Nine experimental runs derived from the L9 orthogonal array design are shown in Table 2. The braking force was taken as measured responses.Applying the simple factorial design for study of the assigned three levels of each parameter, the numbers of permutations would be 27= (3^3). However, the fractional factorial design reduced the number of experiments to 9 runs only.Experimental tests using brake dynamometer are conducted for each row of the orthogonal array and the output response is recorded, as shown in Table2.The experimental observations are further transformed into Signal to noise ratio.

Table2 Experimental design usingL9orthogonal array

Tests	**pressure**	**Speed**	**Angle**	**Results**
1	2.5	54	15	1850
2	2.5	205	30	956
3	2.5	329	45	721
4	6.25	54	30	2230
5	6.25	205	45	1543
6	6.25	329	15	2992
7	10	54	45	2861
8	10	205	15	4261
9	10	329	30	3217

3.2 Signal-to-Noise Ratio

Signal-to-noise (S/N) ratio is used to measure the quality characteristic deviating from the desired value. 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 forces through selection a proper parameters; higher-the-better quality characteristic is employedfor obtaining optimal computed to analyze the deviation between the experimental value and the desired value.

The S/N ratio η(the unit of S/N is dB) is given by:

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

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

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

Where,Y_i is the brake force 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 higher-the-better approach.The S/N analysis is based on the experimental data.It is suggested that quality characteristics are optimized when the S/N response is as larger as possible.

Table 3 Response for S/N ratio

Level	A	B	C
1	60.68	67.15	69.15
2	66.75	65.30	65.55
3	70.62	65.60	63.35
Delta	9.94	1.84	5.80
Rank	1	3	2

IV. RESULTS AND DISCUSSION

From Fig. 3 of S/N ratios plot and from Table3 of S/N ratio response,it is suggested that quality characteristics are optimized when the S/N response is as larger as possible. The response table for S/N ratios using higher-the-better approach is listed based on the experimental data. It is suggested that quality characteristics are optimized when the S/N response is as larger as possible. It is also observed that pressure value 2.5 bar combined with speed 54 rpm and 15 angle is the optimum combination for maximized the brake performance.

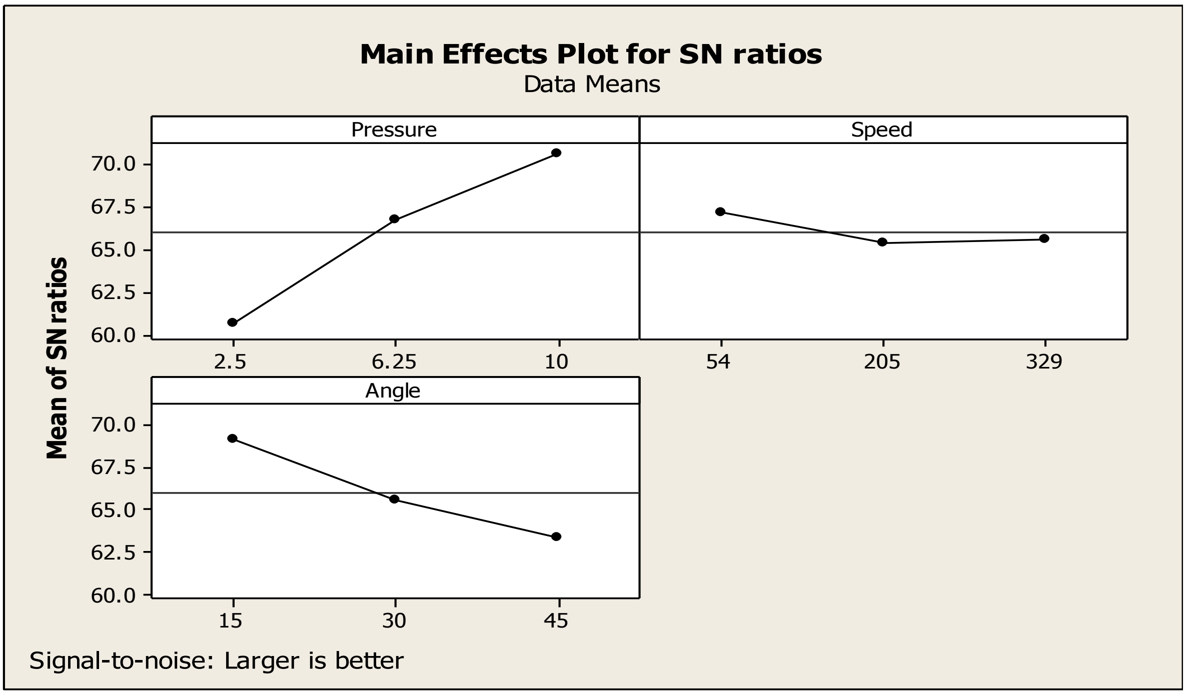

Fig.3 S/N ratios plot of the variables on the brake performance

V. ANALYSIS OF VARIANCE (ANOVA)

In general, Analysis of variance (ANOVA) can be used to understand the relative significance of the process effects on the experimental responses and to estimate the experimental error due to different associated factors. In this study, the ANOVA analysis is conducted to determine the effect of the parameters on wedge brake performance. ANOVA analysis is performed for a 5% ($P < 0.05$) significance level, i.e., for a 95% confidence level to identify the parameters that affect the wedge brake performance. Statistically, F-tests provided a decision at some confidence level that is the realized significance levels, for each source of variation as shown in Tables 4. The F test and P value illustrated that the variation of the process parameter made a big change on the performance characteristics. According to Table 4, applied pressure were found to be the major factor affecting the wedge brake performance whereas, wedge angle were found to be the second important factor. But, a vehicle speed shows a little effect on the brake performance.

Table 4 Analysis of Variance

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	3	10387620	10387620	3462540	90.489	0.00008
A	1	7747521	7747521	7747521	202.471	0.00003
B	1	33	33	33	0.001	0.97782
C	1	2640067	2640067	2640067	68.995	0.00041
Error	5	191324	191324	38265		
Total	8	10578944				

VI. CONTRIBUTIONS OF PARAMETERS

In this section, the effect of each parameterwith different levels can be determinedby averaging the S/N ratios in the experiments design. It can be seen that based on the Taguchi method and S/N ratio contributions of parameters are computed and plotted. Fig.4 shows the contribution of the three parameters on the brake performance. It is found that the applied pressure contributes 56.5 % of the total brake performance. It is followed by the wedge angle, which contributes 33 % of the system performance. And also, rotational speed in the selected range of experimental study is obtained a percentage contribution of 10.5 % only.

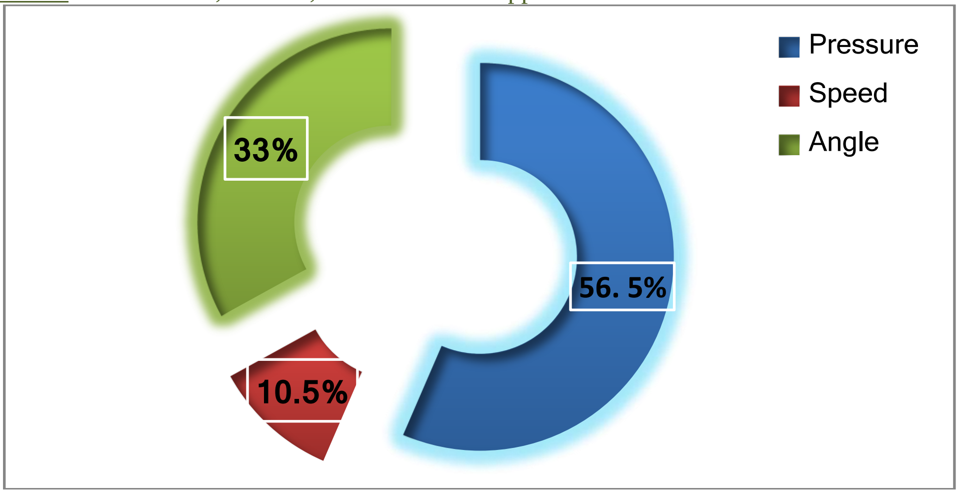

Fig.4 Contribution of parameterson the wedge brake performance

VII. CONCLUSIONS

In this study, Taguchi method is conducted to estimate the effects ofthe optimum parameters and their setting on the wedge brake performance. Taguchi methodwith L9 (33) orthogonal array is performed toinvestigate ranking of the effective parameters namely; the applied pressure, rotational speed and wedge angle on the performance of wedge disc brake.The ANOVA analysis is conducted to examine the significant of each factor. The results revealed that the applied pressure contributes 56.5 % of the total brake performance. It is followed by the angle, which contributes 33 % of the system performance. In addition, the rotational speed contributes a percentage of 10.5 % only. It can be concluded that Taguchi design method exhibit a good performance in the optimizationof different parameters on measuring the braking force of the wedge disc brake.

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