OPTIMIZATION OF THE BRAKE PARAMETER FOR A DISC BRAKE SYSTEM TO IMPROVE THE HEAT DISSIPATION USING TAGUCHI METHOD

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ABSTRACT

Disc brake rotor was proved to have better heat dissipation performance than drum brake as more exposed surfaces had provided to improve the heat transfer. However, overheated surfaces that caused brake fade was still a possibility. In this research, three ventilation parameters of disc brake rotor (number of rotor holes, number of slots and diameter of rotor holes) associated with three factor values levels ranging from minimum, average and maximum were studied experimentally by utilising of Taguchi method. The result obtained from the experiment has pointed that disc brake rotor design with twenty-four 4mm diameter holes and six slots was the optimum design while number of ventilation slots was the most significant parameter that contributed at a rate of 45.25% in heat dissipation performance.

Key words: Disk brake, Heat dissipation, Taguchi method, Ventilated disc brake rotor.

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1. INTRODUCTION

The brake system was worked under the principle by utilising of the friction pads to rub against the respective metal moving surface in order to attain of the stopping motion of certain mechanism. The translation of kinetic energy to heat energy had stopped the moving mechanism. In automotive, there are drum brake system and disc brake system. Disc brake system was more preferred as its characteristics that of higher braking power, longer lifespan, and better heat dissipation.

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Smaller contact area between the brake rotor and brake pad had increased the applied pressure [1]. Disc brake rotor provided more surface exposure to the atmosphere that minimized the possibility of thermal failure [2]. However, high temperature built up on the disc brake rotor at certain conditions such as continuous braking situation was still giving the chances for brake fade to be happening.

Therefore, ventilation features had been implied in the design of disc brake rotor to enhance the cooling performance. Holes, slots or vanes that added to the disc brake rotor formed extra channels for the air to pass through, which improved the air mass flow rate to create a better cooling effect.

By employing appropriate parameters for the respective ventilation features, the pros and cons were able to be balanced. The performance of the disc brake rotor can be improved with no significant effect at all with suitable design of ventilation features. In this research, various parameters of ventilation features for disc brake rotor had been studied by using of Taguchi method. Actual experimentation had been done by adopting of respective method to improve the effectiveness of the optimization process. Through this, the optimum design of ventilation features and the parameter that gave the most significant effect in heat dissipation performance had been identified in an efficient way. The optimum design was proved to be giving the optimum performance in heat dissipation through the confirmation experiment.

2. LITERATURE REVIEW

2.1. Thermal Analysis, Structural Analysis and Brake Performance

Disc brake rotor was needed to be ensured in the optimum operational temperature to dissipate the heat on time for each time of kinetic energy conversion. The disc brake rotor was acted as heat sink, which excess heat could reduce the friction between contact surfaces [3]. It was important for heat to be dissipated as high temperature can cause brake fade or thermo-elastic deformation on the rotor surface [4]. Nevertheless, solid disc brake rotor ranked the least in heat dissipation performance. Ventilation designed disc brake rotor gave better cooling and higher heat flux than the solid brake rotor [3].

It had been said that the heat transfer of disc brake rotor was directly proportional to the number of ventilation features that applied to the design [5]. With combination of different ventilation features, it can greatly improve the cooling effect. However, suitable design should be employed to attain this effect. Different types of design features in each ventilation parameter could affect the performance of the disc brake rotor [6]. Ranging effects could be happened with different design of ventilation features. In order to reach the equity between the pros and cons, appropriate ventilation features with suitable specifications should be considered in designing of disc brake rotor with respect to the intended application of vehicle [6].

Compared to side-ventilation features, axial ventilation features which applied directly on the disc brake rotor surface resulted a more desirable heat dissipation [7]. The reduction of surface area of the rotor had improved the heat transfer on the respective surface [8]. Some research had also indicated that the ventilation features or disc brake properties which could also contribute to the braking performance.

Cross-drilled holes on disc brake rotor guided more fresh air due to pressure drop around holes area whereby increased the heat transfer [9]. Slotted disc brake rotor able to reduce heat generation at a high rate when combined with radial ventilation vanes [5].

In terms of material, cast iron is still the most suitable raw material for disc brake rotor in present automotive application [9]. Cast iron retained the least thermal energy on rotor surface as measured in terms of temperature, which proved it gave the best heat ventilation
performance [10]. Also, cast iron had a higher operating temperature, whereas most alternative materials were not able to reach without additional of the friction layer [11]. Although there are new materials which seem to replace the current; however, in the economical aspect, cast iron is still the most appropriate.

2.2. Taguchi Robust Design and Development Method
Taguchi method, by Dr. Genichi Taguchi, was initially invented to assist industry development in Japan in order to manufacture high-quality products with reasonable pricing had become one of the methods that used worldwide in product optimization process. It was a simple optimization method that suited most of the situation and gave the best experimental efficiency [12].

Inner and outer arrays that proposed by Taguchi method was able to obtain the desired information regarding the relationship between primary and noise variable [13]. Thus, Taguchi robust design and development method was seemed to be the most suitable method in dealing with this research.

Moreover, orthogonal arrays utilised in Taguchi method had efficiently determined the best setting combination of parameters with least experiment performed, which allowed it to be powerful and robust in optimization process [14]. The orthogonal arrays randomised the factor levels in each parameter and organised it into different experiment variables setup accordingly. The method reduced the bias on result by considering the relationship between factors. Significant performance with high result accuracy attained by dealing multiple factors at one time [15]. Other than that, the robustness of the method could be achieved by correctly selecting of signal-to-noise ratio with proper defining of variables into respective categories [16].

As the Taguchi method was emphasized on the factor that had direct effects on the product functional performance, whereas environmental factors were treated as noise, it was suitable to be adopted in product optimization process [17]. Furthermore, Taguchi method had been adopted by other researchers in the optimization of disc brake parameters in terms of brake performance, which experimental results with higher accuracy and consistency had been obtained [18]. Therefore, all of these had strongly pointed that Taguchi method was the best suitable robust method to be adopted in this optimization research.

3. METHODOLOGY

3.1. Experimentation Planning
To perform research on optimization of disc brake parameters in terms of heat dissipation by actual experimentation, Taguchi method had been used. A subject vehicle, Perodua Myvi 1.5 Special Edition (Automatic) had been chosen, which the actual disc brake rotor that installed on the vehicle was the study subject. Three disc brake parameters that affected the heat dissipation performance had been identified along with its respective factor values derived from the minimum, average and maximum values. Table 1 showed the values that were associated with each parameter respectively.
L9 orthogonal arrays in Taguchi method had been used to reduce the number of required experiments. It divided the parameters and its respective factor values into nine different randomise combination, which reduced greatly the number of required experiments to nine experiments instead of twenty-seven. Table 2 illustrates the experiment combinations resulted from the orthogonal arrays.

### Table 1 Parameters of disc brake rotor that intended to be studied

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Criteria</th>
<th>Factor values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Number of rotor holes</td>
<td>12 18 24</td>
</tr>
<tr>
<td>2</td>
<td>Number of slots</td>
<td>0 3 6</td>
</tr>
<tr>
<td>3</td>
<td>Diameter of rotor holes (mm)</td>
<td>3 4 5</td>
</tr>
</tbody>
</table>

Thus, total of nine experiments with randomise combination of factor values of parameters had resulted to be performed. The disc brake rotor prototype samples that used in the experimentation had been made by machining the original radial ventilation disc brake rotor sample according to the combination that resulted.

### 3.2. Experimentation Procedure

The experiment was started by rotating the disc brake rotor sample to the desired rotational speed and temperature was checked with infrared temperature sensing gun. Then, the braking action was applied to slow down the rotor instead of stopping completely. Infrared surface to simulate the braking action of the vehicle. Due to the safety reasons, the braking action was applied for 60 seconds following by 10 seconds cooling time for five times continuously.

The infrared temperature sensing gun was applied again to read the temperature reading on the rotor surface after braking action. After the primary experiments, the optimum design was being figured through the analysis of data by mean and signal-to-noise ratio. The optimum design was then undergoing the confirmation experiment to verify the results accuracy.

The samples were being tested with the usage of customised built disc brake rotor testing machine, which showed in Fig. 1. The disc brake rotor was rotated to the rotational speed that approximately 550rpm, which equivalent to 60km/h for the respective vehicle in actual travelling condition. After that, brake pad was actuated by push rod to rub on the brake rotor surface to simulate the braking action of the vehicle. Due to the safety reasons, the braking action was applied to slow down the rotor instead of stopping completely. Infrared temperature gun had utilised to measure the temperature of disc brake rotor surface before and after the braking process.
185±2mm and 165±2mm were set to be the position to measure the temperature reading as the turbulent air was giving direct contact to the outer faces [19].

The cold and fast moving disc brake rotor “threw out” most heat when rotating at high speed. The highest heating rate was achieved by the disc brake rotor sample with eighteen 3mm diameter holes, six slots (P1-18, P2-6, P3-3) and twenty-four 4mm diameter holes, six slots (P1-24, P2-6, P3-4) having the maximum heat dissipation performance out of others. Both had achieved the same results, 0.022°C/s, which showed the highest heat dissipation performance among the others.

It was also observed that single ventilation feature was not able to bring up the heat dissipation performance effectively. Prototype sample with holes only ventilation feature had given the highest heating rate in the experiments.

Furthermore, all disc brake rotor prototypes that were modified by adding ventilation features was performed better in terms of heat dissipation as the solid disc brake rotor resulted the highest heating rate. The holes and slots served as passage for gases and dust to escape during braking [3].

The experiment data did also notice that the temperature at inner circumference was the highest and decreased when it came to the outer. This was due to the centrifugal force of the disc brake rotor “threw out” most heat when rotating at high speed. The cold and fast moving turbulent air was giving direct contact to the outer faces [19].

4. RESULTS AND DISCUSSIONS

4.1. Primary Experiments

From the primary experimental results showed in Table 3, disc brake rotor sample with eighteen 3mm diameter holes, six slots (P1-18, P2-6, P3-3) and twenty-four 4mm diameter holes, six slots (P1-24, P2-6, P3-4) having the maximum heat dissipation performance out of others. Both had achieved the same results, 0.022°C/s, which showed the highest heat dissipation performance among the others.

Table 3 Primary experimental results

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>Factor values</th>
<th>Temperature before braking (°C)</th>
<th>Temperature after braking (°C)</th>
<th>Temperature difference (°C)</th>
<th>Heating rate (°C/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P1</td>
<td>P2</td>
<td>P3</td>
<td>Reading 1 (outer)</td>
<td>Reading 2 (Middle)</td>
</tr>
<tr>
<td>1</td>
<td>Solid</td>
<td>31.6</td>
<td>32.4</td>
<td>32.5</td>
<td>32.17</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>0</td>
<td>3</td>
<td>31.1</td>
<td>31.2</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>3</td>
<td>4</td>
<td>30.1</td>
<td>30.3</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>6</td>
<td>5</td>
<td>31.8</td>
<td>32.4</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
<td>0</td>
<td>4</td>
<td>30.2</td>
<td>30.2</td>
</tr>
<tr>
<td>6</td>
<td>18</td>
<td>3</td>
<td>5</td>
<td>31.0</td>
<td>31.6</td>
</tr>
<tr>
<td>7</td>
<td>18</td>
<td>6</td>
<td>3</td>
<td>33.2</td>
<td>33.8</td>
</tr>
<tr>
<td>8</td>
<td>24</td>
<td>0</td>
<td>5</td>
<td>30.5</td>
<td>30.5</td>
</tr>
<tr>
<td>9</td>
<td>24</td>
<td>3</td>
<td>3</td>
<td>29.9</td>
<td>29.8</td>
</tr>
<tr>
<td>10</td>
<td>24</td>
<td>6</td>
<td>4</td>
<td>31.5</td>
<td>31.8</td>
</tr>
</tbody>
</table>

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Table 4 Mean of experiment data respectively to factor values

<table>
<thead>
<tr>
<th>Level</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.040</td>
<td>0.043</td>
<td>0.031</td>
</tr>
<tr>
<td>2</td>
<td>0.035</td>
<td>0.032</td>
<td>0.035</td>
</tr>
<tr>
<td>3</td>
<td>0.029</td>
<td>0.028</td>
<td>0.056</td>
</tr>
<tr>
<td>Average</td>
<td>0.035</td>
<td>0.034</td>
<td>0.041</td>
</tr>
</tbody>
</table>

Table 4 showed the mean analysis calculated from the primary experimental results. The third parameter had the highest average mean among the other two parameters, which mean it was the parameter that giving the least performance in heat dissipation. More heat had retained on the surface as the hole diameter increased.

On the other hand, the number of slots had the least effect on heat retaining as resulted the least value in the average mean. Increasing of slot number had lowered the heating rate, which indirectly improved the heat dissipation performance. Hence, disc brake rotor design with less number of holes, less number of slots and larger diameter of holes ranked the least in heat dissipation performance.

From the mean analysis, it concluded that disc brake rotor prototype with twenty-four 4mm diameter holes, six slots (P1-24, P2-6, P3-4) was the optimum design. Disc brake rotor with eighteen 3mm diameter holes, six slots (P1-18, P2-6, P3-3) was not selected as optimum design due to the diameter of rotor holes contributed the least in heat dissipation.

4.2. Signal-to-Noise Ratio
The smaller-the-better quality characteristics in analysis of the signal-to-noise ratio was used for this experimental results. The minimum the heating rate was the expectation that should be obtained at the end to find out the optimum design and most effective parameter that could maximize the heat dissipation. The formula given in the Taguchi method:

\[ \eta = -10 \log \left( \frac{\sum_{i=1}^{n} Y_i^2}{N} \right) \]  

(1)

Where Yi was the result obtained with respect to ith number of experiment, n was the number of experiment and N was the total number of experiments, was used to calculate the signal-to-noise ratio. Table 5 and Fig. 2 illustrated the signal-to-noise ratio of experimental results and its plotted graph respectively.

Table 5 Signal-to-noise ratio of experimental results

<table>
<thead>
<tr>
<th>Level</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28.00</td>
<td>27.35</td>
<td>29.83</td>
</tr>
<tr>
<td>2</td>
<td>28.81</td>
<td>29.77</td>
<td>28.74</td>
</tr>
<tr>
<td>3</td>
<td>30.56</td>
<td>30.54</td>
<td>28.53</td>
</tr>
<tr>
<td>Delta</td>
<td>2.56</td>
<td>3.19</td>
<td>1.30</td>
</tr>
<tr>
<td>Rank</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Percentage (%)</td>
<td>36.31</td>
<td>45.25</td>
<td>18.44</td>
</tr>
</tbody>
</table>
Optimization of the Brake Parameter for a Disc Brake System to Improve the Heat Dissipation using Taguchi Method

Figure 2 Graphs of signal-to-noise ratio versus factor values level respectively to parameters

The smaller-the-better quality characteristics had brought the meaning stated that better heat dissipation performance was associated with higher value in signal-to-noise ratio. The number of slots (P2) was having the highest value, which ranked the first place in heat dissipation performance. The slot ventilation feature in the disc brake rotor design acted as the channel that enhanced the effect of centrifugal force that “threw away” the heat during rotating. The number of rotor holes ranked the second while the diameter of rotor holes ranked the least in heat dissipation performance. This meant that enlarging of ventilation hole did not provide an effective influence on the heat transfer of disc brake rotor.

In overall, all data pointed that disc brake rotor prototype sample with twenty-four 4mm diameter holes, six slots (P1-24, P2-6, P3-4) was the optimum design out of all nine combinations and number of slots was the most significant parameter. This analysis had matched and confirmed the results that obtained from the mean analysis. Therefore, the optimum design had been carried on with confirmation experiment for results verification.

4.3. Confirmation Experiment

The optimum design of disc brake rotor prototype sample with twenty-four 4mm diameter holes and six slots (P1-24, P2-6, P3-4) had been further verified through the confirmation experiment, which recommended in Taguchi method to verify the experiment data. Table 6 showed the experimental results obtained from the confirmation experiment.

<table>
<thead>
<tr>
<th>Number of rotor holes (P1)</th>
<th>Number of slots (P2)</th>
<th>Diameter of rotor holes (P3)</th>
<th>S/N ratio</th>
<th>Predicted result</th>
<th>Experimental result</th>
<th>Result difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>6</td>
<td>4</td>
<td>33.15</td>
<td>0.022°C/s</td>
<td>0.023°C/s</td>
<td>4.35%</td>
</tr>
</tbody>
</table>

The optimum design of the disc brake rotor did show a great result in heat dissipation performance. Less than 5% of result difference between the predicted result and actual experimental result was obtained, which proved the data accuracy and the effectiveness of the Taguchi method. Data obtained through the experiments had been verified and confirmed. Also, disc brake rotor with twenty-four 4mm diameter rotor holes and six ventilation slots (P1-24, P2-6, P3-4) had been confirmed as the optimum design to improve heat dissipation performance through the confirmation experiment.
5. CONCLUSIONS

The testing rig was successfully stimulated the vehicle braking process and differentiate clearly on heat dissipation performance of each prototype sample. Optimum ventilation design and most significant parameter in heat dissipation performance for disc brake rotor had successfully been identified through the experiments by using the testing rig.

It was proved that disc brake rotor with twenty-four 4mm diameter holes and six slots (P1-24, P2-6, P3-4) was the optimum design with heating rate as low as 0.022°C/s.

In addition, number of slots gave an effect at the rate of 45.25% in enhancing of heat dissipation performance in disc brake rotor followed by number of rotor holes and diameter of rotor holes that at the rate of 36.31% and 18.44% respectively. All in all, the research had been completed successfully with effective used of Taguchi method in obtaining of optimum design as well as most efficient parameter in heat dissipation performance of disc brake rotor.

REFERENCES


Optimization of the Brake Parameter for a Disc Brake System to Improve the Heat Dissipation using Taguchi Method


