DESIGN OF EXPERIMENT AND TAGUCHI METHOD APPLICATION IN ANALYSIS OF GEAR OIL PUMP FLOW CAPACITY

Ismar Alagić,
REZ-RDA Central BiH/University of Zenica, Faculty of Mechanical Engineering in Zenica, Štrosmajerova 11/3. BA-7200 Zenica, Bosnia and Herzegovina,
E-mail: ismar@rez.ba, ialagic@mf.unze.ba; alagicismar@yahoo.com

Abstract – Application of experiment planning mathematical model in industrial conditions testing of gear oil pump at company “Pobjeda”, Tešanj is shown in this paper. This paper is supplement to experimental research of gear pump flow capacity.

The experiment was conducted on a testing engine board specially designed for gear pump performances measuring. Optimizations of construction and exploitation factors are very important factor which influences on gear pumps quality and on functional utilization of these pumps. The investigation is realized under exactly established plan with using statistical methods of results treatment with application of regression analyse. The theory of experiment design through the models of the first and second order was applied here to obtain a functional relationship between following parameters: revolution speed, pressure, oil temperature and gear normal pressure angle on the one side and flow capacity on the other side.

The application of this form gives enough precisely results in practice. This paper’s goal is to show that application of design experiment is successful in solving these and similar problems. Also, the application of Taguchi method (L16 experimental plan) in industrial conditions determination of firm “Pobjeda”, Tešanj is shown in this article.

Key words: oil gear pump, experimental design, flow capacity, Taguchi method.

1. Introduction

Oil gear pumps belong in group of rotary pumps. The main characteristics of oil gear pumps are simplicity, compactness and long life over 5000 working hours.

Necessity of exactness theoretical determination of gear pump flow capacity is limited with their wide operating range and also with constant increasing capacity. Theoretical calculation of flow capacity of gear pump with external toothing is very difficult because it include influence a lot of various factors. Also, we need detailed mathematical treatment to calculate volume of gear gap.
Design of experiment and Taguchi method application in analysis of gear oil pump flow capacity

... functional relation between revolution speed, pressure, oil temperature and gear normal pressure angle, is presented. The investigation was carried out on 61319 221 type of oil gear pump. This pump is a single stage pump with following original toothing characteristics:

- Number of teeth  
- Pitch diameter  
- Root diameter  
- Base diameter  
- Tip diameter  
- Face width  
- Normal pressure angle  
- Centre distance  
- Number of teeth of meshing gear

Also, in experiment we were used gear’s with value of normal pressure angle: \( \alpha_{(II)} = 27^\circ \) and \( \alpha_{(III)} = 29^\circ \).

Theoretical value of flow capacity of oil gear pump is given by equation as follows [1]:

\[
Q = \frac{2 \cdot z \cdot b \cdot A \cdot n}{\eta \cos \left( \beta \cdot \frac{\pi}{180} \right)} 
\]

where is:
- \( z \) - Number of teeth;
- \( b \) - face width, mm;
- \( A \) - cross section of gear gap, mm\(^2\);
- \( n \) - revolution speed (rpm), min\(^{-1}\);
- \( \eta \) - efficiency of pump (in this case \( \eta = 0.8 \));
- \( \beta \) - helix angle (in this case \( \beta = 0 \)).

Experiment was performed on a testing engine board (see figure 3) specially designed for these pumps testing with small resistance.

Figure 2. Oil gear pump 61319 221 type.

Figure 3. Test engine board for testing gear pumps.

2. Experimental Design

Within experimental investigation of relationship (1) there have been assumed dependences of flow capacity (\( Q \)) upon oil pressure (\( p \)), rpm (\( n \)), oil temperature (\( t \)) and gear normal pressure angle (\( \alpha \)) in the form of regression polynomial of the first order:

\[
Y = b_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_3 + b_4 \cdot x_4 + b_5 \cdot x_1 \cdot x_2 + b_6 \cdot x_1 \cdot x_3 + b_7 \cdot x_1 \cdot x_4 + b_8 \cdot x_2 \cdot x_3 + b_9 \cdot x_2 \cdot x_4 + b_{10} \cdot x_3 \cdot x_4 + b_{11} \cdot x_1 \cdot x_2 \cdot x_3 + b_{12} \cdot x_1 \cdot x_2 \cdot x_4 + b_{13} \cdot x_1 \cdot x_3 \cdot x_4 + b_{14} \cdot x_2 \cdot x_3 \cdot x_4 + b_{15} \cdot x_1 \cdot x_2 \cdot x_3 \cdot x_4 \]  

... (2)
61319 221, and then the gear pump flow capacity will be examined. Testing the flow capacity will be performed on the test engine board, specially designed for these pumps performances measuring in the company “Pobjeda”, Tešanj, B&H.

Characteristics of test engine board are as follows: Flow indication, from 5.6 to 200 dm³ (maximum flow by section 400 dm³); Pressure indication, from 0 to 2.5 MPa; Vacuum indication, from -1 to 0 MPa; Maximum power of electric motor 70 kW; Maximum pressure loss by normal flow, to 0.1 MPa; Temperature indication, from 0 to 120 °C; Revolution speed (rpm) indication, from 100 to 4000 rpm; Force moment of variable speed hydraulic governor, 0.8 Nm; Volume of oil tank, 80 dm³.

Also, characteristics of working fluid, oil SUPER HD SL. (grade SAE 30, producer INA, Croatia), are:

Specific weight, $\gamma=0.898$ kg/dm³; Viscosity by 50 °C, $\nu=65$ mm²/s; Viscosity index, IV=95; Flash point by Marcusson, 200° C; Freezing point by ASTM, -20° C [2].

Table 1. Levels of model factor in natural and coded values.

<table>
<thead>
<tr>
<th>FACTOR</th>
<th>Lower level</th>
<th>Basic level</th>
<th>Upper level</th>
<th>Interval of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>pressure</td>
<td>p, 10⁻¹ MPa</td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>$x_1$</td>
<td>-1</td>
<td>0</td>
<td>+1</td>
<td></td>
</tr>
<tr>
<td>rpm</td>
<td>n, min⁻¹</td>
<td>1000</td>
<td>1750</td>
<td>2500</td>
</tr>
<tr>
<td>$x_2$</td>
<td>-1</td>
<td>0</td>
<td>+1</td>
<td></td>
</tr>
<tr>
<td>oil temperature</td>
<td>t, °C</td>
<td>80</td>
<td>84</td>
<td>88</td>
</tr>
<tr>
<td>$x_3$</td>
<td>-1</td>
<td>0</td>
<td>+1</td>
<td></td>
</tr>
<tr>
<td>normal pressure</td>
<td>a,</td>
<td>25</td>
<td>27</td>
<td>29</td>
</tr>
<tr>
<td>angle</td>
<td>$x_4$</td>
<td>-1</td>
<td>0</td>
<td>+1</td>
</tr>
</tbody>
</table>

In the Table 1, coded and natural values of model factor are shown, while in the same time equations of transformation are in the shape:

\[
x_i = \frac{X_i - X_{ai}}{w_i} \quad \ldots (3)
\]

where:

- $x_i$ is coded value of model factor;
- $X_i$ is natural value of model factor;
- $X_{ai}$ is basic level of model factor, and
- $w_i$ is interval of variation.

Table 2. Plan-matrix and results of investigation

<table>
<thead>
<tr>
<th>No</th>
<th>$x_0$</th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$x_3$</th>
<th>$x_4$</th>
<th>$x_5/x_2$</th>
<th>$x_6/x_4$</th>
<th>$x_7/x_4$</th>
<th>$x_8/x_4$</th>
<th>$x_9/x_2$</th>
<th>$x_9/x_4$</th>
<th>$x_{10}/x_2$</th>
<th>$x_{10}/x_4$</th>
<th>$y$</th>
<th>$\hat{y}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>131.5</td>
<td>132.332</td>
</tr>
<tr>
<td>2</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>133.8</td>
<td>134.92</td>
</tr>
<tr>
<td>3</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>47.6</td>
<td>48.72</td>
</tr>
<tr>
<td>4</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>53.7</td>
<td>54.532</td>
</tr>
<tr>
<td>5</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>133.1</td>
<td>133.932</td>
</tr>
<tr>
<td>6</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>135.1</td>
<td>136.22</td>
</tr>
<tr>
<td>7</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>51.3</td>
<td>52.42</td>
</tr>
<tr>
<td>8</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>55.5</td>
<td>55.994</td>
</tr>
<tr>
<td>9</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>147.7</td>
<td>148.82</td>
</tr>
<tr>
<td>10</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>152.0</td>
<td>151.37</td>
</tr>
<tr>
<td>11</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>56.6</td>
<td>57.432</td>
</tr>
<tr>
<td>12</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>60.3</td>
<td>61.42</td>
</tr>
<tr>
<td>13</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>149.5</td>
<td>150.62</td>
</tr>
<tr>
<td>14</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>151.6</td>
<td>152.432</td>
</tr>
<tr>
<td>15</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>57.7</td>
<td>58.532</td>
</tr>
<tr>
<td>16</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>62.3</td>
<td>63.42</td>
</tr>
<tr>
<td>17</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>99.4</td>
<td>99.57</td>
</tr>
<tr>
<td>18</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>99.8</td>
<td>99.57</td>
</tr>
<tr>
<td>19</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>102</td>
<td>99.57</td>
</tr>
<tr>
<td>20</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>98.6</td>
<td>99.57</td>
</tr>
<tr>
<td>21</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>105.4</td>
<td>99.57</td>
</tr>
<tr>
<td>22</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>103</td>
<td>99.57</td>
</tr>
<tr>
<td>23</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>104.4</td>
<td>99.57</td>
</tr>
</tbody>
</table>

Multy-factor complete orthogonal first order plan N=2⁴ + n₀, with replication in central point n₀ times is used for function form $Q = f(p, n, t, u)$.

In our case (four factors), number of replication of experiment in central point is n₀ = 7. Therefore, the number of experimental points is: N=2⁴ + n₀ = 2⁴ + 7 = 23. By regression analysis of data from the Table 2, regression model of first order in coded values has
been obtained:

\[
\hat{Y} = 99,57-1,719 x_1+42,969 x_2-0,919 x_3-5,894 x_4+0,606 x_1 x_2-0,106 x_1 x_3-0,106 x_2 x_3+0,156 x_2 x_4-2,294 x_2 x_5+0,131 x_3 x_5+0,019 x_1 x_2 x_3+0,169 x_1 x_3 x_4+0,169 x_2 x_3 x_4+0,181 x_2 x_3 x_5 x_4 
\]

…(4)

Using the transformation equations (3) and model (4) is transformed into model with natural values:

\[
Q=217,004-83,094
\]

\[
\hat{Y}=99,57-1,729
\]

\[
2,294
\]

\[
-5,89,4
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]

\[
\cdot
\]
4. Application of Taguchi method

The Taguchi method is based on statistical design of experiments and is applied at the parameter design stage to establish optimum process settings or design parameters.

The basic concept of the Taguchi Method through application example in order to determine flow capacity of gear oil pump is presented in this article. This article is supplement to experimental research of gear pump flow capacity. Combination of working pressure, revolution per speed, working oil temperature, normal pressure angle as design characteristic of gear pump and type of oil has essential influence on achievement of flow capacity as output characteristic of gear oil pump. All above five factors were used for the experiment. The experiment was carried out using a standard Taguchi’s experimental plan with denotation L16 (2^15). The S/N calculations are based on larger the better S/N ratio. The experiment was conducted on a testing board specially designed for gear pump performances measuring. Application of Taguchi method in industrial conditions determination of flow capacity of gear oil pump in company “Pobjeda”, Tešanj is shown in this article. Obtained test results are of practical importance, especially in the field of gear pumps design.

The experimental plan has two levels. There are 13 degrees of freedom regarding the number of levels of control factors and number of desired interactions between control factors. The experiment was performed according to Taguchi experimental plan with designation L_{16} (2^{15}). An orthogonal array with arranged control factors and their interaction to columns is presented in table 2. Where designations 1 and 2 mean 1st and 2nd level of each control level. According to that we have made 16 experimental runs at control factors’ level like it is determined by the orthogonal array.

<table>
<thead>
<tr>
<th>Table 3. The levels of the factors.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor</td>
</tr>
<tr>
<td>pressure, p [10^{-1} MPa]</td>
</tr>
<tr>
<td>rpm, n [min^{-1}]</td>
</tr>
<tr>
<td>oil temperature, t [°C]</td>
</tr>
<tr>
<td>normal pressure angle, α [°]</td>
</tr>
<tr>
<td>oil type (producer of oil)</td>
</tr>
</tbody>
</table>

The Larger-the-Better approach of Taguchi method has been used for analysis of experimental results. The Signal-to-Noise (S/N) ratio is calculated according to the equation:

$$\eta = S / N = -10 \log_{10} \left( \sum_{i=1}^{n} y_i^2 \right) \quad \ldots (8)$$

Each measurement of flow capacity has been repeated three times, as can be seen from table 3.

<p>| Table 4. Plan of an experiment and results based on L15 experimental plan. |
|-----------------|----------------|---------|</p>
<table>
<thead>
<tr>
<th>No</th>
<th>C</th>
<th>E</th>
<th>CxE</th>
<th>B</th>
<th>CxB</th>
<th>BxE</th>
<th>AxE</th>
<th>A</th>
<th>AxC</th>
<th>AxB</th>
<th>DxE</th>
<th>CxD</th>
<th>D</th>
<th>Measured flow capacity, Q[dm³]</th>
<th>S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
</tr>
</tbody>
</table>

Figure 5. Influence optimization of rpm and normal pressure angle (α) on flow capacity.

Figure 6. Influence optimization of rpm and pressure on flow capacity.
Control factors and their interactions are sorted in relation to the difference values. The all control factors and their interactions are shown in table 4. We can see that the strongest influence is exerted by control factors B (rpm), D (normal pressure angle) and interaction AxB. All other control factors and interactions have a weak influence on the S/N ratio of the considered flow capacity.

[Table 5: Signal-to-Noise Ratio response graphs for significant control parameters and their interactions.]

According to the table 5, we can determine which control factors and their interactions have a very strong influence on the flow capacity of the oil gear pump. Optimal input working conditions of these control factors can be very easily determined from S/N response graphs in figure 7. The best flow capacity value is at the higher S/N values in the mentioned response graphs. Expected value of S/N ratio was calculated by following expression:

\[ \eta = \overline{\sigma} + (\overline{B_1} - \overline{C_1}) + (\overline{T_1} - \overline{C_1}) + |(\overline{A_1}B - \overline{C_1}) - (\overline{A_1} - \overline{C_1}) - (B_1 - \overline{C_1})| \]

\[ \text{(9)} \]
Design of experiment and taguchi method application in analysis of gear oil pump flow capacity

\[ \eta = \bar{A_1}B_2 + \bar{D}_1 - \bar{A}_1 = 55.18 \]  

...(10)

The \( \eta \) value derived from expression (9) was used to calculate flow capacity \( Q \) according to expression:

\[ \eta = 10^{20} = 10^{55.18} = 579.78 \text{ dm}^3/\text{h} \]  

...(11)

The calculated flow capacity is 579.8 dm\(^3\)/h, this value is very close to the value calculated by expression (1) \( Q = 583.15 \text{ dm}^3/\text{h} \).

The analysis of variance ANOVA of S/N ratios is shown in figure 8.

Figure 8. Analysis of variance using QI Macros.

5. Conclusion

Based on presented experimental research and results analysis, following can be concluded:

• Systematically, by applying theory of experimental design, dependence of oil gear pump flow capacity value upon the revolution speed, pressure, oil temperature and gear normal pressure angle, has been investigated;

• Experimental investigation has been performed on a testing engine board specially designed for these pumps performances measuring in industrial conditions at company “Pobjeda”, Tesanj, Bosnia and Herzegovina;

• For the purpose of reliable predicting the flow capacity value of mentioned oil gear pump can be used experimentally obtained polynomial dependence of the first order:

\[ Q = \hat{Q} = 217.004 - 83.094p + 0.21n - 7.067\alpha + 0.001n\alpha \]  

...(12)

\[ Q = \pi bnm(d_k^2-d_f^2)10^{-6} \]  

...(13)

\[ Q = 6.5bnmz10^{-6} \]  

...(14)

\[ Q = 7bndm10^{-6} \]  

...(15)

\[ Q = \pi bna(d_k-a)10^{-6} \]  

...(16)

\[ Q = (\pi/4) bn(d_k^2-d_f^2)10^{-6} \]  

...(17)

\[ Q = 0.785 bn(d_k^2-d_f^2)10^{-6} \]  

...(18)

\[ Q = \pi bndh10^{-6} \]  

...(19)

\[ Q = 0.875 bn(d_k^2-d_f^2)10^{-6} \]  

...(20)

\[ Q = (31.4/60)bn(d_k^2-d_f^2)(1/cos\beta_0)10^{-6} \]  

...(21)

\[ Q = (\pi/2)bn[d_k^2-a^2(d_k^2/3d_f^2)]10^{-6} \]  

...(22)

\[ Q = (47/60)bn(d_k^2-d_f^2)(1/\cos\beta_o)10^{-6} \]  

...(23)

\[ Q = \frac{\pi}{2} b n [d_k^2-a^2(d_k^2/3d_f^2)]10^{-6} \]  

...(24)

\[ Q = \frac{\pi}{2} b n [d_k^2-a^2(d_k^2/3d_f^2)]10^{-6} \]  

...(25)
Design of experiment and taguchi method application in analysis of gear oil pump flow capacity

\[ Q_{\text{t}} = 2A_{\text{bnz10}} \times 10^{-6} \]  
(24)  

\[ Q_{\text{t}} = 2A_{\text{bnz10}}10^{-6} \]  
(25)  

\[ Q_{\text{t}} = 2\pi bn\{(z+1)-\left(\frac{\pi}{2}\cos\alpha/12\right)\}10^{-6} \]  
(26)  

\[ Q_{\text{t}} = 2\pi bn\{[\pi^2-r^2-m\cos\alpha]\}10^{-6} \]  
(27)  

Deviation limits between mentioned equations and obtained equation of the first order are as follows: -4% and +7%.

- Based on performed experiment, can be concluded most influence factors on flow capacity of gear oil pump are as follows:
  - design of gear, housing of pump and cover of pump;
  - radial and axial clearance;
  - type and temperature of fluid and gear tooth profile.

- The experiment has been performed on oil gear pump of type 61319 221, and because of that, stated conclusions can not be applied for the other types of these pumps, but the same methodology of design experiment can be used for other types of these pumps.

- In this article, the way of optimisation of input working characteristics in order to determine of flow capacity of oil gear pump, using the Larger-the-Better Taguchi method approach, is shown. Using the Taguchi method, the flow capacity of gear oil pump was optimised. An L16 orthogonal array was used to accommodate the experiments. Analysis of the result of experiment obtained information regarding the most influencing factors on flow capacity. The results revealed that the rpm, the normal pressure angle, and the interaction between rpm and pressure could significantly affect the flow capacity. By consideration of technical effects, the optimal levels were chosen to be A1, B2, C1, D1 and E1, corresponding to pressure of 0.2 MPa, rpm of 2500 min⁻¹, oil temperature of 80°C, normal pressure angle of 25° and oil type of INA producer.

Finally, it can be concluded that according to the experimental results, Taguchi method approach used for determination of flow capacity of oil gear pump, makes possible to obtain good quality of pump output characteristic, which is very close to the value calculated by theoretical expression (1).

6. References


