Taguchi versus Full Factorial Design to Determine the Influence of Process Parameters on the Impact Forces Produced by Water Jets Used in Sewer Cleaning

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Abstract. The regular cleaning of the materials deposited in sewer networks is realized, especially with equipment that uses high pressure water jets. The functioning of this equipment is dependent on certain process parameters that can vary, causing variations of the impact forces. The impact force directly affects the cleaning of sewer systems. In order to determine the influence of the process parameters on the impact forces produced by water jets the method of research used is the experiment. The research methods used is that Taguchi design and full factorial design. For the experimental determination of the impact forces a stand for generating water jets and a device for measuring the forces of impact are used. The processing of data is carried out using the Software Minitab 17.

1. Introduction

Industrial cleaning is a classic application of water jets technology. In the late 1950s, when reliable high pressure pumps were built, the usage of water jets spread widely in the field of pipes and sewerage cleaning. Phenomena that occur in the cleaning water jets are complex. Adler [1] describes mechanisms occurring at the impact of a jet with a surface. Leach et al [2], Leu et al [3] and Guha et al [4] analyzed pressure distribution along centreline of the water jet. A number of papers have studied the influence of nozzle geometry on water jet [5,6,7].

The aim of the current paper was to determine the influence of the process parameters on the impact forces produced by waterjets. For determine the influence of the process parameters are used two research methods: Taguchi design and Full factorial design. In order to measure the impact forces between the water jet and a flat and rigid surface, we designed and built a stand for generating pressure jets, as well as a device to measure the impact force.

2. Apparatus used and methodology of the measurements

In order to measure the impact forces between the water jet and a flat and rigid surface, we designed and built a stand for generating pressure jets, as well as a device to measure the impact force.

2.1. Stand to generate pressure jet

Schematic diagram of the stand to generate pressure jet is shown in figure 1.
Component parts of stand: (1) electric motor (2) flexible coupling; (3) high pressure pump, 4) pressure regulator, 5) pressure gauge, 6) nozzle, 7) tap water, 8) water tank, 9) chassis.

Water coming out of the high pressure pump (3) goes into the pressure regulator (4). Through it adjusts the pressure and flow of water in the path of the high pressure water. This pressure corresponds to the one at the outlet of nozzle.

2.2. Device for the measurement of the impact force
In figure 2 is represented the principle diagram of the device for the measurement of the impact force of the water jet and a flat and rigid surface.

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Main component parts of the device are: 1) high-pressure hose, 2) support nozzle, 3) nozzle block, 4) nozzle, 5) water jet, 6) flat and rigid target plate, 7) collection path water, 8) scaled container for measurement of the flow of water jet, 9) piezoelectric sensor mounting, 10) piezoelectric sensor, 11) data acquisition Personal Daq3000, 12) computer for the processing of data; 13) support plate, 14) acrylic tube, 15) rods for adjusting distance x.
From high pressure water hose (1) come water at a certain pressure $p$ desired. At the outlet of nozzle is generated a water jet (5) that striking target plate (6), who is located at a certain distance $x$ in front of the nozzle. The jet (5) generates an impact force at a time when he meets target plate (6). This force produces axial movement of target plate. This movement is converted into an electric signal by the piezoelectric sensor (10). Electrical signal is collected by data acquisition Personal Daq/3000 (11), which forward data to a computer (12) using DaqView soft processes data actually obtained.

2.3. Process parameters and geometric configuration of nozzles
In the water jet cleaning process involved a series of parameters [8]. These parameters can be divided into two major groups, namely: 1) Parameters which shall be defined according to the contact area between the water jet and the surface to be cleaned and 2) the process parameters. In the measurement of the impact forces of a stationary water jet and flat and rigid surface the process parameters involved (figure 3).

They can be divided into two groups, namely hydraulic parameters and the performance parameters. Hydraulic parameters characterized the system high pressure pump-nozzle are represented by work pressure ($p$), volume flow ($Q$) and nozzle diameter ($D$).

The performance parameters refer to the process of cleaning itself, and are the following:
1) The diameter $D$ of nozzle. The values used are $D=1$ mm, $1.5$ mm and $2$ mm. The material for nozzles is stainless steel. Geometric configuration of the nozzles used is shown in figure 4.
2) The pressures $p$ used to perform the measurements have the values $p=100$ bar, $p=120$ bar, $p=140$ bar, $p=160$ bar, $p=180$ bar and $p=200$ bar.
3) Cleaning distance $x$ (distance from nozzle to target plate). To perform the measurements distance $x$ has been fixed at the values $x=25$ mm, $x=50$ mm, $x=75$ mm, $x=100$ mm, $x=125$ mm, $x=150$ mm, $x=175$ mm, $x=200$ mm.
4) $\alpha$ – impact angle (the angle formed by jet with the target plate); in this work $\alpha = 60^\circ$, $75^\circ$ and $90^\circ$.

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3. Results
For determine the influence of the process parameters are used two research methods: Taguchi design and Full factorial design.

3.1. Taguchi method
In table 1 are presented the values of the used parameters for Taguchi method.

For Taguchi method, each parameter has 2 values, the minim and the maxim, in concordance with the experimental domain.
In table 1 are presented the values of parameters for Taguchi method.

| Parameter          | Value 1 (minimum) | Value 2 (maximum) |
|--------------------|-------------------|-------------------|
| Nozzle diameter D [mm] | 1                 | 2                 |
| Pressure p [bar]   | 100               | 200               |
| Impact angle α [°] | 60                | 90                |
| Distance x [mm]    | 25                | 200               |

Based on the parameters established in accordance with Table 1 the impact forces in Table 2 were determined. For each experiment was performed three measures of impact force and still it has worked with F_med, representing the arithmetic average of the three forces measured.

| Experiment no | Parameters          | Impact force F [N] |
|---------------|---------------------|--------------------|
|               | Diameter D [m]      | 1                  |
| 1             | 1                   | 100                |
| 2             | 1                   | 200                |
| 3             | 1                   | 200                |
| 4             | 1                   | 200                |
| 5             | 1                   | 100                |
| 6             | 1                   | 100                |
| 7             | 1                   | 200                |
| 8             | 1                   | 200                |
| 9             | 2                   | 100                |
| 10            | 2                   | 100                |
| 11            | 2                   | 200                |
| 12            | 2                   | 200                |
| 13            | 2                   | 200                |
| 14            | 2                   | 100                |
| 15            | 2                   | 200                |
| 16            | 2                   | 200                |

| Source       | DF (degree of freedom) | SS (sum of square) | Contribution |
|--------------|------------------------|--------------------|--------------|
| Regression   | 10                     | 9897,72            | 99.76%       |
| Diameter     | 1                      | 6387,61            | 64.38%       |
| Pressure     | 1                      | 2253,08            | 22.71%       |
| Distance     | 1                      | 53,12              | 0.54%        |
| Angle        | 1                      | 281,91             | 2.84%        |
| Diameter*Pressure | 1       | 757,39            | 7.63%    |
| Diameter*Distance | 1       | 7,72             | 0.08%    |

On the basis of the data in table 2 and using the method Taguchi has conducted an analysis of the variance to determine the influence of each parameter and their interactions on the impact force. In Table 3 is presented the analysis of the variance, using Minitab 17.
Table 3. Analysis of Variance (Taguchi method). (continued)

| Source                  | DF (degree of freedom) | SS (sum of square) | Contribution |
|-------------------------|------------------------|--------------------|--------------|
| Diameter*Angle          | 1                      | 103.67             | 1.04%        |
| Pressure*Distance       | 1                      | 7.02               | 0.07%        |
| Pressure*Angle          | 1                      | 42.01              | 0.42%        |
| Distance*Angle          | 1                      | 4.20               | 0.04%        |
| Error                   | 5                      | 23.58              | 0.24%        |
| Total                   | 15                     | 9921.29            | 100.00%      |

Based on table 3 (using Taguchi method) results the contribution of the parameters and their interactions on the impact force $F$:
- nozzle diameter $D$, with a percentage of influence of 64.38%;
- pressure $p$, with a percentage of influence of 22.71%;
- interaction between nozzle diameter $D$ and pressure $p$, with a percentage of influence of 7.63%;
- impact angle $\alpha$, with a percentage of influence of 2.84%.

The distance parameter and all the other interactions have a value less than 1.04%.

3.2. Full factorial method

In table 4 are presented the values of the used parameters for Full factorial method.

Table 4. The values of the parameters for Full factorial method.

| Parameter       | Values                                      |
|-----------------|---------------------------------------------|
| Nozzle diameter $D$ [mm] | 1, 1.5, 2 |
| Pressure $p$ [bar]          | 100, 120,140,160,180,200                   |
| Impact angle $\alpha$ [$^\circ$] | 60, 75, 90 |
| Distance $x$ [mm]          | 25, 50,75,100,125,150,175,200              |

Taking into account that there are four parameters, the number of values which they take each of them and using the Full factorial design results a number of 143 experiments. Just like in the case of Taguchi method, for each experiment have carried out a number of three measurements to determine the impact force. As a result there are a number of 432 measurements. With this in mind, for brief of this paper, we dare not to present the table with the values obtained.

Using the Full factorial method has conducted an analysis of the variance to determine the influence of each parameter and their interactions on the impact force. In Table 5 is presented the analysis of the variance, using Minitab 17.

Table 5. Analysis of Variance (Full factorial method).

| Source                  | DF (degree of freedom) | Seq. SS (sum of square) | Contribution |
|-------------------------|------------------------|-------------------------|--------------|
| Regression              | 10                     | 162559                  | 99.14%       |
| Diameter                | 1                      | 116939                  | 71.32%       |
| Pressure                | 1                      | 29592                   | 18.05%       |
| Distance                | 1                      | 389                     | 0.24%        |
| Angle                   | 1                      | 5959                    | 3.63%        |
| Diameter*Pressure       | 1                      | 7596                    | 4.63%        |
| Diameter*Distance       | 1                      | 148                     | 0.09%        |
| Diameter*Angle          | 1                      | 1523                    | 0.93%        |
| Pressure*Distance       | 1                      | 20                      | 0.01%        |
Table 5. Analysis of Variance (Full factorial method). (continued)

| Source          | DF (degree of freedom) | Seq. SS (sum of square) | Contribution |
|-----------------|------------------------|-------------------------|--------------|
| Pressure*Angle  | 1                      | 385                     | 0.24%        |
| Distance*Angle  | 1                      | 5                       | 0.00%        |
| Error           | 421                    | 1406                    | 0.86%        |
| Total           | 431                    | 163965                  | 100.00%      |

Based on table 5 (using Full factorial method) results the contribution of the parameters and their interactions on the impact force $F$:
- nozzle diameter $D$, with a percentage of influence of 71.32%;
- pressure $p$, with a percentage of influence of 18.05%;
- interaction between nozzle diameter $D$ and pressure $p$, with a percentage of influence of 4.63%;
- impact angle $\alpha$, with a percentage of influence of 3.63%.

The distance parameter and all the other interactions have a value less than 0.93%.

4. Conclusions

In table 6 is presented the contribution of the parameters and their interactions on the impact force $F$, using Taguchi method and Full factorial method.

Table 6. Contribution of parameters and their interactions (Taguchi versus Full factorial).

| Source          | Taguchi method | Full factorial method | The difference |
|-----------------|----------------|-----------------------|---------------|
| Regression      | 99.76%         | 99.14%                | 0.62%         |
| Diameter        | 64.38%         | 71.32%                | 6.94%         |
| Pressure        | 22.71%         | 18.05%                | 4.66%         |
| Distance        | 0.54%          | 0.24%                 | 0.3%          |
| Angle           | 2.84%          | 3.63%                 | 0.79%         |
| Diameter*Pressure| 7.63%         | 4.63%                 | 3%            |
| Diameter*Distance| 0.08%        | 0.09%                 | 0.01%         |
| Diameter*Angle  | 1.04%          | 0.93%                 | 0.11%         |
| Pressure*Distance| 0.07%         | 0.01%                 | 0.06%         |
| Pressure*Angle  | 0.42%          | 0.24%                 | 0.16%         |
| Distance*Angle  | 0.04%          | 0.00%                 | 0.04%         |
| Error           | 0.24%          | 0.86%                 | 0.62%         |
| Total           | 100.00%        | 100.00%               | 0.00%         |

Based on the results of experimental work presented in this paper it is found that:
1) Regardless of the method used (Taguchi or full factorial) the classification of parameters and their interactions in the order of importance is the same:
   - The most important parameter is the diameter of the nozzle, with a percentage of influence of 64.38% for Taguchi method and 71.32% for Full factorial method;
   - The second parameter is the pressure of water jet, with a percentage of 22.71% for Taguchi method and 18.05% for full factorial method;
   - The third parameter is the impact angle, with a percentage of 2.84% for Taguchi method and 3.63% for Full factorial method;
   - The distance parameter, with a percentage of 0.54% for Taguchi and 0.24% for Full factorial method is virtually insignificant;
   - Between interactions only diameter and pressure have an important contribution with 6.63% for Taguchi method and 4.63% for Full factorial method;
- All other interactions that have a low importance in both cases (Taguchi and Full factorial methods).
2) In the both cases, for our experimental domain, the distance parameter have an insignificant value.
3) Although between the two cases there are differences between the calculated values, the order of importance of the parameters and their interactions is the same. But for Taguchi method were carried out 48 measurements while for full factorial were carried out a number of 432 measurements.

The final conclusion: is more convenient to make a research using Taguchi method to determine the influence of the parameters and the interactions between them, because the number of measurements is significantly less than in the case of the full factorial method.

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