Optimizing the Equation of Impact Forces Produced by Water Jets Used in Sewer Cleaning

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Abstract: *The purpose of this paper is to optimize the equation of the impact forces produced by water jets used in sewer cleaning. The functioning of the cleaning sewer is dependent on certain process parameters, which can vary, causing variations of the impact forces. The research method used is Taguchi design of experiment. To be able to make the experiments there was used a stand to generate the water jets and a device to measure the impact forces. In the first part of paper was determined the percentage of influence of parameters involved in the process and then there was developed a multiple linear regression model in three different ways to optimize the prediction of the proposed equation.*

Keywords: *Impact force, water jet, Taguchi method, multiple linear regression model*

1. Introduction

Industry water jet technology is frequently used in a lot of areas such as: concrete hydro demolition, jet cutting for different type of materials, mechanical processing of minerals, medical applications, rock fragmentation, and surface preparation for protective coatings [1].
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 [2] describes mechanisms occurring at the impact of a jet with a surface. Leach et al [3], Leu et al [4] and Guha et al [5] analyzed pressure distribution along centreline of the water jet. Several papers have studied the influence of nozzle geometry on water jet [6, 7].
The regular cleaning of the materials deposed 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 [1] that can vary, causing variations of the impact forces. The impact forces directly affect the cleaning of sewer systems.
To determine an equation who described the values of impact forces in concordance with the process parameters is necessary to realised practical experiments to determine the values of impact forces for different set-up values of process parameters [8].
Using the data obtained there can be determined linear regression model to describe the process studied. In some cases, it is indicated to optimise the regression [9].
In this paper, the research method used is Taguchi design of experiments [10]. After determining impact forces, in concordance with the experimental domain set-up, was determined a linear regression model and this regression model was optimised to increase the degree of prediction for this model.

2. Apparatus used and methodology of the measurements

To measure the impact forces produced by water jet, were used and built a stand for generating pressure jets, as well as a device to measure the impact force [8].

2.1 Stand to generate pressure water jets

Schematic diagram of the stand to generate pressure jet is shown in figure 1.

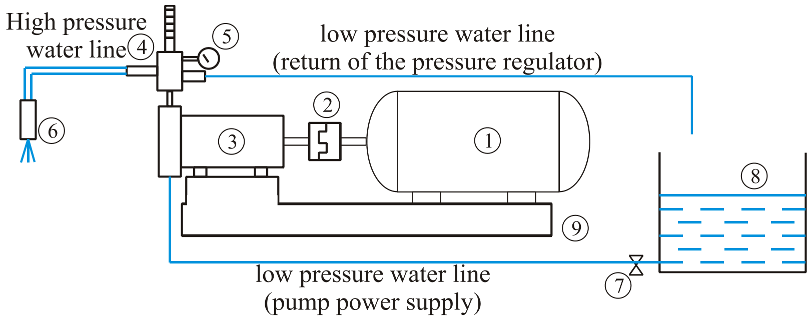

Fig. 1. Schematic diagram of the stand to generate pressure jet

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 measurement the impact forces

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

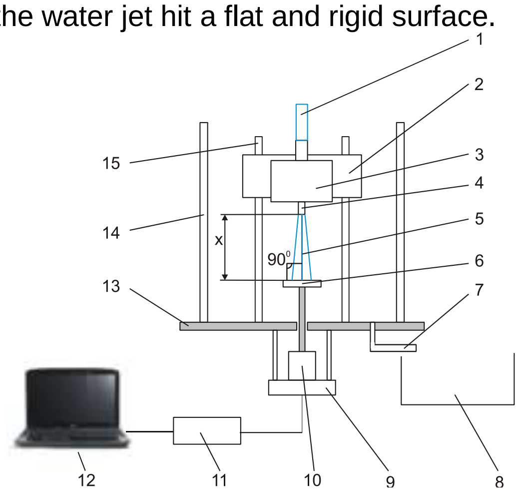

Fig. 2. Diagram of the device for measuring the impact force of the water jet

Main component parts of the device are: 1) high-pressure water 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 Daq/3000, 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) there comes 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 Methodology of the measurements

The research method of this study is the experiment. To determine the values of impact forces produced by water jets is used the Taguchi method. To determine the impact forces, it is necessary to set up the experimental domain.
In the water jet cleaning process a series of parameters are involved [1]. These parameters can be divided into two major groups, namely: 1) target parameters which shall be defined according to

the contact area between the water jet and the surface to be cleaned and 2) process parameters. In the measurement of the impact forces of a stationary water jet and flat and rigid surface the process parameters are involved (figure 3).

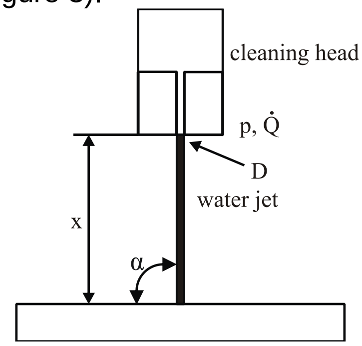

Fig. 3. Process parameters

Setting up the experimental domain:
The process parameters that influence the impact force are: 1) D nozzle diameter, [mm]; 2) P water pressure, [bars]; 3) x distance between the nozzle and impact surface, [mm]; 4) α impact angle (angle formed by the jet and impact surface), [^{0}].
The value of diameter of nozzle are D=1mm, 1.5mm and 2mm. These are common values used in equipment to maintenance and cleaning of sewers.
The pressures used to perform the measurements have the values p=100 bars, 120bars, 140bars, 160bars, 180bars and 200bars. For the maintenance sewers, are used high pressure water pumps which generate a maximum pressure of 200 bars.
To perform the measurements distance x has been fixed at the values x=25 mm, 50 mm, 75 mm, 100 mm, 125 mm, 150 mm, 175 mm and 200 mm.
The impact angle α has values 60^0, 75^0 and 90^0. For cleaning heads, usual value of the angle of impact α is 75^0. If impact angle α decrease below 60^0 lead to a drop in of the impact forces.
In table 1 are presented the process parameters and levels values according with Taguchi method.

Table 1: Process parameters and level values

Abbreviation	Parameter	Name	Value 1 minimum Notation (1)	Value 2 maximum Notation (2)
A	Parameter 1	Nozzle diameter	1mm	2mm
B	Parameter 2	Pressure	100bars	200bars
C	Parameter 3	Distance x	25mm	200mm
D	Parameter 4	Angle α	60^0	90^0

Corresponding to the 4 parameters and second degree interactions of the parameters, for Taguchi method result an orthogonal array L16 (2^4). In conclusion, it is necessary to make a plan of experiments which contains 16 experiments.

3. Results

For each of the 16 experiments (determined according to the Taguchi design of experiments) three sets of measurements of the impact force were performed. For each experiment there was determined the average force (F_{med}). The data are summarized in table 2.

Table 2: The measured force F according to the parameters set

No. of exp.	Parameters				Impact force F [N]			
	A	B	C	D	1	2	3	F_{med}
1	1	100	25	60	8.08	7.69	7.94	7.46
2	1	100	25	90	10.49	10.48	10.36	9.95
3	1	200	200	60	14.79	14.92	14.55	13.69

4	1	200	200	90	19.32	18.70	19.08	18.25
5	1	100	200	60	6.39	6.15	6.40	6.83
6	1	100	200	90	7.84	7.83	8.03	9.10
7	1	200	25	60	17.12	16.98	16.69	15.87
8	1	200	25	90	21.67	21.72	21.83	21.16
9	2	100	200	60	29.06	29.94	29.46	26.01
10	2	100	200	90	36.97	36.71	36.21	34.68
11	2	200	25	60	65.37	65.10	64.80	64.99
12	2	200	25	90	86.00	85.98	86.24	86.65
13	2	100	25	60	30.82	31.31	30.72	30.19
14	2	100	25	90	40.44	40.30	40.18	40.26
15	2	200	200	60	59.95	59.47	60.14	57.78
16	2	200	200	90	76.32	76.30	76.35	77.04

3.1 Determining the contributions of the parameters and their interactions

To calculate the contributions of parameters and their interactions we have used the data in table 2. Using the method Taguchi we have 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 (Minitab 17)

Source	DF (degree of freedom)	SS (sum of square)	Contribution
Regression	10	10008.3	99.80%
Diameter	1	6213.7	61.96%
Pressure	1	2279.1	22.73%
Distance	1	68.8	0.69%
Angle	1	344.8	3.44%
Diameter*Pressure	1	895.0	8.93%
Diameter*Distance	1	25.0	0.25%
Diameter*Angle	1	126.8	1.26%
Pressure*Distance	1	7.1	0.07%
Pressure*Angle	1	46.5	0.46%
Distance*Angle	1	1.4	0.01%
Error	5	19.7	0.20%
Total	15	10027.9	100.00%

From table 3 can be seen only 3 parameters and 2 interactions have a significant contribution to the values of impact forces for experimental domain established: diameter D, pressure p, angle α, interaction between diameter D and pressure p and interaction between diameter D and angle α.

3.2 Determining the regression equation of impact forces

According to the results obtain in table 3, the next step is to determine the equation of the impact forces using only the parameters and interactions previously set.
Using Minitab 17, the multiple linear regression model of impact forces for Taguchi method was determined (equation 1):

$$F_{med} = 23.9 - 33.6 \cdot A - 0.2101 \cdot B - 0.254 \cdot D + 0.2992 \cdot A \cdot B + 0.375 \cdot A \cdot D \quad (1)$$

This multiple linear regression model was obtaining without Box-Cox transformation.
In table 4 is presented the analysis of variance of equation (1).

Table 4: Analysis of Variance for equation 1

Source	DF (degree of freedom)	SS (sum of square)	Contribution
Regression	5	9859.4	98.32%
Diameter	1	6213.7	61.96%

Pressure	1	2279.1	22.73%
Angle	1	344.8	3.44%
Diameter*Pressure	1	895.0	8.93%
Diameter*Angle	1	126.8	1.26%
Error	10	168.5	1.68%
Total	15	10027.9	100.00%

The regression statistics of equation (1) are: R squared: 98.32%, R squared adjusted: 97.48% and R squared predicted: 95.70%.
To optimise the equation (1), the next step is to be made a regression using Box-Cox transformation with rounded λ. Result the equation (2):

$$ln(F_{med}) = -0.646 + 1.311 \cdot A + 0.00668 \cdot B + 0.00958 \cdot D \quad (2)$$

In table 5 is presented the analysis of variance of equation (2).

Table 5: Analysis of Variance for equation 2

Source	DF (degree of freedom)	SS (sum of square)	Contribution
Regression	5	10.40	99.73%
Diameter	1	7.79	74.47%
Pressure	1	2.27	21.71%
Angle	1	0.33	3.16%
Diameter*Pressure	1	0.003	0.03%
Diameter*Angle	1	0.000	0.00%
Error	10	0.066	0.63%
Total	15	10.47	100.00%

The regression statistics of equation (2) are: R squared: 99.37%, R squared adjusted: 99.06% and R squared predicted: 98.39%.
Another possible optimisation of equation (1) is realised made a regression using Box-Cox transformation with λ=0.5. There results the equation (3):

$$(F_{med})^{0.5} = 0.28 + 0.08 \cdot A - 0.00209 \cdot B - 0.0003 \cdot D + 0.01469 \cdot A \cdot B + 0.01706 \cdot A \cdot D \quad (3)$$

In table 6 is presented the analysis of variance of equation (3).

Table 6: Analysis of Variance for equation 3

Source	DF (degree of freedom)	SS (sum of square)	Contribution
Regression	5	71.44	99.12%
Diameter	1	50.78	70.47%
Pressure	1	15.92	22.09%
Angle	1	2.30	3.20%
Diameter*Pressure	1	2.15	3.00%
Diameter*Angle	1	0.26	0.36%
Error	10	0.63	0.88%
Total	15	72.07	100.00%

The regression statistics of equation (3) are: R squared: 99.12%, R squared adjusted: 98.68% and R squared predicted: 97,75%.
In table 7 are presented the regression statistics for all of three equation determined.

Table 7: Regression statistics for all 3 equations

Type of regression	Equation no.	R squared	R squared adjusted	R squared predicted
without transformation	(1)	98.32%	97.48%	95.70%

rounded λ transformation	(2)	99.37%	99.06%	98.39%
λ=0.5 transformation	(3)	99.12%	98.68%	97.75%

4. Conclusions

1) In this work, it is presented a methodology to determine the impact forces produced by water jets used in sewer cleaning. The impact forces dependent on certain process parameters.
2) The research method used is Taguchi design of experiment. After applying Taguchi itinerary for calculating the percentage of influence of parameters and their interactions of the impact forces, it is found:
- nozzle diameter D is the largest influence, with a percentage of 61.96%;
- in the second place is pressure P with a value of 22.73%;
- interaction between nozzle diameter D and pressure p with a value of 8.93%;
- the impact angle α with a value of 3.44%;
- interaction between nozzle diameter D and impact angle α with a value of 1.26%.

3) For the experimental domain, the parameter distance x has a percentage of influence of only 0.69% for impact forces, virtually insignificant.
4) According with the influence of parameters and their interactions, was realised a multiple linear regression model in three different ways to optimise the prediction of the proposed equation:
- first type regression without transformation with R squared predicted 95.70%;
- second type regression using rounded λ transformation with R squared predicted 98.39%;
- third type regression using λ=0.5 transformation with R squared predicted 97.75%.

5) The best prediction is given by the regression using rounded λ transformation, followed by the regression using λ=0.5 transformation. The lowest degree of prediction is given by the regression without transformation.
6) It can be observed that it is possible to improve the prediction of the equation who describe the impact forces only using different type of regression and using the same measured values of the impact forces.

References

[1] A. W. Momber, “Hydroblasting and Coating of Stell structures”, Oxford: Elsevier Ltd, 2003;
[2] W. F. Adler, “The Mechanics of Liquid Impact. Treatise on Materials Science and Technology”, 1979. pp. 127-183;
[3] S. J. Leach, G. L. Walker, “Some Aspects of Rock cutting by High Speed Water Jets”, Philosophical Transactions of the Royal Society of London, Series A, Vol. 260, pp. 295-308, July 1966;
[4] M. C. Leu, P. Meng, E. S. Geskin, L.Tismeneskiy, “Mathematical modelling and experimental verification of stationary waterjet cleaning process”, Journal of Manufacturing Science and Engineering, 120(3), 1998, 571-579;
[5] A. Guha, R. M. Barron, R. Balachandar, “An Experimental and Numerical Study of Water Jet Cleaning Process”, Journal of Materials Processing Technology, pp. 610-618, 2011;
[6] M. Annoni, L. Cristaldi, M. Faifer, M. Norgia, ”Orifice Coefficients Evaluation for Water Jet Application”, Sept. 22-24, 2008, Florence, Italy, 16th IMECO TC4 Symposium, ”Exploring New Frontiers of Instrumentation and Method for Electrical and Electronic Measurement”, pp. 761-766;
[7] S. Dimitrov, S. Simeonov, S. Cvetkov, ”Static Characteristics of the Orifices in a Pilot Operated Pressure Relief Valve”, “Hidraulica” (No. 2/2015) Magazine of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatronics, ISSN 1453 – 7303, pp.35-39;
[8] N. Medan, S. Ravai Nagy, ” Determining the Equation of the Impact Forces Produced by Water Jets Used in Sewer Cleaning”, Innovative Manufacturing Engineering & Energy International Conference 2015 (IMANEE 2015), Applied Mechanics and Materials Vol. 809-810 (2015), pp. 1579-1584;
[9] M. Rusănescu, A. Purcărea, ” Validation of a Multiple Linear Regression Model”, “Hidraulica” (No. 4/2015) Magazine of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatronics, ISSN 1453 – 7303, pp. 66-70;
[10] D.C. Montgomery, “Design and analysis of experiments”, 8th edition, Wiley, 2013.