INNOVATIVE APPROACH TO ADVANCED MODULATED WATERJET TECHNOLOGY

Milena Kušnerová, Josef Foldyna, Libor Sitek, Jan Valíček, Sergej Hloch, Marta Harničárová, Milan Kadnár

Original scientific paper

The paper examines an analytical model of modulated pulses of a high-speed waterjet with a base frequency for waterjet technology. It required laboratory measurements of fundamental oscillations frequency, its prediction and verification. A hydrodynamic system generates a modulated liquid jet at a certain pressure due to a resonant chamber being integrated into the system. The theoretical model was developed particularly on the basis of a set of dimensions and the used liquid pressure which represent the system. A significant performance improvement was achieved in surface disintegration of material being machined.

Keywords: modulated waterjet, analytical model, resonance chamber

Inovativni pristup naprednoj moduliranoj tehnologiji vodenog mlaza

Izvorni znanstveni članak

U radu se ispituje analitički model moduliranih impulsa vodenog mlaza velike brzine s osnovnom frekvencijom za tehnologiju vodenog mlaza. Za to su bila potrebna laboratorijska mjerenja osnovne frekvencije oscilacija, njeno predviđanje i verifikacija. Hidrodinamički sustav generira modulirani vodeni mlaz kod određenog tlaka zbog rezonantne komore ugrađene u sustav. Teorijski model je naime razvijen na osnovi niza dimenzija i primijenjenog tlaka tekućine koji predstavljaju sustav. Postignuto je značajno poboljšanje kod dezintegracije površine obrađivanog materijala.

Ključne riječi: modulirani vodeni mlaz, analitički model, rezonantna komora

1 Introduction

In the last century, a waterjet technology infiltrated many application areas [1] such as cutting, drilling, turning, milling, surface cleaning, or removal of surface layers as well as repair of concrete structures. This technology is often being used for disintegration of all common and modern technical materials, producing relatively smooth surfaces. The cutting performance can be significantly improved by adding abrasive particles into the stream of high-speed water. Despite the advantages, the waterjet technology shows some limitations for its use [2, 3, 4]. One of the main reasons is that the performance of waterjets is not competitive with existing conventional mechanical systems [5 ÷ 8]. The widespread use of waterjet technology is dependent on a substantial improvement in efficiency and cutting performance. One way to increase efficiency is the use of acoustic pressure, which helps to increase the hydrodynamic pressure [9]. This paper is devoted in part to a discussion of certain theoretical aspects and results of measurement for disintegration of materials with the modulated water jet. Experimental data were obtained from measurements and a comparison was made between experimentally measured and theoretically predicted values of the fundamental frequencies of oscillation of the liquid jet.

2 Current state of problem

A process of generating high-frequency pressure pulsations in liquid via high-pressure system is one of the possibilities to increase the effectiveness of waterjet technology for removal of surface layers or cleaning applications and also for other applications. This is because the waterjet exiting the nozzle is continuous, but it has a variable axial velocity component as a result of pressure modulations. At a certain distance from the nozzle, this originally continuous waterjet breaks-up into the individual water "bunches" and the jet begins to behave as the modulated jet. A cutting ability of such modulated jet significantly increases due to the fact that impact pressure generated by the impact of water "bunch" on the material being disintegrated is considerably higher than the stagnation pressure generated by the impact of continuous jet of the same parameters [10, 11, 12]. A concept of integration of Helmholtz resonators into aerodynamic systems is well known in the physical (acoustic) literature. Occasionally, some journals paid attention to the practical usage of resonant cavities also used in hydrodynamic systems. The modulated liquid flow is presented by various authors [13, 14]. However, this topic has not yet been completely processed and optimized by calling attention to a point, so that its application relates only to specific pressures and relatively small geometric elements of the hydrodynamic acoustic system elements. As a result, it is essential to complete steps needed to achieve the goal of determination of the analytical model for the fundamental oscillation frequency of hydrodynamic flow in the oscillating system that can theoretically be solved only within the reliably measured input parameters. A basic setup for modulation of the waterjet using the principle of the hydrodynamic oscillating system is presented in Fig. 1, where E_k – kinetic energy (J), E_p – potential energy (J), m_w – water mass flow (l/min), m_v – air mass flow (l/min), b – material thickness (mm), z – standoff distance (mm), φ – angle attack (°), v – speed of head (mm/min), p – liquid pressure from 5 MPa to 25 MPa, r_p – radius of supply lateral tube (mm), l_p – length of supply lateral tube (mm), r_{hVK} – radius of upper part of the entry chamber (mm), l_{hVK} – length of upper part of the entry chamber (mm), r_{dVK} – radius of lower part of the entry chamber (mm), l_{dVK} – length of lower part of the entry chamber (mm), r_H – radius of connecting neck of resonant chamber (mm), l_H – length of connecting neck of resonant chamber (mm), r_K – radius of resonant chamber (mm), l_K – length of resonant

chamber (mm), r_{VT} – radius of exit tube (mm), l_{VT} – length of exit tube (mm) and r_0 – radius of nozzle (mm).
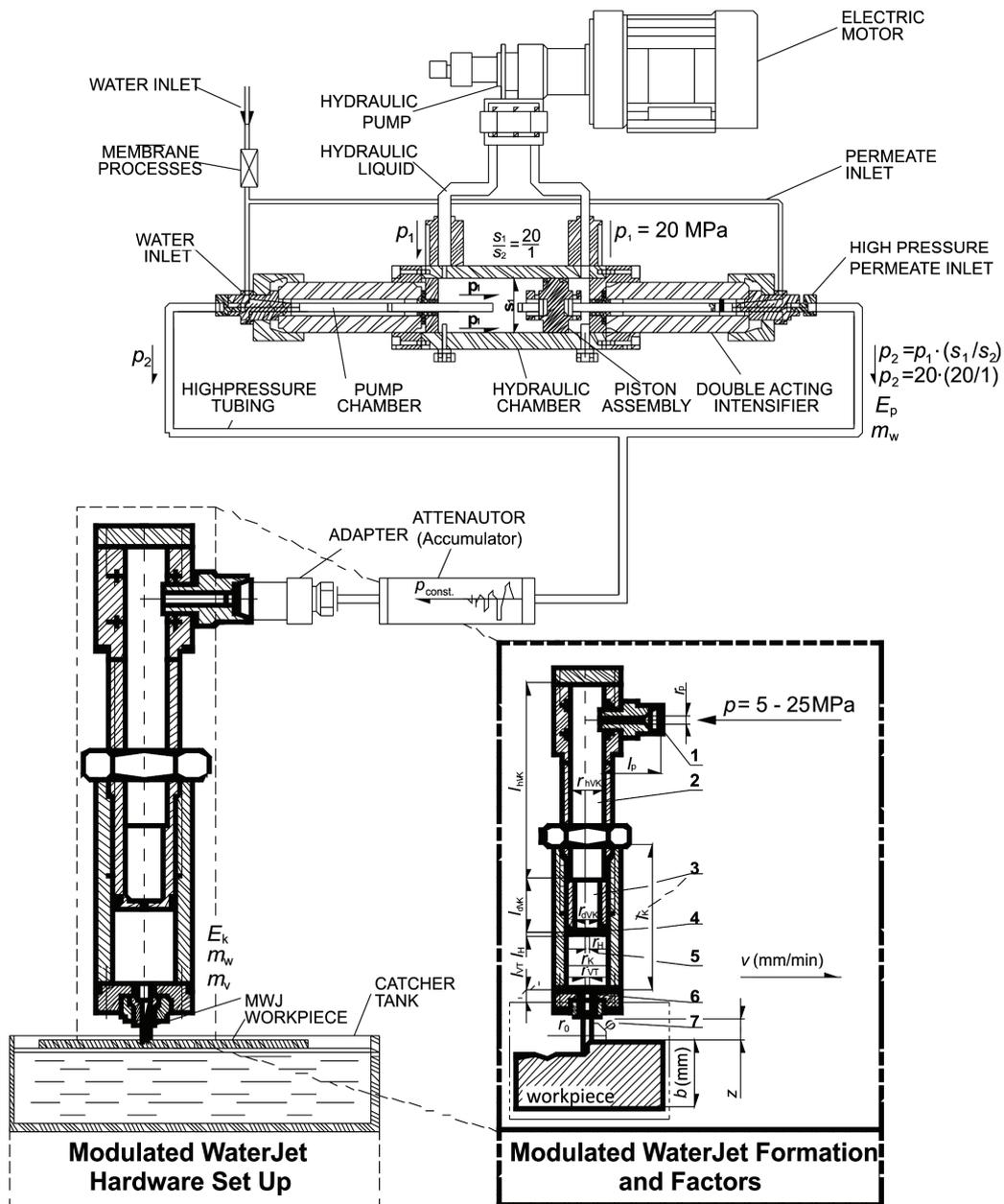

Figure 1 Modulated waterjet technology set up with the cutting head based on hydrodynamic oscillating system

3
Experiments

A hydrodynamic flow system generates a continuous water jet, which is used for disintegration of the material. The system consists of two major parts, i.e. elements: cylindrical chambers (positions 2 and 3 in Fig. 1) and cylindrical tubes (positions 1, 6 and 7 in Fig. 1). A schematic diagram of the hydrodynamic oscillating system is shown in Fig. 1. Water is forced into the system by a plunger pump (at a certain pressure ranged from 5 MPa to 25 MPa), enters an inlet chamber (1) through a flow - pipe. This chamber consists of an upper (2) and a lower (3) part. Water exits the system through an output tube, which may be a specially modified nozzle (6, 7) with regard to the application needs (cutting or surface cleaning). If a resonant chamber (5) with an entry tube

(4) is integrated into the system, then it is the hydrodynamic acoustic system. The experiments were carried out at the Institute of Geonics of the Academy of Sciences of the Czech Republic in Ostrava [15 ÷ 21]. There were performed the laboratory force measurements of the jet being modulated in the oscillating system in time domain, and after the Fast Fourier Transform the measurement records were obtained of the relevant amplitudes of forces depending on the resonant frequencies. The pressure of the liquid was set at discrete values of 5 MPa, 10 MPa, 15 MPa, 20 MPa and 25 MPa. The liquid jet was generated by the plunger pump delivering 43 l/min and at a maximum operating pressure of 120 MPa. The operating pressure was measured at the outlet of the pump with a piezoresistive pressure sensor Kristal RAG25A1000BC1H. The force effects of the jet were measured by a patented apparatus for the

measurement of a stagnation force of the jet, consisting of the piezoelectric force sensor Kistler 9301A and the charge amplifier Kistler 5007 (Fig. 2). Data collection and processing was performed using a notebook with a docking station equipped with a National Instruments DAQ card-PCI-MIO-16E-1 and controlled by the graphic development environment NI LabVIEW FDS, version 7.
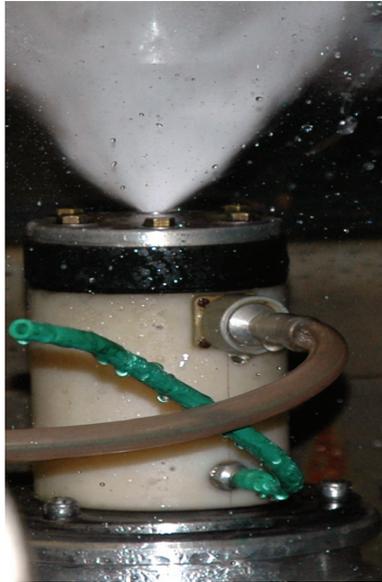
Figure 2 Piezoelectric force sensor Kistler 9301A during experiments

The sampling frequency for a signal obtained by the sensor was 250 000 samples per channel, there were five records of each measurement (262 144 samples per record). The stored records were filtered by a low-pass Butterworth filter with the cutoff frequency of 25 kHz during processing. A spectral analysis was performed by using the FFT with the Hanning window without averaging. Total of 186 direct frequency measurements were carried out using various values of input parameters (i.e. liquid pressure and geometric dimensions of the system).
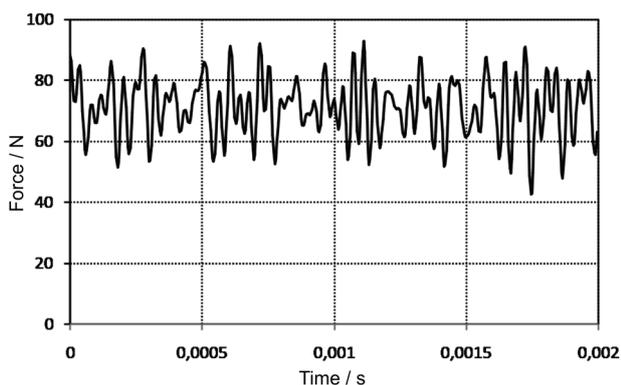

Figure 3 Time domain of measurement of stagnation force at operating pressure of 15 MPa

4
Results and discussion

An example of obtained experimental results at operating pressure of 15 MPa is presented in Fig. 3 and in Fig. 4. As it can be seen in Fig. 4, the fundamental resonant frequency was around 8,3 kHz. The amplitude of

the force has the value of about 5,6 % of static component of the force; the values of components of higher harmonic frequencies of spectrum are relatively high as well (the first higher harmonic component corresponds to 1,4 % of static component of the force, see Fig. 4).
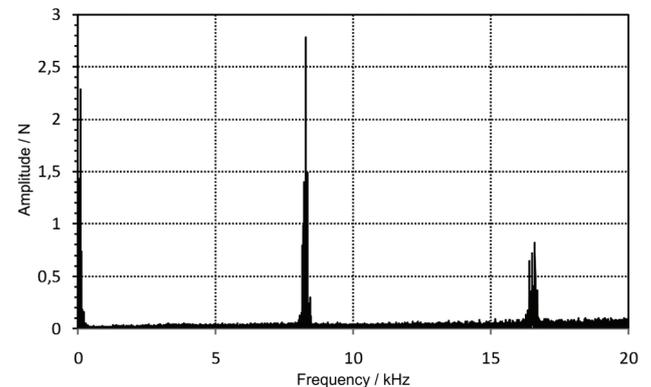

Figure 4 Frequency domain of measurement of stagnation force at operating pressure of 15 MPa

4.1
Analytical model of hydrodynamic system

The modified system generates the frequency-modulated oscillations depending on the main input parameters (i.e. geometrical dimensions of elements and liquid flow velocities). The fundamental frequency of liquid oscillations is an output parameter, which can be used to predict both the amplitude and energy of acoustic oscillations. In general physics, inspiration could be taken from the acoustic theory, mechanical or electromagnetic resonant circuits, which have been developed as general oscillatory systems based on empirical knowledge of long-term measurements and verification. The functionality of physical elements of these oscillating systems (tubes and chambers) can theoretically be evaluated by typical acoustic parameters. The tubes are represented by an acoustic mass and the chambers by an acoustical capacitance [22]. A primary precondition is that certain specific geometric conditions must be fulfilled; otherwise, the systems will not either oscillate, or the standing waves will occur. According to the acoustic theory [22] particles oscillate inside the tube as a rigid body; there is neither compression nor dilution within them, therefore a carrying medium shows minimal elasticity. On the other hand, particles do not oscillate in the chambers as the rigid body; there is simultaneous compression and also dilution at all locations of the considered volume, therefore the carrying medium shows maximal elasticity. Acoustic mass m_a [15 ÷ 21] and acoustical capacitance c_a [15 ÷ 21] is defined according to the acoustic theory. In the case of oscillating system with the aquatic carrying medium, the analogy with the theory of acoustic circuits is used. Nevertheless it is necessary theoretically to derive and numerically to evaluate characteristic acoustic parameters for the carrying liquid medium; markedly different properties of the liquid carrying medium must be respected (especially relatively low compressibility of water compared to the considerably high compressibility of air). Mainly in the chambers, the acoustic mass is not negligible with respect to the acoustical capacitance. The following methods are

used to solve the defined problem (i.e. the explicit determination of the fundamental frequency of oscillations of the given system). The solving method [15 ÷ 21] is based on the use of the equation of motion (1), generally describing a phenomenon of self-oscillations in the system. A common second order linear differential equation will be set up and solved with the constant coefficients without the right side, with a variable y as the elongation of acoustic oscillations; ω_0 as the fundamental angular frequency and the fundamental frequency f_0 is expressed by equation (1):

$$f_0 = \frac{1}{2\pi} \cdot \sqrt{\frac{1}{\overline{k}_{\mathrm{rcc}} \cdot m_{\mathrm{a}} \cdot c_{\mathrm{a}}}}, \mathrm{Hz}. \tag{1}$$

As the actual acoustic masses of all tubes vibrate in the hydrodynamic system altogether within the one complex, there is an assumption that the converted coefficient is identical or similar for all tubes and chambers given in such system, therefore the practical total acoustic mass is expressed by equation (2):

$$m_{\mathrm{as}} = k_{\mathrm{rcc}} \cdot m_{\mathrm{a}}. \tag{2}$$

The converted coefficient (the relative correction correlation coefficient) k_{rcc} provides more precisely evaluation for the resistance force, which is experimentally in compliance with the theoretical prediction of powerful turbulent water circulation [16, 17, 18]. It applies that the total impedance is equal to the sum of the partial impedances in the oscillating circuits. There is again the assumption that this applies for the given hydrodynamic oscillating system consisting of elements being connected in series and that their total acoustic mass m_{a} corresponds to the sum of partial acoustic masses, and also that the reciprocal value of total acoustical capacitance c_{a} is equal to the sum of reciprocal values of partial acoustical capacitances. In this specific case, the system consists of three tubes (supply tube, connecting neck and nozzle exit, $i = 3$) and two chambers (entry chamber and single resonant chamber, $j = 2$). That can be expressed by equation (3):

$$m_{\mathrm{a}} = \sum_{i=1}^{3} m_{\mathrm{a}i}, \mathrm{kg/m^4}; \ \frac{1}{c_{\mathrm{a}}} = \sum_{j=1}^{2} \frac{1}{c_{\mathrm{a}j}}; \ c_{\mathrm{a}}, \mathrm{m^4 \cdot s^2/kg}. \tag{3}$$

The creation and the verification of the model of fundamental frequency of the own system was based on the data obtained from direct measurements of tuneable geometric dimensions of elements, operating pressure (and indirect measurements of the flow velocity and acoustic oscillation velocity being derived from the measurements), direct frequency measurements and various other indirect measurements by means of table values, regressions and calculations. Tab. 1 shows an example of the results representing the evaluation of the relative differences $\rho_{\Delta f}$ between the measured frequencies f_{ZM} and predicted fundamental oscillation frequencies f_0 (1) according to the proposed relation (4) and also the arithmetic average of the partial relative differences for

the given discrete values of liquid pressure p expressed by the equation (4) is as follows

$$\rho_{\Delta f} = \frac{|f_0 - f_{\mathrm{ZM}}|}{f_{\mathrm{ZM}}} \cdot 100 \ \%. \tag{4}$$

Table 1 An example of comparison of theoretical and experimental results f_0, f_{ZM}

p / MPa	m_{a} / kg/m^4	c_{a} / m$^4 \cdot$s^2/kg	f_0 / kHz	f_{ZM} / kHz
5	$1{,}88664 \times 10^5$	$8{,}72681 \times 10^{-14}$	4796,5	5200
10	$1{,}89174 \times 10^5$	$4{,}36341 \times 10^{-14}$	6774,2	6200
15	$1{,}89671 \times 10^5$	$2{,}90894 \times 10^{-14}$	8285,7	8300
20	$1{,}90159 \times 10^5$	$2{,}18170 \times 10^{-14}$	9555,2	9000
25	$1{,}90640 \times 10^5$	$1{,}74536 \times 10^{-14}$	10669,6	11700
$\overline{k}_{\mathrm{rcc}} = 0{,}0668720$			$|\overline{\rho}_{\Delta f}| = 6{,}4 \%$	

5
Conclusions

The mentioned frequency model has not yet been used in technical practice. This new model is designed for the high - speed liquid flow in the hydrodynamic acoustic system of extremely small dimensions (in order of mm) and relatively low liquid pressures (to 50 MPa) and in principle is analogous to the fundamental frequency of oscillations in the aerodynamic – acoustic system. However, typical hydroacoustic parameters differ with regard to different physical environments. The aim is to predict not only the fundamental frequency, but in addition, by using them also to predict oscillation amplitudes of the fluid in the interpolated interval of pressure from 5 MPa to 25 MPa and by extrapolation to 30 MPa. For effective disintegration of materials, the system requires more energy what can be achieved by a higher fluid pressure, or by properly modulated energy. This is because the impact pressure of the discontinuous flow waterjet is significantly higher than the stagnation pressure of the continuous flow waterjet of the same parameters. In this paper, the comparison is made between the predicted and measured fundamental frequencies of the liquid oscillations. Prediction and verification of the values were performed using the analytical model being developed from the knowledge of the input and output parameters of the hydrodynamic acoustic system. These parameters were represented by a set of direct measurements carried out at the Institute of Geonics AS CR in Ostrava. The degree of agreement between the theoretically expected and measured results of the fundamental frequency of oscillations of the system does not exceed 6,4 %. In terms of meeting the needs of technical practice, the proposed method for prediction of the fundamental oscillation frequency can be considered as satisfactorily accurate. The analysis and conducted experiments have shown that the pressure oscillations generated by the flow are not high enough when compared with the pulse oscillations of the flow of the same parameters. It is advisable to use the resonance chamber as an amplifier, i.e., amplifying element of the hydrodynamic system for generating pulses, because it

acts as a secondary acoustic source. This prediction model can be applied especially to find effective parameter settings for primary input parameters, i.e., to find a suitable fluid pressure and geometric dimensions of the elements of the system.

Acknowledgments

6
References

[1] Hreha, P. et al. Water jet technology used in medicine. // Tehnički vjesnik - Technical Gazette, 17, 2(2010), pp. 237-240.
[2] Hloch, S. et al. Experimental study of surface topography created by abrasive waterjet cutting. // Strojarstvo, 49, 4(2008), pp. 303-309.
[3] Hloch, S.; Valíček, J.; Simkulet, V. Estimation of the smooth zone maximal depth at surfaces created by abrasive waterjet. // International Journal of Surface Science and Engineering, 3, 4(2009), pp. 347-359. doi: 10.1504/IJSURFSE.2009.027420.
[4] Radvanska, A. et al. Technical Possibilities of Noise Reduction in Material Cutting by Abrasive Water-jet. // Strojarstvo, 51, 4(2009), pp. 347-354.
[5] Valíček, J. et al. An investigation of surfaces generated by abrasive waterjets using optical detection. // Strojniški vestnik - Journal of Mechanical Engineering, 53, 4(2007), pp. 224-232.
[6] Valíček, J. et al. Experimental analysis of irregularities of metallic surfaces generated by abrasive waterjet. // International Journal of Machine Tools and Manufacture, 47, 11(2007), pp. 1786-1790. doi:10.1016/j.ijmachtools.2007.01.004.
[7] Valíček, J.; Hloch, S.; Kozak, D. Surface geometric parameters proposal for the advanced control of abrasive waterjet technology. // The International Journal of Advanced Manufacturing Technology, 41, 3-4(2009), pp. 323-328. doi: 10.1007/s00170-008-1489-2.
[8] Valíček, J.; Hloch, S. Optical measurement of surface and topographical parameters investigation created by abrasive waterjet. // International Journal of Surface Science and Engineering, 3, 4(2009), pp. 360-373. doi: 10.1504/IJSURFSE.2009.027421.
[9] Valíček, J.; Hloch, S. Using the acoustic sound pressure level for quality prediction of surfaces created by abrasive waterjet. // The International Journal of Advanced Manufacturing Technology, 48, 1-4(21010), pp. 193-203. doi: 10.1007/s00170-009-2277-3.
[10] Foldyna, J.; Sitek, L.; Švehla, B.; Švehla, Š. Utilization of ultrasound to enhance high-speed water jet effects. // Ultrasonics Sonochemistry, 11, 3-4(2004), pp: 131-137. doi:10.1016/j.ultsonch.2004.01.008.
[11] Vijay, M. M. Ultrasonically generated cavitating or interrupted jet. U.S. Patent No. 5(1992), pp. 154, 347.
[12] Vijay, M. M.; Foldyna, J. Ultrasonically Modulated Pulsed Jets: Basic Study. In 12th International Conference on Jet Cutting Technology, N.G. Allen, Editor, BHR Group Conference Series, Mechanical Engineering Publications Limited, London 13, (1994), pp. 15-35. ISBN 80-85849-93-3.
[13] Turull, I. R.; Rocasalbas, S. S. Studies on Helmholtz resonators with short neck and variable geometry. // Acta Acustica United With Acustica, 92, 1(2006), S87. ISSN 1610-1928.
[14] Shen, Z. H.; Wang, Z. M. Theoretical analysis of a jet-driven Helmholtz resonator and effect of its configuration on the water jet cutting property. In 9th International Symposium on Jet Cutting Technology, Sendai, Japan, 1988, pp.189-201. ISBN 0947711498X.
[15] Kušnerová, M.; Hlaváč, L. M. Self vibrating chambers with continuous passage of liquid. Transactions of VŠB-TUO of Ostrava. Mechanical Series, Ostrava, 1(LII), 2006, pp. 127-134. ISSN 1210-0471.
[16] Kušnerová, M.; Valíček, J.; Müller, M.; Hrabě, P.; Pella, A.; Radvanská, A., Analysis of acoustic parameters of hydrodynamic system and its application. In: 8th International Scientific Conference on Technology Systems Operation, Prešov, 2007, pp. 214-216. ISBN 978-80-8073-900-3.
[17] Kušnerová, M.; Valíček, J.; Müller, M.; Hrabě, P.; Radvanská, A.; Pella, A.; Derivation of hydrodynamic system acoustic parameters. In: 8th International Scientific Conference on Technology Systems Operation, Prešov, 2007, pp. 217-219. ISBN 978-80-8073-900-3.
[18] Kušnerová, M.; Valíček, J.; Hloch, S.; Radvanská, A. Convert coefficients for the analytical model of the frequency of the water dynamic system. In Conference on Applications and Design in Mechanical Engineering Universiti Malaysia Perlis (UniMAP), 2007. http: //www. unimap.edu.my/cadme07
[19] Kušnerová, M.; Valíček, J.; Hloch, S.; Ergić, T.; Ivandić, Ž. Derivation and Measurement of the Velocity Parameters of Hydrodynamic Oscillating System. // Strojarstvo, 50, 6(2008), pp. 375-379. ISSN 0562-1887.
[20] Sitek, L.; Vala, M.; Vašek, J. Investigation of high pressure water jet behaviour using jet/target interaction. Proc. of the 12th Int. Conf. On Jet Cutting Technology, Mech. Eng. Public. Ltd., London, 13, 1994, pp. 59-66. ISBN 80-85849-93-3.
[21] Vala, M. The measurement of the non-setting parameters of the high pressure water jets. Geomechanics, Rakowski (ed.), Balkema, Rotterdam, 93, (1994), pp. 333-336. ISBN 90 5410 354X.
[22] Kuttruff, H. Room acoustics. Applied Science, Publishers Ltd., London, 1973, pp. 457. ISBN 0-419-24580-4.

Authors' addresses

Milena Kušnerová
Institute of Physics
Faculty of Mining and Geology
VŠB - Technical University of Ostrava
17. listopadu 15, 708 33 Ostrava – Poruba, Czech Republic
milena.kusnerova@vsb.cz

Josef Foldyna
Institute of Geonics of the ASCR, v. v. i.
Institute of Clean Technologies for Mining and Utilization of Raw Materials for Energy Use
Studentská 1768, 708 00 Ostrava-Poruba, Czech Republic

Libor Sitek
Institute of Geonics of the ASCR, v. v. i.
Institute of Clean Technologies for Mining and Utilization of Raw
Materials for Energy Use
Studentská 1768, 708 00 Ostrava-Poruba, Czech Republic

Jan Valíček
Institute of Physics
Faculty of Mining and Geology
VŠB - Technical University of Ostrava
17. listopadu 15, 708 33 Ostrava – Poruba, Czech Republic

Sergej Hloch
Faculty of Manufacturing Technologies of Technical University of
Košice with a seat in Prešov
Bayerova 1, 080 01 Prešov, Slovak Republic

Marta Harničárová
Nanotechnology Centre
VŠB -Technical University of Ostrava
17. listopadu 15, 708 33 Ostrava – Poruba, Czech Republic

Milan Kadnár
Department of Machine Design
Faculty of Engineering
Slovak University of Agriculture in Nitra
Tr. A. Hlinku 2, 949 76 Nitra, Slovak Republic