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ULTRASONIC PULSATIONS OF PRESSURE IN A WATER JET CUTTING TOOL

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Original scientific paper

Water flow in a tool for water jet cleaning and cutting is evaluated in this paper. There are ultrasonic pulsations of high pressure in the given domain. The efficiency of the amplification of high pressure pulsations in the transitional space between larger and smaller pipes is analysed. Three types of transitional spaces are compared in the paper: step change, conical and radius change of pipe diameters.

Keywords: *high pressure, transitional space between larger and smaller pipe, ultrasonic pulsations, water jet cutting*

Ultrazvučne pulzacije tlaka u alatu za rezanje vodenim mlazom

Izvorni znanstveni članak

U ovom se radu izračunava protok vode u alatu za čišćenje i rezanje vodenim mlazom. U danom području postoje ultrazvučne pulzacije visokog tlaka. Analizira se efikasnost pojačanja pulzacija visokog tlaka u prijelaznom prostora između većih i manjih cijevi. U članku se uspoređuju tri tipa prijelaznih prostora: postepena promjena te promjena konusa i polumjera promjera cijevi.

Ključne riječi: *prijelazni prostor između veće i manje cijevi, rezanje vodenim mlazom, ultrazvučne pulzacije, visoki tlak*

1
Introduction

Despite the impressive advances made recently in the field of water jetting, substantial attention of a number of research teams throughout the world is still paid to the further improvement of the technology. An obvious method of the water jetting performance improvement is to generate jets at ultra-high pressures. The feasibility of cutting metals with pure water jets at pressures close to 690 MPa was investigated already in early nineties of the last century [1]. Such a high pressure, however, induces extreme overtension of high-pressure parts of the cutting system which has adverse effect on their lifetime.

An alternate approach is to eliminate the need for such high pressures by pulsing the jet. It is well known that the collision of a high-velocity liquid mass with a solid generates short high-pressure transients which can cause serious damage to the surface and interior of the target material. Therefore, exploitation of effects associated with water droplet impingement on solids in a high-speed water jet cutting technology should lead to considerable improvement of its performance, better adaptation to more and more demanding environmental requirements, and consequently to more beneficial use of the technology also from the economical point of view.

Generating sufficiently high pressure pulsations in pressure water upstream the nozzle exit can lead to creation of such a pulsating water jet. Pressure pulsations are transferred into the output nozzle, where the energy of pressure is transformed to kinetic (velocity) energy and dissipation energy. Pulsations of the energy create pulsations of the water jet at the exit from the nozzle. Hence the water jet divides into clusters of droplets at certain standoff distances from the nozzle exit, see Fig. 1. This type of jet is called a pulsating water jet. The advantage of such a pulsating jet over a continuous one is based on the fact that the initial impact of clusters of droplets of the pulsating jet on the target surface generates impact pressure p_i that is several times higher than the stagnation pressure p_s generated by the action of a continuous jet under the same working conditions. In addition, the action of a pulsating jet induces fatigue stress in the target material due to the cyclic loading of the target surface. This further improves the efficiency of the pulsating liquid jet in comparison with the continuous one [2, 3].

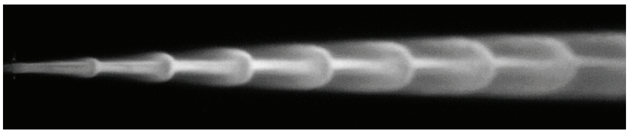

Figure 1 Pulsating water jet, shape of the water jet at the output of the output nozzle

Problems related to the generation and propagation of pressure pulsations with frequency in the order of tens of kHz in liquid under pressure of tens of MPa and subsequent discharge of the liquid influenced by the pulsations through the orifice in the air (producing pulsating liquid jet with axial velocity in the order of hundreds meters per second) are very complex. Partial information on this topic can be found in publications dealing with processes of a fuel injection for combustion in diesel engines (see e.g. [4] or [5]) and/or underwater acoustics [6]. Only a few more detailed studies of fundamentals of the process of excitation and propagation of acoustic waves (high frequency pressure pulsations) in liquid via high-pressure system and their influence on forming and properties of pulsating liquid jet are available (e.g. [7] to [10]).

The research problems presented in the paper are focused on high pressure compressible water flowing in the domain of the tool for water jet cutting and propagation of pressure pulsations in the tool. A vibrating body termed waveguide brings into the fluid flow high pressure pulsations through its periodic linear length changes (mainly in the direction of rotation axis). The assembly of the tool is shown in Fig. 2. With regard to the space filled by water, we can say that such a tool is mostly a system of cylinders and cones placed consecutively in line, except for the input hole, see Fig. 2.

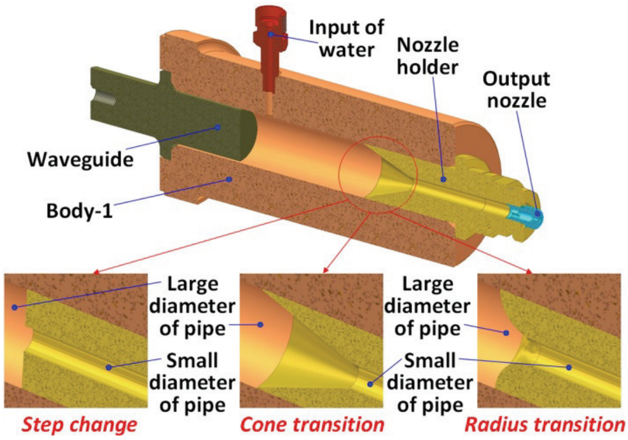

Figure 2 The assembly of a tool for the water jet cutting and given transition regions

The purpose of the tool design is to create producible shapes, which allows the propagation of pressure pulsations from the space around the waveguide into the space of the output nozzle with the highest possible efficiency. Generally speaking, if one reduces the diameter of the pipe, pulsations of pressure in the pipe with a smaller diameter can be amplified. This is valid in the space where pressure energy is significantly higher than kinetic energy. Then, the shape of the transition region between large and small pipes could strongly influence the value of pressure pulsation amplification. The influence of selected possible shapes of the transition area between larger and smaller pipes on the amplification of pressure pulsations is investigated. The efficiency of the high pressure pulsation amplification is studied with regard to the shape of the transitional region.

2
Geometrical configurations

There are several possibilities for designing the transition between large and small pipes. However, the question is: "What is the best possible solution?"

We should choose some realizable interval of transition types, because it is very hard to find the best solution from all possibilities available. In the first step, we can define three basic transitions with regard to their geometry and manufacturing (see Fig. 2):

1) simple step change of diameters;
2) conical change of diameters; and
3) radius change of diameters.

The above-mentioned transitional regions create mutually different variants of the geometry and they also offer the possibility of simple manufacturing. We would like to find a certain configuration of the geometry, which will be used in standard practice with a high efficiency of pressure pulsations transfer. Therefore, the requirement of simple manufacturing represents one of the main parameters to be taken into account.

The tool for water jet cutting consists of several parts, such as body-1, waveguide, nozzle holder, etc. Body-1 represents the main part of the tool assembly. All important parts are connected to the body-1 part, see Fig. 2. The waveguide vibrates axially and, due to this change of its geometry, in time creates pulsations of pressure in the flowing water. The nozzle holder holds the output nozzle, which produces the final water jet. The total length of a large diameter cylinder can be adjusted by the nozzle holder to tune a given space. The place where water flows from the body-1 to the nozzle holder represents our crucial point of interest. The above-mentioned transitional regions have been placed at that point.

3
Method of evaluation of given geometries

We have several possibilities as to how to evaluate the contribution of a given geometry setting to the amplification of pressure pulsations. One of them is direct measurement of effects of individual geometries, which involves the manufacturing of designed transitional regions between larger and smaller pipes, and subsequent measurement of effects given the geometry setting, e.g., using pressure sensors. Another method is the creation of a mathematical model of the given domain based on the physical equations of fluid flow. This approach can be much faster and cheaper if one has such code and the necessary experience available. Of course, the third (and optimal) approach is the combination of both above-mentioned methods. We have created a mathematical model of the water jet tool using commercial CFD software ANSYS®. Very good agreement between experiment and results from the CFD model was reported in our previous work [11].

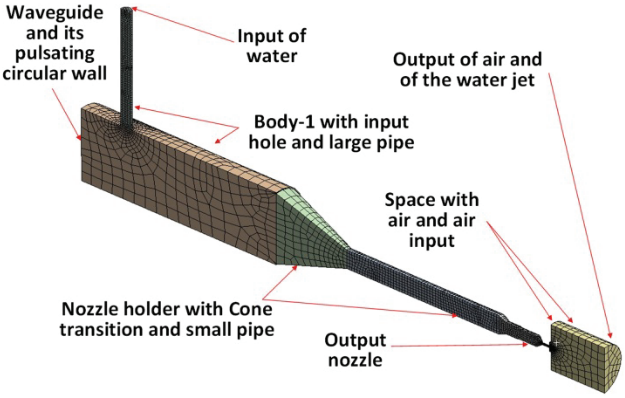

Figure 3 The geometry of a tool used in the CFD model

4
CFD model

The water flow in the tool for water jet cutting is a complicated physical problem. It comprises 3D two-phase compressible turbulence time-dependent fluid flow with moving wall. There are sub-domains with low velocities and very high velocities, see Fig. 3. This fact complicates the description of turbulent flow in the given domain. Due to the presence of high velocities in the output nozzle, cavitation should also be included into the CFD model. The calculation of wave propagation necessitates precise description and setting of the given problem with regard to both mathematics and physics.

Turbulent fluid flow was physically defined using the Navier-Stokes equation adjusted by the RANS method. A realizable k-ε turbulence model was used in the calculations. The model should be able to describe with sufficient accuracy the given type of regions with low and high velocities. The following system of equations was solved:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_i)=0. \tag{1}$$

The first expression (1) shows the shape of the continuity equation for compressible flow, where ρ is density, t is time, x_j is component of coordinate and u_i is component of velocity.

$$\begin{aligned}&\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}(\rho u_i u_j)=-\frac{\partial p}{\partial x_i}+\\&+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right]+\\&+\frac{\partial}{\partial x_j}\left(\mu_\mathrm{t}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\left(\rho k+\mu_\mathrm{t}\frac{\partial u_l}{\partial x_l}\right)\delta_{ij}\right).\end{aligned} \tag{2}$$

The second equation (momentum equation) shows the special shape of the Navier-Stokes equation for turbulent fluid flow, where p is pressure, μ is viscosity, μ_t is turbulent viscosity and k is turbulent kinetic energy. Equations (1) and (2) also have been called Reynolds-averaged equations. The terms in equation (2) placed on the third line define Reynolds stresses.

$$\mu_\mathrm{t}=\rho C_\mu\frac{k^2}{\varepsilon}. \tag{3}$$

$$\begin{aligned}&\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left(\left(\mu+\frac{\mu_\mathrm{t}}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right)+\\&+G_k+G_b-\rho\varepsilon-Y_M+S_k.\end{aligned} \tag{4}$$

$$\begin{aligned}&\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left(\left(\mu+\frac{\mu_\mathrm{t}}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right)+\\&+\rho C_1 S_\varepsilon+\rho C_2\frac{\varepsilon^2}{k+\sqrt{\nu\varepsilon}}+C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b+S_\varepsilon.\end{aligned} \tag{5}$$

There are other unknown parameters that can be described by equations (3), (4), and (5), where ε is turbulent dissipation energy, and for other terms, see [12]. Equations (1)-(5) create a closed system for one phase compressible turbulent isothermal fluid flow. More exactly, the above-mentioned system of equations needs to define compressibility ($\rho(p)$, $a(p)$) and equations describing turbulent flow need to be complemented with some equations describing fluid flow at the wall. This is necessary because the ratio of molecular viscosity and turbulent viscosity is completely different at the wall and in the middle stream. In this case, equations describing turbulent flow have been completed with non-equilibrium wall function, see [12]. This approach substitutes exact solution of the fluid flow in the given sub-layers of boundary layer with the help of empirical formulas.

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}(\alpha_q\rho_q)+\nabla\cdot\left(\alpha_q\rho_q\vec{v}_q\right)=S_{\alpha_q}+\sum_{p=1}^{n}(\dot{m}_{pq}-\dot{m}_{qp})\right]. \tag{6}$$

$$\sum_{q=1}^{n}\alpha_q=1. \tag{7}$$

Equations (6) and (7) complete the above-mentioned system of equations with the possibility to solve multi-phase flow, where α_q is volume fraction of the q^th phase, ρ_q is density of the q^th phase, for other terms, see [12].

Due to the necessity to calculate water flow as compressible, it is obligatory to complement the above-mentioned equations with relations for density and sound speed as a function of pressure. It is possible to use equation (8) as a base to derive equation (9).

$$K=-\rho\frac{\mathrm{d}p}{\mathrm{d}\rho}. \tag{8}$$

$$\rho=\frac{\rho_\mathrm{ref}}{\left(1-\dfrac{K}{p-p_\mathrm{ref}}\right)}. \tag{9}$$

It is possible to use equation (8) as a base to derive equation (9), where K is bulk modulus of water. For the description of the sound speed, a simple linear equation (10) will be used (see [7]):

$$a=b\cdot p+d, \tag{10}$$

where a is sound speed and b, d are constants.

In the CFD model, the part termed waveguide was represented only by the front circular area, see Figs. 1 and 3. The space or distance between the large pipe diameter and the diameter of the waveguide arm was neglected. The movement of the head circular waveguide wall has been defined by the following equation:

$$v_\mathrm{pulsator}=A\cdot\omega\cdot\cos(\omega\cdot t), \tag{11}$$

where v_pulsator is velocity moving of the waveguide wall in direction of its rotational axis, A is amplitude of oscillations, ω is angular velocity, t is time. Equations (9), (10), (11) have been implemented in CFD code as user-defined functions.

Above mentioned equations create a closed system and allow the solution of 3D two-phase turbulent compressible flow of water in the tool and out of the tool in incompressible air. The effect of cavitation was neglected in this case. The partial differential equations are solved with the help of the numerical method known as method of control volumes. Using these procedures, a suitable model for studying high pressure pulsations propagation in the given geometry was created.

5
Calculated results

As indicated above, the objective was to evaluate the efficiency of pressure pulsation transfer in selected configurations of the geometry, see Fig. 2. Now, it is necessary to find correct parameters, which should be evaluated and compared. The output nozzle, or its cylinder with the smallest diameter, is the place where pressure energy or pressure pulsations are transformed to kinetic and dissipation energy, see Fig. 4. Pulsating kinetic energy of water in the output nozzle cylinder with the smallest diameter creates the final shape of the water jet at the output of the tool or of the output nozzle. It is valid that higher amplitude of pressure pulsations in front of the output nozzle produces higher amplitude of velocity in the smallest cylinder of the output nozzle. Therefore, the evaluated parameter was velocity in the smallest cylinder of the output nozzle, more exactly, maximum value of velocity on the depicted cross-sectional area, see Fig. 4.

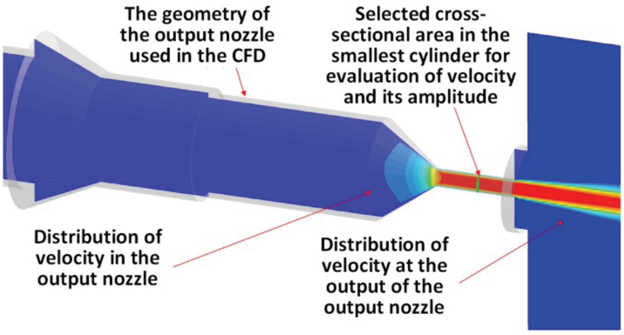

Figure 4 The geometry of the output nozzle used in the CFD model with distribution of velocity (red color shows highest velocities, deep blue color shows lowest velocities)

Fig. 5 illustrates evaluated velocities in time. It is possible to see that the variant with radius transition between big and small diameter (see Fig. 2) produces maximum amplitude of normalized velocity v_z (orange colour). Then, the variant with cone transition follows (blue colour), and the variant with diameter jumping (green colour) produces minimum amplitude of normalized velocity v_z, see Fig. 5.

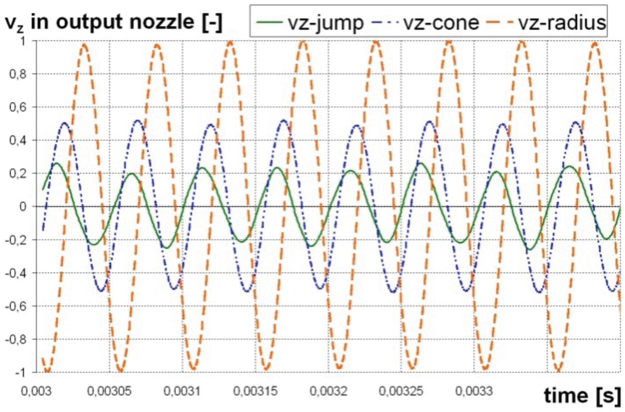

Figure 5 Maximum values of the normalized velocity v_z in direction of the output nozzle rotational axis (cross-sectional area in the smallest cylinder of the output nozzle)

The size of the normalized velocity amplitude defines the efficiency of the high pressure pulsations transfer in the given geometry of the tool for water jet cutting, and also defines efficiency of cutting. Higher amplitudes of velocity at the output from the output nozzle will produce pulsating water jet with well-developed pulses at certain standoff distances from the nozzle exit. Subsequently, such a pulsating water jet will produce higher impact pressures on the surface area of the cut materials. Contrarily, low amplitude of normalized velocities will produce poorly developed pulsating water jet, with very low impact pressures on the surface area of the cut material, resulting in low cutting efficiency, and its effects will roughly correspond to the effects of a continuous water jet.

6
Conclusion

Three geometrical variants of the tool for water jet cutting were compared in this paper using a CFD model of the tool. The objective of the calculations was to determine the amplitude of velocity in the smallest cylinder of the output nozzle as a response to high pressure pulsation, and to compare given geometrical variants with regard to the efficiency of high pressure pulsation transfer in the tool for water jet cutting. The highest amplitude was calculated for variants with the radius transition. It is possible to expect that the variant with radius transition will produce the best pulsating water jet for given boundary conditions (input pressure, amplitude of waveguide vibrations, output nozzle diameter, etc.). The other two variants of the transition region produce lower amplitudes of velocity at the nozzle exit that will result most likely in poorly developed pulsating water jets. In this case, higher amplitude of vibrations of the waveguide would be required to obtain the same amplitude of velocity as in the case of radius transition. This would require more energy for vibrations of waveguide and better material of the waveguide, due to the presence of higher stresses.

Three fixed geometrical variants have been resolved here. Generally, it is possible to find cases with the highest pulsations of pressure and velocity if the length of the tool is changed, or if the nozzle holder is moved with respect to the body-1. In other words, global extremes of pulsations should be found for given variants, and then such results could be compared with each other. This approach will be used in future studies of the problem.

Nevertheless, this study shows that it is also necessary to choose the correct shape of the transition region between large and small pipe diameter, if high efficiency of cutting is requested. The design can be supported by numerical modelling of flow with the help of available CFD code.

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