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Analytical, Numerical, and Experimental Research Approaches to Influence of Vibrations on Hydroelastic Processes in Centrifugal Pumps

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Abstract**—**The problem under research is that of unpredictable modes occurring in two-stage centrifugal hydraulic pump as a result of hydraulic processes caused by vibrations of structural components. Numerical, analytical and experimental approaches are considered. A hypothesis was developed that the problem of unpredictable pressure decrease at the second stage of centrifugal pumps is caused by cavitation effects occurring upon vibration. The problem has been studied experimentally and theoretically as of today. The theoretical study was conducted numerically and analytically. Hydroelastic processes in dynamic “liquid – deformed structure” system were numerically modelled and analysed. Using ANSYS CFX program engineering analysis complex and computing capacity of a supercomputer the cavitation parameters were established to depend on vibration parameters. An influence domain of amplitudes and vibration frequencies on concentration of cavitation bubbles was formulated. The obtained numerical solution was verified using CFM program package developed in PNRPU. The package is based on a differential equation system in hyperbolic and elliptic partial derivatives. The system is solved by using one of finite-difference method options – the particle-in-cell method. The method defines the problem solution algorithm. The obtained numerical solution was verified analytically by model problem calculations with the use of known analytical solutions of in-pipe piston movement and cantilever rod end face impact. An infrastructure consisting of an experimental fast hydro-dynamic processes research installation and a supercomputer connected by a high-speed network, was created to verify the obtained numerical solutions. Physical experiments included measurement, record, processing and analysis of data for fast processes research by using National Instrument signals measurement system and Lab View software. The model chamber end face oscillated during physical experiments and, thus, loaded the hydraulic volume. The loading frequency varied from 0 to 5 kHz. The length of the operating chamber varied from 0.4 to 1.0 m. Additional loads weighed from 2 to 10 kg. The liquid column varied from 0.4 to 1 m high. Liquid pressure history was registered. The experiment showed dependence of forced system oscillation amplitude on loading frequency at various values: operating chamber geometrical dimensions, liquid column height and structure weight. Maximum pressure oscillation (in the basic variant) amplitudes were discovered at loading frequencies of approximately 1,5 kHz. These results match the analytical and numerical solutions in ANSYS and CFM.

Keywords**—**Computing experiment, hydroelasticity, physical experiment, vibration.

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I. INTRODUCTION

THE problem of cavitation occurrence in pumps is urgent, and a great number of scientific papers are devoted to this problem [1], [2], [4]-[7], [13]-[15]. Experimental researches in scientific works by V. Ya. Chaplygin and A. M. Matveenko are limited with low frequencies (< 200 Hz) [8]-[10]. S. I. Perevoshchikov studied influence of hydrodynamic processes on vibration in centrifugal pumps [22]. Nevertheless, there is insufficient number of works on influence of vibrations on hydrodynamic processes.

The given scientific work considers the possibility of modeling the unpredictable effects in the case of operation of high technology engineering items. Particularly, unpredictable pressure decrease may be observed at upper stages during the operation of multi-stage centrifugal pumps. Vibrations are supposed to be able to cause cavitation, which results in pressure loss, wear and destruction of elements of high technology products.

II. EXPERIMENTAL RESEARCH

In order to carry our experimental research, a unique experimental research installation was created to study vibrations influence on fast hydroelastic cavitation processes with regard to mutual influence of liquid and deformed structure. Besides, this installation provides an opportunity to verify numerical solutions obtained with the supercomputer [17], [21].

The experimental research installation is a system (Fig. 1) consisting of a model working chamber, a loading unit and a measuring and computing complex (IZVK). The model chamber is a pipe with flanges for installation on the skid (base) and attachment of additional equipment, as well as with fittings for hydrophones installation. Sections of the working chamber and elements for structure natural oscillation frequencies adjustment may be installed as the additional equipment. Different liquids may be used as the working fluid. It is possible to use additional equipment to increase the pressure and to change the working fluid temperature. The measuring and computing complex consists of: three pressure sensors (hydrophones), three vibration acceleration sensors PCB 352C03, a signal matching module, a National Instruments (NI) PXI 1050 chassis with an installed 8-channel module NI PXI 4472B for dynamic signals measurement and LabVIEW.11 software, a device for acceleration and

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modulation of the input signal, and a loading unit on the basis of the piezoceramic emitter.

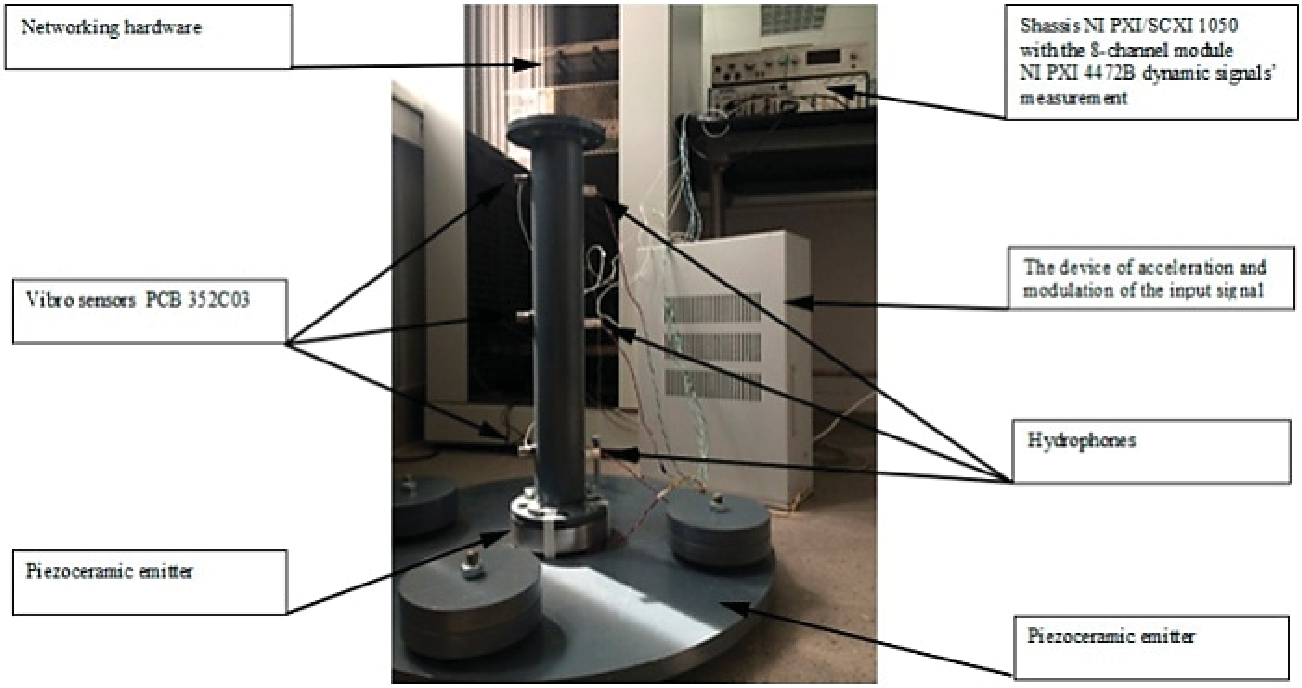

Fig. 1 General view of the experimental research installation

Control signals formed in the LabVIEW.11 software package are sent for excitation of oscillations in the loading unit. Amplitude and frequency of these signals may depend on the result of the spectral analysis of an output signal from hydrophones and vibration sensors during their processing via supercomputer.

Physical experiments were conducted including: measurement, recording, processing, and analysis of data using the National Instrument signals measurement system and the Lab View software.

In the course of physical experiments, dependences of amplitudes of system-forced oscillations on loading frequency were obtained at different: geometrical dimensions of the working chamber, height of a liquid column, weight characteristics of the structure. The results are given in the form of graphic curves.

A series of experiments was conducted in the model experimental installation for the evaluation of influence of weight characteristics on oscillation modes. In the course of experiments, the weight of the load installed on the model chamber varied from 0 to 10.4 kg. A series of experiments was performed for each case by changing the set signal frequency within the range from 50 to 5,000 Hz. The graphs have frequency values in Hz laid off on the axis of abscissas and the calculated maximum root mean square (RMS) of the signal amplitude, without the signal constant component, laid off on the axis of ordinates.

The signal analysis showed that acceleration is clearly observed at frequency approx. 1,500 Hz (Fig. 2).

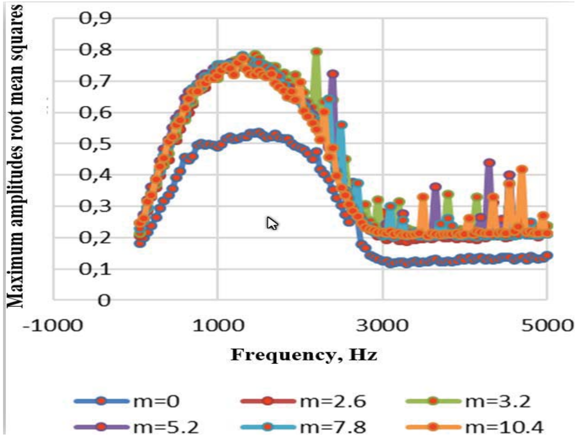

Fig. 2 Dependence of maxima of amplitude root mean squares on frequency at different weights of the installed load

In case of loading frequency 2,500 Hz, sudden change of maxima of signal amplitude RMS is observed. At m=0 kg the dramatic rise occurs at 2,650 Hz; at m=2.6 kg – 3,000 Hz; at m=3.2 kg – from 2,200 to 2,400 Hz; at m=5.2 kg – 2,400 Hz; at m=7.8 kg – 2,350 Hz; at m=10.4 kg – 2,500 Hz. It is probably related to the fact that the system responds to the structure natural partial frequency which is approximately 2,470 Hz which is obtained in the course of the modal analysis in the ANSYS system (at m=0 kg) (Fig. 3).

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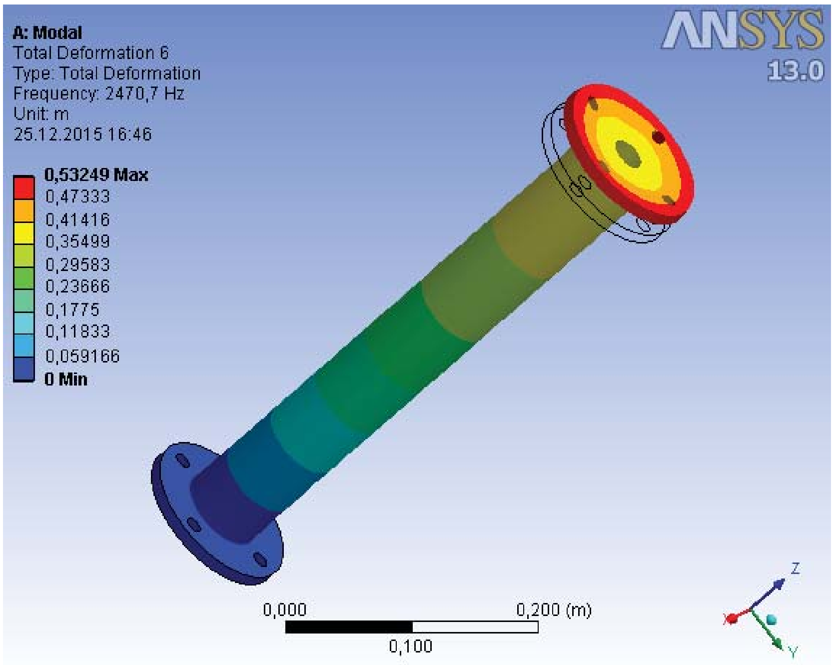

Fig. 3 Structure natural frequency

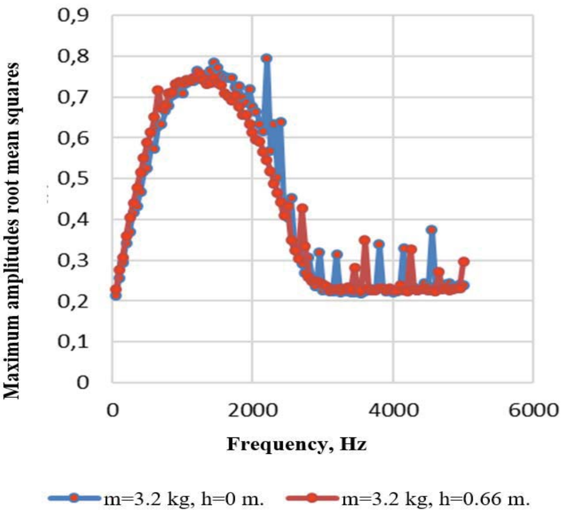

Fig. 4 Dependence of maxima of amplitude root mean squares on frequency at the same weight of the installed load, m=3.2 kg, and different values of the load height

A series of experiments was conducted in the model experimental installation for the evaluation of influence of structure geometrical characteristics on oscillation modes. Influence of structure geometrical characteristics on oscillation processes was evaluated according to two parameters: chamber height and height of the liquid column. In the first case, height of the working chamber varied from 0 to 0.66 m, with the weight being constant and equal to 3.2 kg. In the second case, height of the liquid column varied from 0.74 to 1.1 m. A series of experiments was conducted for each case changing the set signal frequency within the range from 50 to 5,000 Hz. As a result of the changed signals analysis, it can be noted that the channel height varying within the set range influences on oscillation characteristics of the working fluid within 10% (Fig. 4).

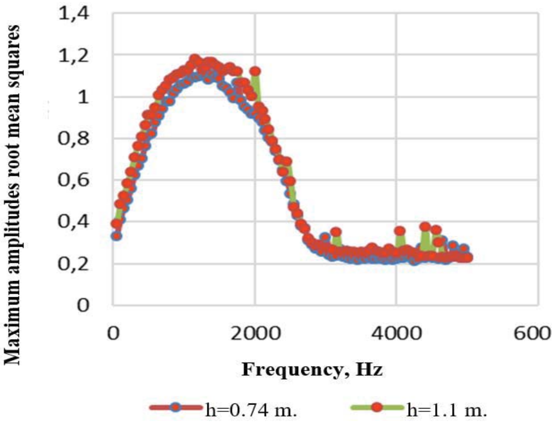

Fig. 5 Dependence of maxima of amplitude root mean squares on frequency (at different cases of change of height of the liquid column)

During comparison of two estimated cases when height of the liquid column varied in the course of experiments, it is observed that increase of height of the liquid column is also accompanied with the increase of maxima of signal amplitude RMS within 10% (Fig. 5).

III. COMPARISON OF THE PHYSICAL EXPERIMENT WITH A NUMERICAL SOLUTION OBTAINED IN CFM

The numerical experiment was conducted with the use of the CFM software package developed in the Perm National Research Polytechnic University (PNIPU). The package is based on the solution of a differential equation system in hyperbolic and elliptic partial derivatives [3], [12].

A pipe simulating a bypass channel of a two-stage centrifugal pump is used as a calculation model. Geometrical dimensions of the pipe correspond to dimensions of the hydraulic volume of the working chamber of the experimental research installation.

The following physical model was stated: processes occurring in the structure and the liquid are considered in the dynamic two-dimensional arrangement; the structure is homogeneous; structure material is elastic; the liquid is considered compressible; the contact of the liquid with a movable wall is preserved; pipe walls are impermeable, thermally non-conductive and smooth; and gravitation is not taken into account.

A mathematical model is developed in accordance with the accepted physical model. The mathematical model of a hydro-dynamic process is based on the laws of conservation of mass, momentum and energy, the equation of state of compressible liquid, initial and boundary conditions recorded with regard to stiffness of the loading system. The mathematical model for the deformed structure also includes the laws of conservation of mass and momentum and ends with Cauchy equations, the generalized Hooke's law, as well as initial and boundary conditions recorded with regard to stiffness of the loading system.

The Particle-in-cell method, which is one of finite-difference methods was chosen as a method of solution of the initial differential equation system.

The accepted method determines a problem solution algorithm, which includes several steps. The first steps are designated for hydro-dynamic problem solution, and subsequent steps – for evaluation of parameters of structure dynamic stress-strain state [12], [20].

Testing of the proposed algorithm for solution of dynamic hydroelasticity problems was conducted on the model problem about piston movement in a pipe filled with liquid. The computational scheme is given in Fig. 6.

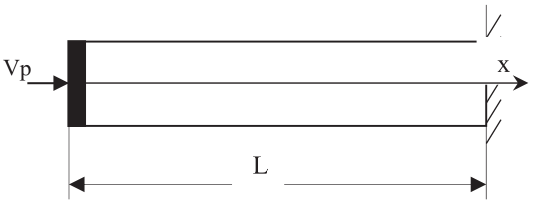

Fig. 6 Computational scheme

The following initial conditions were set: L=0.5 m – pipe length; Pin = 450*106 Pa – liquid internal pressure; V = 10 m/s – piston speed; p= 1000 kg/m^3 – liquid density; K = 5.0 – adiabatic index for liquid. Herewith, the structure is not deformed at this step, but this can be taken into account hereafter.

At the moment of movement start, a compression wave will move with speed N1 in the fluid at rest in front of the piston. Reaching the wall, the forward wave will reflect from it, and the reflected wave will travel with speed N3 in the direction, which is reversed to the direction of the moving liquid (Fig. 7) [19].

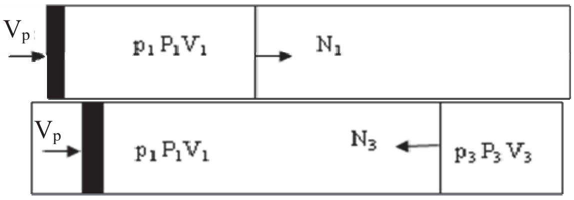

Fig. 7 Incident and reflected waves

Simulation results for the incident wave are given in Fig. 8. As it can be seen, the incident wave front ran over half of the pipe length. Oscillations caused by numerical effects are observed behind the wave front. Moreover, after the reflection, these effects disappear. Simulation results for the reflected wave are given in Fig. 9.

As a result of the obtained numerical solution analysis, it can be noted that the value of the natural frequency of the hydraulic volume is 1,520 Hz, and the wave is able to reach the wall, reflect from it and return at this frequency.

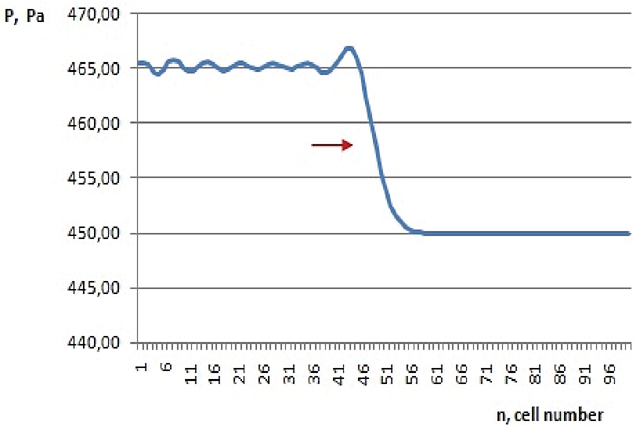

Fig. 8 Pressure change along the pipe length at t=0.16*10^{-3} s

IV. COMPARISON OF ANALYTICAL, NUMERICAL AND EXPERIMENTAL SOLUTIONS

The analytical analysis of the model problem was conducted with the use of known analytical solutions on in-pipe piston movement and cantilever rod end face impact [19].

TABLE I
COMPARISON OF ANALYTICAL, NUMERICAL AND EXPERIMENTAL SOLUTIONS

Controlled parameters	Results of the numerical solution (aver.)	Results of the analytical solution	Results of the experimental solution
P1, Pa	465*10^6	465*10^6	-
X1, m	0,24	0,24	-
N1, m/s	1,515	1,515	-
P1, Pa	480,6*10^6	480,6*10^6	-
X1, m	0,36	0,36	-
N1, m/s	1,525	1,525	-
f, Hz	1,520	1,562	1,500

Table I contains results of comparison of numerical and analytical solutions on the following parameters: P1 – incident wave pressure; X1 – shift of the shock incident wave front from the initial position; N1 – speed of the incident wave front; P3 – pressure of the reflected wave; X3 – shift of the shock reflected wave front from the initial position; N3 – speed of the reflected wave front, f – natural frequency of hydraulic volume of the working chamber.

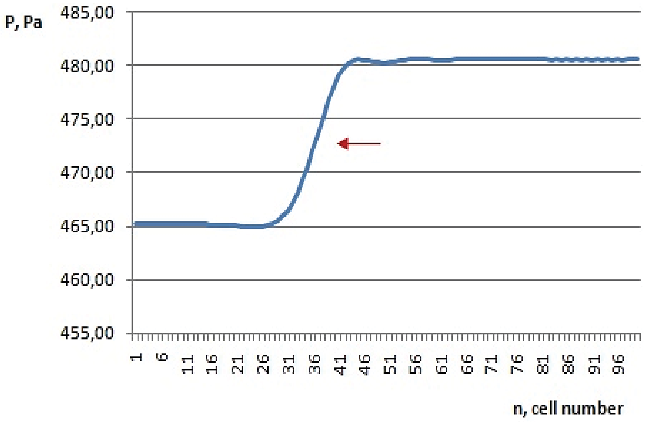

Fig. 9 Pressure change along the pipe length at $t=0.57*10^{-3}$ s

Comparative analysis of numerical and analytical solutions showed that solution results coincide with acceptable accuracy. A certain "smearing" of the shock wave front connected with scheme viscosity is observed in the numerical solution.

Upon comparison of obtained analytical, numerical and experimental results, one may notice that they are almost the same, and natural frequency of hydraulic volume of the working chamber is approximately 1,500 Hz in all cases.

V. COMPARISON OF THE PHYSICAL EXPERIMENT WITH THE NUMERICAL ONE OBTAINED DURING SOLUTION IN THE ANSYS CFX PROGRAM

Alongside with all above mentioned experiments, numerical modelling and hydroelastic processes analysis in the dynamic "liquid – deformed structure" system were conducted with the use of the licensed engineering analysis software complex ANSYS CFX and computation capacities of the supercomputer of the Common Use Centre "High-Production Computation System Centre" of the Perm National Research Polytechnic University [11], [16], [18].

A pipe simulating a bypass channel of a two-stage centrifugal pump was used as a calculation model. Geometrical dimensions of this pipe coincide with dimensions of the working chamber of the experimental installation.

The physical model was stated in the following arrangement: vibrations were stimulated with piston movement (an analogue of the deformed wall) in the closed pipe filled with liquid; processes were considered in the dynamic three dimensional arrangement; the flow was multiphase, a model of incompressible liquid (water) was chosen as a carrier phase, and gas (steam) was chosen as a carried phase; mutual influence of phases was taken into account; condition of cavitation occurrence is $P_{abs} \leq P_{sat}(T_{abs})$; pipe walls are impermeable, thermally non-conductive and smooth.

In accordance with the developed physical model, a mathematical model was accepted which is based on the laws of conservation of mass, momentum and energy [1]-[6]. Herewith, convection diffusion transfer of mixed components and the turbulent flow pattern are taken into account. The equation system ends with a turbulence model, as well as initial and boundary conditions.

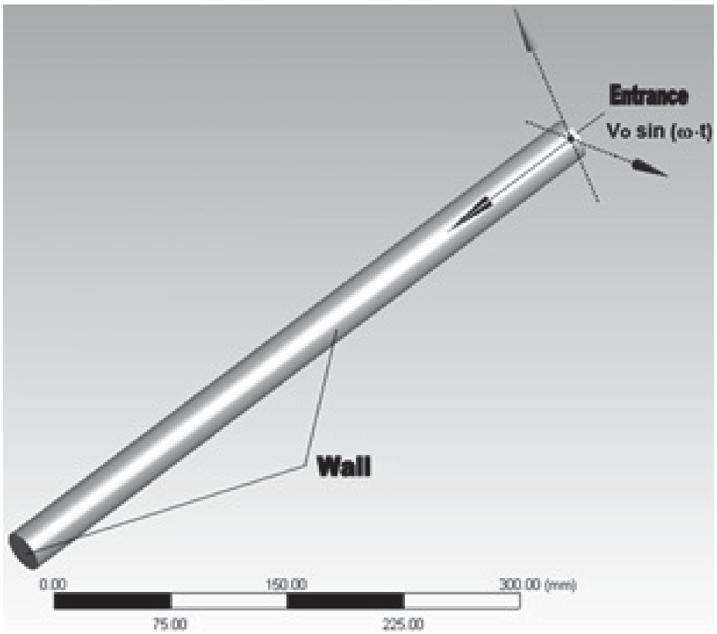

Fig. 10 Solid model and boundary conditions

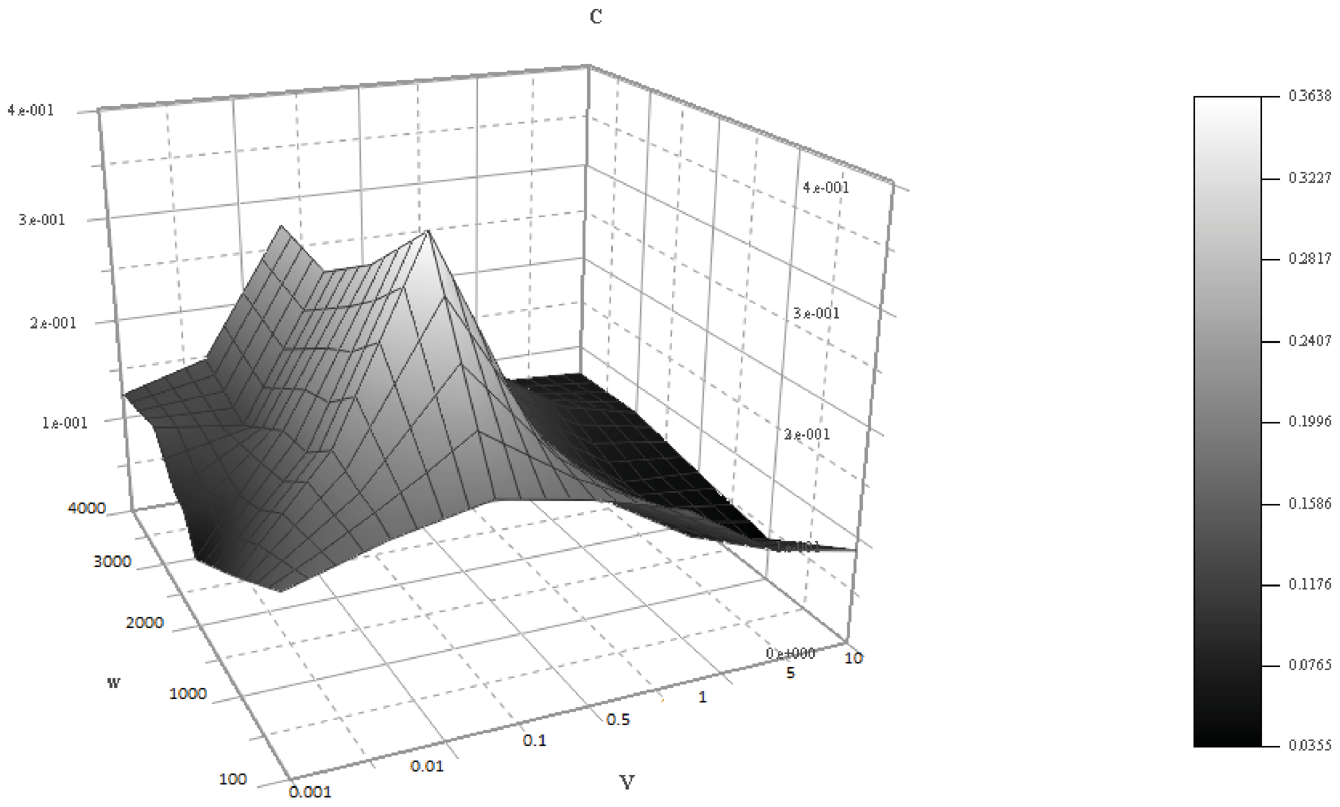

Fig. 11 Area of cavitation occurrence during vibrations

A solid model and boundary conditions are shown on Fig. 10. A condition of the "logarithmic law" type is set for the "Wall" boundary. Wall vibrations are set with the piston movement equation $V = V_0 \sin(\omega t)$, where V is the piston speed, V_0 is the initial piston speed (amplitude), ω is the oscillation frequency, and t is the time.

The plan of conducting computational experiments foresaw the variation of V_0 values within the range 0.001-10 m/s and ω within the range 500-4,000 Hz. All calculations were conducted for the value of initial pressure in the closed volume 1 MPa at initial temperature T=20 °C.

As a result of calculations, a certain area of cavitation occurrence, where C>0, and unacceptable values of vibration parameters at which cavitation is maximum were obtained. In Fig. 11, the variation of speed is laid off on the X axis, frequency change – on the Y axis, weight content of the carried phase – on the Z axis.

In the course of the numerical solution analysis, dependence of cavitation parameters on vibration parameters was revealed, and the maximum is detected at frequency about 1,500-2,000 Hz. Water "boiling" is also visually detected at these frequencies during the physical experiment. It is noticed that increase or decrease of vibration frequency causes decrease of concentrations. When the wall surface movement speed of 0.1 m/s maximum concentration of cavitation bubbles observed. When the wall surface movement speed changes, the concentration of cavitation bubbles decreases. In such a way, an influence domain of vibration amplitudes and frequencies on concentration of cavitation bubbles was formulated.

Results obtained in the ANSYS CFX program are consistent with experimental, analytical and numerical (CFM) solutions.

VI. CONCLUSION

In the course of physical and computational experiments (ANSYS CFX), occurrence of cavitation effects upon vibrations was detected. Intensification of cavitation effects was detected at frequencies close to the resonance ones for the given system. On the basis of obtained results, it can be assumed that the unpredictable pump pressure decrease may be caused by occurring hydrogasdynamic processes which depend on structure elements vibrations.

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Ms. Gaynutdinova is the co-author of the Patent for an invention "*Sposob Provedeniya Eksperimenta po Osushchestvleniyu i Nablyudeniyu Akusticheskikh Protsessov v Zhidkoi Srede i Ustroistvo dlya Ego Osushchestvleniya*" [Method of Conducting an Experiment on Realization and Monitoring of Acoustic Processes in the Liquid Medium and the Device for its Implementation] (application registration number No. 2015139637 dated September 17, 2015).

Ms. Gaynutdinova is the winner of the open competition for the grant of the Lobachevsky State University of Nizhni Novgorod for postgraduates and graduate students of Russian and foreign higher education institutions and scientific organizations within the framework of the agreement No. 02.V.49.21.0003 between the Ministry of Education and Science of the Russian Federation and the State University of Nizhni Novgorod dated August 27, 2013 (Order of the Rector of the State University of Nizhni Novgorod No. 1798-LS dated June 30, 2014). D. F. Gainutdinova was (in 2014) a holder of the RF Government grant for those studying specialties corresponding to priority areas of modernization and technological development of the Russian Economy (Order of the Ministry of Education and Science of the Russian Federation No. 711 dated July 01, 2014 on the basis of the minutes of the meeting of the expert committee of the Ministry of Education and Science of the Russian Federation).

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The area of expertise of V. Ya. Modorsky includes problems of numerical and experimental modelling of aero-, gaso- and hydroelastic processes and evaluation of structure stress-strain state, programming and high-production computations, etc.

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