High speed visualization of self-oscillation of axisymmetric cavitating cavity in a square vortex chamber

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Abstract. An experimental investigation of the multiphase turbulent flow in a square vortex chamber was carried out to examine the self-oscillation of a cavitating cavity in a wide range of flow rates and pressure conditions. Such phenomenon is observed behind turbine runner when the hydraulic units operate at full load regime at high flowrate, and leads to significant flowrate and pressure pulsations in the entire hydraulic system. The dynamics of the cavity over time, and the frequency of the volumetric oscillations frequency was studied via high speed visualization. The grey-scale images of the vortex cavity were binarized. By assuming an axially symmetric flow, the volume of cavity for each frame was integrated, and further investigated using FFT. Quantitative information on the structure of a single-phase flow was also obtained using the PIV technique.

1. Introduction

The swirling flows can be found in many technical devices and applications: cyclone separators to separate solid particles from the gaseous phase, a vortex generators to improve stability of the flame in combustion chambers, and hydraulic turbines operating at part load regimes with extensive recirculation zone. The variety of effects associated with the flow swirl (formation of recirculation zone, stationary and non-stationary vortex structures) attracts close attention of researchers for many years. Dealing with multiphase swirling flow the study becomes much more complicated. The two-phase flow resulting from cavitation processes, greatly complicates the task of research and the analytical description of the swirling flows and the coherent vortex structures arising in them. The occurrence of a vapor (gas) volume corresponds to the introduction of a compliant element into the system, which is an additional source of unsteady pulsations. The first paragraph after a heading is not indented.

One of the problems caused by cavitation appearance in fluid machinery is the interaction with the flow path. It is generally recognized that cavitation has a significant impact on the power and operational characteristics of hydraulic units [1-3]. Compared with partial load conditions, when pressure pulsations are caused by the precession of a spiral vortex rope, in hydraulic turbines operating at full load at high discharge conditions cavitation oscillation of axisymmetric vortex rope volume is observed in the draft tube cone. This in turn leads to significant flowrate and pressure pulsations in the entire hydraulic system. Rheingans [4] was one of the first to draw attention to the problem of non-stationary processes in flow systems in the presence of cavitation. He associated the power fluctuations of a hydroelectric power plant with non-stationary phenomena occurring in the flow path, and also made attempts to classify and describe them. A more detailed systematic description was

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presented a few decades later [5, 6]. An analytical study of the characteristics of non-stationary cavitation in a wide frequency range was performed by Tsujimoto et al. [7]. Otsuka et al. [8] investigated the cavitation characteristics on the basis of a closed cavity model, in which variations in the cavity length are allowed. It was found that this model smoothly transforms into quasistationary calculations at the lower frequency limit, in contrast to the model with a fixed cavity size. It is also shown that the influence of the cavitation number on the cavitation compliance and the flow mass gain factor depends on the frequency of perturbations. Comparing with experimental data, it was found that the model describes non-stationary cavitation processes only at a qualitative level. In the swirl free conditions, Streeter [9] developed a method for calculating the cavitating flow in pipes. The model describes the passage of a rarefaction wave through a liquid and the formation of a cavitation cavity. After that, the speeds of each phase are calculated separately. The cavitating flow is enhanced by “shock” fronts of the fluid. Equations are derived for determining the velocity of shock fronts and increasing the pressure in them.

To account for the interaction of the liquid column with the cavitation (gas) cavity in the work of Chen et al. [10] developed a one-dimensional model. It was found that the effect of the diffuser of the conical section destabilizes the regime at all flowrates. While the swirl effect stabilizes/destabilizes the system at high/low flow rates than at the flow rate at which the integral swirl parameter is close to zero. In both cases, the oscillation frequency is determined from the cavitation compliance and the size of the conical section. It has been shown that in the general case the amplitude of the flow rate fluctuation is much larger in the downstream of the runner as compared to that in the upstream. Later, the Chen model was refined by Kuibin et al. [11]. In their work, it was noted that the Bernoulli equation gives an averaged pressure in the cross section of the channel but not pressure on the wall. Moreover, the pressure correction due to the swirl of flow should depend on the radius of the cavitation cavity, which was not considered in the Chen model. Also, an analytical model of a cavitating vortex rope was developed, and various vorticity distributions for axisymmetric vortices were considered. It is shown that the swirl effect on the condition of flow stability in a hydraulic system is rather weak, and its effect decreases with increasing volume of the cavitation cavity. The developed semi-empirical model of a two-phase helical vortex rope predicts frequencies that are in good agreement with the experimentally measured data at different gas contents. Among the latest experimental works, it should be pay attention to the study by Muller et al. [12, 13]. They showed that the characteristic breathing motion of the cavitation vortex rope is governed by an important variation of the flow swirl in the draft tube. It was found that the torque on the runner shaft is synchronized with the cavity oscillation. Based on the analysis of the wall pressure synchronized flow visualizations they proposed potential governing mechanism, identifying the swirl variation due to the development of cavitation on the runner blades as the key factor.

Due to the complexity of conducting experiments on full-scale hydro turbines or model stands, as well as a large number of factors affecting the vortex flow patterns, it has been attempted to isolate the experimental modeling of the formation of an axisymmetric vortex cavitation cavity in a square vortex chamber. To create a flow swirl, a combination of stationary and rotating swirler is used, which allows us to obtain velocity distributions, similar to the distributions behind a real turbine runner. Such an approach made it possible to very carefully control the main parameters: flow rate, swirl intensity and cavitation number for an isolated study of their influence on the dynamics of the cavitating vortex cavity.

2. Experimental setup and techniques
Measurements are carried out at the test facilities of the Kutateladze Institute of Thermophysics, Laboratory of Ecological Problems of Heat Power Industry, on a vertical closed-loop experimental test rig with the square vortex chamber made of Plexiglas (figure 1), providing an optical access for PIV measurements and high-speed visualization technique. The swirl generator (combination of stationary and rotating vane swirlers) designed to simulate flow in a Francis turbine operated at different discharge conditions partially reproduces the swirl generator designed at Politehnica University of
Timisoara, Romania [14]. The swirl intensity is varied by changing two main parameters: flow rate and runner rotational speed. The detailed description of experimental setup can be found in [15]. A sealed expansion tank with a free surface and a vacuum pump connected to it is installed in the upper part of the hydraulic test rig, this allows varying pressure level in vortex chamber controlling cavitation inception number.

To perform the visualization of the vortex flow pattern, a high-speed CMOS camera PCO 1200.hs is used at 820 frames per second. The high temporal resolution allowed to resolve most of the frequencies when using the fast Fourier transform to the imaging data.

![Figure 1. View of experimental setup, the main flow direction is downwards, the runner is rotated clockwise; 1 – stationary swirler, 2 – runner, 3 – magnetic couple, 4 – square vortex chamber, 5 – electric motor supply runner speed up to 3000 rpm; max Re = 10^6.](image)

During visualization, the searchlight was installed opposite the camera behind the working area, visualizing the cavitation cavity to the light. With the selected lighting scheme, due to the scattering of light at the interface, the obtained images contained a uniform light background with darker areas corresponding to the cavitating cavities. For each received half-tone eight-bit frame, a procedure to increase the contrast was carried out - one percent of the lower and upper brightness values of the pixels were discarded, and the remaining values were scaled to a range of 0-255. To determine the boundaries of the vapor-gas cavity, images were binarized – each pixel was assigned to one of two classes – the cavitation cavity or the background. The Otsu method was used to calculate the binarization threshold for the halftone image, this algorithm allows to divide the pixels into two classes, calculating such a threshold that the intraclass dispersion is minimal. Assuming that the cavitation cavity is quasi-symmetric with respect to the axis of the vortex chamber, the image area was integrated over the angle and the cavity volume was calculated, which after calibration was converted to cubic centimeters. Based on the temporal realization of the cavitation cavity volume for each mode, spectrograms were calculated using fast Fourier transform. Also, PIV system is used to obtain velocity distribution in vertical cross section in cavitation free conditions. For each investigated regime the 5000 images have been collected.

3. High-speed visualisation and PIV results
Flow similar to the flow behind the runner of the Francis turbine operated at a full load has been experimentally reproduce in a square vortex chamber. Figure 2 shows a series of images obtained from high-speed flow visualization with a shooting frequency of 850 frames per second. The selected images cover a half cycle and shows the different stages of the oscillation of the cavitation cavity at a
low-frequency. It can be seen that fragment “D” has a significantly larger cavity volume compared to “A”. As the volume of the vortex cavity increases in the flow path, the hydrodynamic resistance increases, which is accompanied by significant pulsations of the liquid column and its effect on the runner of the model turbine. Also, as the diameter of the cavitation cavity increases, the local section decreases and the local parameter of the flow swirling increases. The study of the mechanism of such self-excited oscillations is an important task in the safe operation of natural hydraulic units.

Figure 2. Evolution of vortex volume in time, $N = 860$ rpm, $Q = 112$ m$^3$/h.

Figure 3 shows the spectrum obtained using the fast Fourier transform; it can be seen that several frequencies dominate the spectrum: 3.9Hz, 9.9Hz, 30.5Hz and 121.8Hz. By decomposing the original signal at these frequencies, it is possible to obtain images of the change in volume at each frequency. The frequency of 3.9 Hz is dominant and corresponds to low-frequency “breathing” motion with the highest amplitude. Other frequencies 9.9 and 30.46 are presumably large-scale modulation of low-frequency oscillations of the volume, and the frequency 121.8 corresponds to waves propagating along the vortex, resulting in the formation of small local constriction reducing the cavity volume.

Figure 3. Power spectral density of volume pulsation, $N = 860$ rpm, $Q = 112$ m$^3$/h.

It is important to study the effect of the pressure variation (cavitation number) on the characteristics of the phenomenon of self-excited oscillations. A series of experiments was carried out at a fixed flow rate and runner rotational speed and a variation of the additional vacuum in the tank connected to the
hydraulic test rig. Figure 4 shows two spectrograms corresponding to different pressure conditions. The $dP$ value in the figures corresponds to the additional vacuum in the working section relative to the atmospheric pressure without considering the liquid level. It can be seen that, with a smaller pressure drop, $dP = -33$ kPa, the vortex cavity has much smaller volume. Analyzing the spectral characteristics, it can be found that large-scale volume pulsations at low frequency 3.9 Hz disappear, but pulsations at a frequency of 30 Hz remain and dominate.

![Figure 4](image)

**Figure 4.** Comparison at volume oscillation spectrum normalized on maxima of spectrum amplitude at different pressure level, $dP$ – pressure drop relative to atmosphere measured in vacuum chamber connected with upper part of test rig, $N = 860$ rpm, $Q = 112$ m$^3$/h.

To obtain quantitative information on the flow structure, a series of PIV measurements were carried out in the central vertical cross section of the vortex chamber. Figure 5 shows the averaged distribution of the axial velocity component, streamlines are also plotted. It can be seen that the main flow is concentrated in the central region, and in the near-axial zone a deceleration area forms and there is a significant deficit in axial velocity. A torus-shaped vortex is presumably formed in the near-wall region, which is associated with a sudden expansion of the swirling flow at the entrance to the vortex chamber. The accumulated PIV data are planned to be used in the future for POD and DMD analysis, which will allow a comparison between the obtained frequencies and the vortex structures.

4. Conclusion

Using the methods of experimental modeling in a square vortex chamber it has been reproduced qualitatively similar flow pattern as observed in a draft tube of Francis turbine operated under full load conditions. This study attempts to correlate these observations with a full load surge phenomenon in Francis turbine. Large-scale vapor-gas cavities is observed, the volume of which can oscillate significantly in time, which is an additional source of unsteady flowrate and pressure pulsations in the hydrodynamic path. Using high-speed visualization and digital image analysis allow us to obtain four different oscillation frequencies: 3.9 Hz, 9.9 Hz, 30.5 Hz, 121.8 Hz at $Q = m^3$/h. Reducing the diameter of the cavitation cavity by varying the pressure in the experimental test rig suppresses low-
frequency volume oscillations. Gathered PIV data can be used for further POD analysis or as case for CFD study.

Figure 5. Streamlines and axial velocity distribution in central vertical cross section.

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