Investigations of unsteady flow in the draft tube of the pump-turbine model using laser Doppler anemometry

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Abstract. The measurements and video observation of unsteady flow in the draft tube cone of the pump-turbine model were conducted in the Laboratory of Water Turbines, property of OJSC "Power machines" - "LMZ". The prototype head was about 250 m. The experiments were performed for the turbine mode of operation.
Measurements were taken for the unit speed value n11 corresponding to rated head in the generating mode of operation, for a wide range of guide vanes openings at loads ranging from partial to maximum value. The researches of the velocity field in function of the Thoma number were carried out in some operating conditions.
The mean values and RMS deviations of the velocity components were the results of laser measurements. The curves of the intensity of the vortex versus the guide vane opening and the Thoma number were plotted. The energy velocity spectra were presented for the points at which the most pronounced frequency precession of the helical axial vortex was observed.
Video recording and laser Doppler anemometry were made in the operating conditions of the developed cavitation. Based on the results of video observations and energy spectra obtained via LDA, vortex frequencies were determined i.e. the frequencies of the vortex precession under the runner in the draft tube cone.

1. Purpose and objectives of the test
The purpose of this test was to determine the structure of the flow in the draft tube cone of Francis pump-turbine model, as well as to obtain experimental data to verify the method for calculating.
To achieve this goal, the following was studied:

- velocity fields for a wide range of guide vane opening for loads ranging from partial to maximum value at the unit speed of rotation at unit speed of rotation close to the optimum one were obtained in the generating mode of operation;
- effect of cavitation on the velocity profiles was investigated;
- visual observation of the vortex structure through a transparent cone of the draft tube model;
- vortex precession frequencies under the runner were determined;

This paper describes the experimental setup, the measurement technique and data processing, the test results analysis and conclusions.
2. Condition measurements and experimental equipment

Tests were conducted on a closed circulation type stand in the laboratory of water turbines. This stand has been designed for the model tests of Francis pump-turbines. This pump-turbine model was tested at the operating condition for heads no more than 250 m. The flow structure was determined by using laser Doppler measurements speed (LDMS) "LAD LMZ-05". Model block was between the pressure and vacuum tanks. Head was created by means of basic pump. Nominal runner diameter was 460 mm. Measuring velocity fields were made at the turbine modes fore head of 25 m. Optimum point of the machine corresponded to the parameters as followers: n11 = 81.4 rpm, Q11 = 0.28 m³/s, A0=59.6%A0max. Maximum guide vanes opening 100 %. The Thoma number model was determined by a differential pressure transducer and electronic barometer for measuring atmospheric pressure in accordance with the recommendations of the IEC. Model tests were carried out in accordance with IEC 601931.

LDMS was set at the standard trolley with wheels removed. Laser beams came in the draft tube cone model from the side of right bank through a glass flat 148 × 158 × 17 mm. Draft tube cone was manufacture of Plexiglas. From the side of upstream and outside of the adapter visual observation of flow vortex structures in the draft tube cone was made using a video system "Rotor-3" Development of St.Petersburg State Electrotechnical University (Fig.1).

![LDMS "LAD LMZ-05" and the visual observation "Rotor -3" pump-turbine model](image)

Position of the optical axis LDMS was directed with respect to cone diameter and the horizon. In the point where beams were crossing, flow velocity was measured. Layout of the optical axis LDMS with respect to the cone and glass is shown in Fig.2. Distance between cone wall and water level in the cone was equal to 25.5 mm which was measured directly by laser Doppler anemometer (LDA). Cone diameter in the water was 371.1 mm and was measured also by LDMS. In Fig.2 one can see that the coordinate z = 198.3 mm in the water corresponds to the geometric axis of symmetry of the cone. While measuring coordinate z in the air, it is necessary to decrease coordinate z in the water 1.33 times. Radius 172.8 mm is the actual radius of the circular section of the cone at the level of the optical axis of the LDA.

Coordinate values (z) in the air and water are shown in Fig.2.
Note: 371.1 (279) - coordinate \( z \) in the water and in the (air) correspondingly.

3. Test method

Doppler velocity measurement method based on measuring the frequency of the laser radiation scattered of moving subject (in our case such objects are natural particles suspended in stand water). By means of LDMS axial and circumferential projections of flow rate which are perpendicular to the optical axis of LDA are measured. This possibility is provided by changing the orientation of the surface.

When turning surface on angle 90° back and forth per second by the laser beam from point 2 to point 3 and back periodically "rotated", and point 1 ray does not change its position. Turning surface plane rays is controlled automatically in depending on the amount and accuracy measurements of Doppler outbreaks in both coordinates (Fig. 3).

Positive direction circumferential \( V_x \) and axial \( V_y \) velocity projections are shown in Fig. 3. Positive values of peripheral speed at the far from the cone wall the direction of runner rotation and negative values correspond to opposite direction. Positive values of the axial velocity correspond to upward direction, against the main stream direction. Tests were conducted for the Thoma number 0.45 without effect of cavitation and 0.1- with cavitation mode.
4. Results of measurements and visual observations

Velocity measurement values held in the projections of 54 points along the cone diameter of the draft tube from the inner surface of glass to the inner cone wall surface. In each point 2000 verified Doppler bursts with time interval 150 seconds were measured. The resulting data of the circumferential and the axial component velocity is converted to a spline.

Point with coordinate \( z = 0 \) corresponds to the inner surface of the glass flat (point number 1), the point with coordinate \( z = 25.5 \) mm (point number 4). Thus, the first four points refer to the points in glass flat, the last point with coordinate \( z = 371.1 \) mm lies on the opposite wall of the cone. All points are equidistant with an interval of 6.92 mm. One of the points 198.3 lies on the geometric axis of symmetry of the cone (black line is on graph).

Tests were carried out at the partial loads \((A_0=44\% A_{0\text{max}})\), optimum load \((A_0=59.6\% A_{0\text{max}})\) and forced load \((A_0=76\% A_{0\text{max}})\).

There are mean values circumferential and axial velocity projections, their standard RMS deviation, as well as the energy spectra of the circumferential component velocity are shown in graphical forms in Figs. 4-5 while at steady state operating condition of the turbine for optimum unit speed rotation \( n_{11\text{opt}} \), guide vanes opening \( A_0 = 44\% A_{0\text{max}} \) and Thoma numbers of 0.45 and 0.1.

Mean axial velocity component \( V_y \) in the center of the swirling flow is directed towards to negative. Because of cavitation influence (Thoma number 0.1) the positive range of the axial component increases and shifts away from the geometric axis of symmetry (Fig.4).

Mean circumferential velocity \( V_x \) increases from negative values to positive values, at a value of Thoma numbers 0.45. At are value of Thoma numbers 0.1 positive values of the velocity shift from the symmetry axis of the cone. RMS deviation shows that in the center of the flow inhomogeneous velocity field are formed (Fig.5).

Energy spectra of the circumferential velocity component Thoma number of 0.45 there is a pronounced vortex frequency is equal to 4.33 Hz. Thoma number for 0.1 vortex frequency increases to 4.45 Hz (Fig.5).

Displacement of axial and circumferential velocities due to the formation of the vortex, which is offset from the axis of symmetry of the cone and in the core of which a vapor cavity is formed (Fig.6).
Fig. 5. Mean values of the circumferential velocity projection, RMS deviation, energy spectra of the circumferential component velocity; mode n1opt, A0 = 44% A0max

Video observation shows that the vortex is twisted in the direction of the rotation runner (Fig. 6).

Fig. 6. Visual observation of the flow vortex.
Figure 7 shows the circumferential component of the velocity projection at mode of $n_{11} = 0.91 n_{11\text{opt}}$, $A_0 = 44\% A_{0\text{max}}$, $\sigma = 0.1$. Direction swirling vortex flow pattern periodically changes its form. Vortex flow pattern is converted into a double vortex and in a few seconds it precess with frequency of approximately 10 Hz, and then in a few seconds it is converted into a single vortex with frequency of approximately 1 Hz and after it this process repeats. It should be noted that such a process of formation and decay of the vortex was always achieve at this mode. In spite of that, vortex in this mode is instable, energy spectra of circumferential velocity is stable with the main frequency $f = 3.66$ Hz. Projection of mean axial velocity and RMS deviation refers to the previous mode.
Fig. 7. Circumferential component of the velocity projection, energy spectra of circumferential velocity; mode $n_{11} = 0.91n_{11\text{opt}}$, $A_0 = 44\%A_0\text{max}$, $\sigma=0.1$. At optimal mode (Thoma number 0.1) spring up only two thin vortexes. At upper edge level of the cone vortex disappears. There by circumferential velocity component in the geometric symmetry axis increases rapidly and becomes positive value. Constructed energy spectra did not reveal the vortex frequency (Fig. 8).

When testing at the mode for $n_{11\text{opt}}$, $A_0 = 76\%A_0\text{max}$, $\sigma=0.1$, the flow forms as a large column vortex (Fig. 9). In these circumstances it was impossible to determine the values of velocities projections in the cavitating vortex area.

Mean value of circumferential velocity after for $\sigma=0.45$ flow direction becomes negative, because the flow is twisted against the runner revolution. Mean value of flow axial velocity becomes negative, except of countercurrent zone (Fig. 9).

Mean flow velocity values in depend on the guide vanes opening ($A_0\%$) is shown in Fig. 10. Circumferential velocity at partial loads is positive. At the optimum loads for guide vane opening 59.6%, the velocity reaches its maximum positive value. At forced mode the velocity decreases sharply and when maximum guide vane opening becomes negative value.
Mean axial velocity with an increasing the guide vanes opening reduces and at forced loads (70-100%) it begins to increase (Fig. 10).

**Fig. 9.** When testing at the mode for $n_{1\text{opt}}, A_0=76\%A_{\text{max}}$, the flow is formed as a large vortex.

**Fig. 10.** Mean flow velocity values versus guide vanes opening ($A_0 \%$)
5. Conclusion

• while using laser Doppler anemometer "LAD LMZ-05" it was possible to investigate unsteady flow in the draft tube of the pump-turbine model and to get reliable measuring results of different two-phase flow velocity parameters;
• velocity fields for a wide range of guide vane opening from partial to maximum value at the unit speed of rotation to the optimum one were obtained in the generating mode of operation;
• it is found that cavitation influences on velocity profiles of the flow in case of formation of the vortex in the vapor phase;
• the obtained results can be used for developing of the theory of concentrated vortices;
• it is recommended to perform further tests of the flow structure, non-steady phenomena and cavitation using laser anemometry.

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