Developing the complex method for flow investigation in a hydro-turbine model using laser anemometry and video recording

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Abstract. The complex technique using laser and video equipment in test conditions at the setups of the Laboratory of water turbines of the Leningrad Metal Plant has been developed to conduct laser measurements of velocity fields and video recording of cavitation phenomena based on the integration of the laser systems ("LAD - 0xx" and "Track-07 S"), created at the Kutateladze Institute of Thermophysics SB RAS (IT SB RAS) and JSC "IOIT." The Doppler anemometer allowed to achieve experimental distribution of the circumferential, axial, and radial velocity components at each point along the radius of the suction tube cone section of test experimental setup which has give information about vortex structure in suction turbine. The developed PTV method is described. The investigation of cavitation behind the turbine blade at test setup at velocities of 8-10 m/s is presented.

1. Introduction
Improving the efficiency, reliability and quality of hydroturbines and other hydraulic devices is an urgent task due to intense competition in the world market and in view of the trend of increasing requirements for energy efficiency and safety.

Hydrodynamic design of turbines and similar systems is realized by analyzing and varying the geometry in the numerical simulation of flow characteristics in the flow-through channel. To describe real flows in various technical devices, an acceptable accuracy of the numerical solution can be obtained only with a computational grid whose cells are smaller than the smallest vortex. It is very time consuming in terms of calculations using even modern computers. Therefore, in practice, different turbulence models are used to simplify the calculation of real flows [1]. All turbulence models have one common drawback: it is impossible to predict which of the semi-empirical assumptions about the relationship between the turbulent tangent stress and the averaged flow motion would most closely correspond to physical reality. Therefore, any mathematical model must be verified by experimental studies. Verification of compliance of the results of numerical simulation with the real characteristics of the turbulent flow is carried out on special hydrodynamic setups with the use of modern measuring systems.

The aim of the work is to create methods for integrated and coordinated use of laser and video systems in the study of the flow behind the model hydroturbine.

These methods are expedient in the model testing of new flow-through parts to solve the following problems: prediction of nonstationary phenomena on full-scale turbines (cavitation, pressure
pulsations), improvement of design methods for flow-through parts, and verification of numerical models for calculating the flow in the flow parts of hydraulic turbines [2-3].

In the course of review and analysis of existing methods (visualization and measurement of velocities) of flow research using laser and video technology in the investigation and improvement of hydraulic turbines, it has been found that for the study of qualitative and quantitative characteristics of kinematic parameters of hydraulic flows, it is necessary to use high-precision methods for diagnosing the flow behind the impeller, such as high-speed visualization in combination with point measurements by laser Doppler anemometry. It is possible to combine high-speed visualization with methods based on the flow rate measurement by analyzing the images of particle tracks in the flow (Particle Tracking Velocimetry).

2. Description of the experimental setup
In order to improve the hydraulic turbine safety and to increase their efficiency, the three-dimensional flow velocity should be measured in the cone of the suction pipe. Measurements of the three-dimensional flow velocity directly at the hydroelectric power station are difficult to realize, since there is no direct access to the flow in the suction pipes. Therefore, the best alternative to measurements directly at hydroelectric power station is to measure hydrodynamic flow parameters on large-scale models of hydraulic turbines [4-5].

To optimize the turbine parameters, three-dimensional flow velocity measurements were carried out at different turbine operating modes. Acceptable accuracy of flow rate measurement was provided and comparison with the result of direct measurements, as well as with those of calculations and experimental data of other authors was carried out. On the basis of the obtained experimental data, the influence of the hydroturbine operating modes on the structure and characteristics of the flow in the cone of the suction pipe was studied [6-7].

The flow in the draft tube cone behind the impeller of a model of adjustable-blade turbine was studied in a pilot plant of OJSC "Power machines" – "Leningrad Metal Works", based on the cavitation energy setup (CES) and a complex LAD-056. To conduct experiments on the diagnostics of 3D profiles of the flow velocity in the cone of the suction pipe, the hydroturbine model PL 30-46, z=5, φ=+15º (5 blades, blade angle φ=+15º) was chosen. This model and the flow part are the model of an adjustable-blade turbine with capacity of 20.1 MW installed at "Utanen" hydroelectric power station, Finland.

![Figure 1. Scheme of experimental setup.](image1)

1 – viewport, 2 – 3D LDA, 3 – coordinate-moving device, l – distance from the axis of blade rotation to the optical axis of LDA (l=0.291 m).

![Figure 2. Layout of the measuring system LAD-056 LMZ.](image2)
3. Description of methods

3.1. Method of laser Doppler anemometry

The technique has been developed for conducting experiments on laser probing of nonstationary and cavitating flow and for processing laser sensing information using the equipment of laser Doppler measuring system "LAD-056 LMZ". The technique allows determining stationary and non-stationary integral characteristics of the flow (flow rate, angular momentum, energy, amplitude, frequency, etc.) and characteristics of concentrated vortices (core diameter, energy, circulation, amplitude, frequency, etc.) in the flow part: in the inter-blade channel, in the suction pipe, in the wakes behind the profiles and in the gaps of the blade-runner chamber for adjustable-blade turbines.

The data analysis results from creating the database on the values of circumferential and axial velocity components at the measurement point and the corresponding result of pressure measurement on the wall of the suction pipe of the flow part of the hydraulic turbine model. The integral characteristics of the flow behind the impeller of the turbine model are estimated on the basis of approximate determination of the vortex flow structure from the measured average velocity profile. The meter was designed and manufactured by "IOIT" OJSC and IT SB RAS, Novosibirsk, Russia (Fig. 1). The anemometer allows measuring three projections of the velocity vector in the range 0.001..30 m/s with a relative error not exceeding 0.1 %. The positioning device allows shifting the measuring unit in the area of 250 x 250 x 250 mm with an accuracy of 0.1 mm. This method also serves to measure local pulsations of the flow velocity. The photo of the measuring system LAD-056 LMZ on the experimental setup is presented on fig. 2.

Laser Doppler anemometers "LAD-0xx" have been upgraded with the aim of increasing performance and sensitivity of detectors registering the scattered radiation. The registration frequency of preprocessor's analog to digital converter was increased from 20 MHz to 60 MHz, which enlarged the measurement velocity range in 3 time. And preprocessor's analog to digital converter bit depth was enlarged from 8 to 10 bit, which allowed to increase sensitivity on 20 %.

To reduce the measurement error, a special immersion container was implemented (Fig. 3). The container allows the optical axes of the devices to be located normal to the air-glass-water interface in the horizontal and vertical planes. The use of the immersion container served to increase the depth of penetration into the flow from 150 to 506.8 mm (full diameter of the flow section). This enabled diagnostics of 3D velocity profiles in the cone of the suction pipe.

![Figure 3. Geometric positioning of 3D LDA LAD-056 in relation to the immersion container.](image)

As an example, we present the results of experiments, during which the data were obtained on the distribution of the three components of the flow velocity behind the impeller of the hydroturbine model for the selected operation mode (Fig. 4.). Fig. 4 demonstrates a graph of experimental distribution of the

![Figure 4. Distribution of normalized velocity components along the radius in the regime No. 1 \(n11=129.7 \text{ rpm}, Q11=1.729 \text{ m}^3/\text{s}\).](image)
normalized circumferential ($V_\theta$), axial ($V_x$), and radial ($V_r$) velocity components at each point along the radius of the suction tube cone section for the selected operating mode. Velocity values are normalized on the superficial velocity. Along the horizontal axis, units of the radius of the suction pipe cone are plotted (radius $R$ is 253.4 mm). A negative value of the axial projection of velocity $V_x$ means that the flow is directed downwards towards the main flow, and the values $V_x>0$ correspond to the counterflow (the flow is directed upwards). A positive value of the circumferential projection of the velocity $V_\theta >0$ corresponds to the flow swirl in the direction of the impeller rotation at the near radius. A positive value of the radial velocity $V_r$ agrees with the direction from the center of the cone of the suction pipe to the walls. The number of points where the velocity was measured is 32. The averaging time in each point was 40 s. The circumferential velocity ($V_\theta$) everywhere, from the wall ($r/R=-1$) to the center of the circle ($r/R=0$) was of one sign, i.e. everywhere the fluid rotated in the direction of the impeller rotation. On the axis of the cone, there is a zone of sharp linear change in the circumferential velocity, which indicates the presence of a large vortex with a vertically located axis, rotating in the direction of the impeller rotation. It may be seen from the graphs that the distribution of the axial velocity ($V_x$) over most of the radius is uniform, except for a small area near the axis, where the velocity value rises to zero, i.e. the flow is decelerated behind the bluff body. The suction pipe weakly expands down the flow, which entails the appearance of a weak radial motion. In the middle of the radius there is an area where the radial velocity is negative $V_r<0$ and the fluid flows to the center of the cone.

3.2. Method of velocity measurement by particle tracks (Particle Tracking Velocimetry, PTV)

A complex method of simultaneous flow studies based on the integration of IT SB RAS lasers and high-speed video camera has been developed. The method of diagnosing the flow structure and nonstationary phenomena in the flow behind the impeller in the entire volume of the suction pipe provides: a qualitative study of the flow structure by the high-speed video, scanning the velocity field in the maximum available volume of the suction pipe, high-precision speed measurements by laser Doppler anemometry, pressure measurement on the walls of the suction pipe, reconstruction of the field of velocity and pressure using phase averaging in full cross-section and over the average profile by vortex core modeling.

Implementation of the technique using the methods of Particle Tracking Velocimetry (PTV) was carried out as follows: video stream was recorded, then using the software the video stream was processed using video signal processing algorithms by PTV. The algorithm for processing the system video signal by the PTV method consists of the following stages: elimination of interlacing; determination and adaptive subtraction of the background image, highlighting the particle images ("dash" and "dot" elements); binding the images into tracks, identifying the tracks of particles, constructing the vector field, and the vector field postprocessing.

**Figure 5a.** One frame of video sequence after interlacing removal.

**Figure 5b.** Background calculated by averaging on several frames of a video sequence.

**Figure 5c.** Subtracting the background, converting to black and white image, and inverting.
At the first step, the algorithm obtains the video sequence (fig. 5a) from the camera and eliminates interlacing (Fig. 5b). The adaptive statistical filtering algorithm is used to cut the background based on the dispersion and average brightness of one pixel in different frames of the video stream (Fig. 5c). If necessary, the background can be evaluated several times per experiment to increase the adaptability of the algorithm to slow changes in the scene. Further, for each frame of the sequence, the static part is filtered in order to separate information only about the tracks of particles in the frame (5c).

After adaptive filtering, the image is divided into connected areas that have not been filtered (6a). To determine the linear dimensions of the track, algorithms have been developed on the basis of the modified Hough transform and on the search for geometric shapes on the ground of morphological analysis. In the algorithm based on the modified Hough transform, the directions of the maximum and minimum length of the region are determined for each connected region of the image. The directions are determined by a modified Hough transform. The minimum length of the connected area is used to estimate the track width. The maximum length of the track is used to estimate the length of the track. The area and the center of the track mass are also determined. Connecting tracks to determine the direction of particles motion is implemented in the form of maximizing the weight functions of many criteria. The used criteria are the ratio of the minimum lengths of tracks, the ratio of the maximum lengths of tracks, the difference of angles of tracks, the difference of angles between the track and the vector connecting the centers of mass of areas, and the presence of tracks crossing the vector, connecting the centers of mass of areas. Next, for each connected region, we define the neighboring area, for which the weight function takes the maximum value. On the basis of information about the centers of mass of neighboring regions, marked as "line" and "point", the particle displacement vector is constructed (Fig. 6b).

The threshold algorithm of the weight function confidence is used to eliminate obviously incorrect vectors. The threshold algorithm of weight function confidence eliminates vectors built at a weight function value lesser than the threshold. After processing all frames, statistical vector filtering may be also performed. Filtering can be performed both in space, one frame at a time and using information about the maximum permissible velocity gradient, and in time, using information about the maximum permissible pulsations. The resulting vector field is superimposed on the background image (Fig. 6c).

The method testing is illustrated in fig. 7 and 8. fig. 7 shows the occurrence of cavitation behind the turbine blade at velocities of 8 m/s (Fig. 7a) and 10 m/s (fig. 8b). The video frequency is 6200 frames per second. The frame exposure time is 160 µs.
Figure 7. The flow at the occurrence of cavitation: a) velocity of 8 m/s, b) velocity of 10 m/s. Video frequency of 6200 frames per second. Frame exposure time of 160 µs.

Figure 8a. Visualization frame in the presence of laser radiation. Figure 8b. Vector field resulting from video data processing.

Fig. 8 shows the reconstruction of velocity vectors using PTV algorithms. The system of laser scanning of spatial flow in real time provides high-speed visualization of flows using a powerful light flux generator "laser sheet" as an illuminator and measures the vector fields of hydraulic flow at a speed of up to 30 m/s with an error not exceeding 10 %.

Conclusion
Algorithms of combined use of laser and video equipment as applied to test conditions on hydraulic setups have been developed. Laser Doppler anemometers "LAD-0xx" have been upgraded with the aim of increasing performance and sensitivity of detectors registering the scattered radiation. The technique of research of high-frequency processes behind the blade edges (Karman vortices) with the use of the Track-S 07 complex (IT SB RAS) and a high-speed video camera has been developed.

The complex technique using laser and video technology in test conditions at the setups of the Laboratory of water turbines of the Leningrad Metal Plant has been developed to conduct laser
measurements of velocity fields and for video recording of cavitation phenomena based on the integration of the laser systems ("LAD - 0xx", "Track-07 S"), created at Kutateladze Institute of Thermophysics SB RAS (IT SB RAS) and "IOIT" OJSC.

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