Application of a laser-Doppler anemometry for the study of unsteady flow structure in a model micro-hydro turbine

S I Shtork¹, I V Litvinov¹,², E Yu Gorelikov¹,², D G Mukhin¹, S V Dremov¹,² and D A Suslov¹,²

¹S S Kutateladze Institute of Thermophysics SB RAS, 630090, Russia, Novosibirsk, Lavrentyev Avenue, 1
²Novosibirsk State University, 630090, Russia, Novosibirsk, Pirogova Street, 1
E-mail: shtork@itp.nsc.ru

Abstract. Current work deals with an LDA characterization of the velocity distributions and pressure pulsation maps in an axisymmetric draft tube for the flow conditions corresponding to wide range of the operating regimes of the micro-hydro turbine unit. For the detailed analysis of the velocity profiles, three characteristic regimes corresponding to part-load regime with precessing vortex core formation, best efficiency regime and overload regime of hydro turbine operation were selected. To capture spatial characteristics of the unsteady flow for part-load regime a phase averaging procedure for the LDA data has been employed.

1. Introduction

Hydropower is the oldest and currently most developed clean energy area employing renewable energy sources [1, 2]. Hydropower has high efficiency and flexibility in load control. Currently, the share of hydropower in the global balance of power generation is about 16%. In many countries, it represents the major source of energy production, as, for example, in Norway (99%), Brazil (86%), Switzerland (76%), Sweden (50%). At present, along with large hydropower plants, small hydropower industry occupies a rather prominent place in the world. The great interest in small hydropower is due to the fact that small hydropower plants can operate both autonomously and are included in the power grid. Low-power hydro stations can be installed on small rivers or streams. As energy sources for small hydropower plants, natural elevation changes on various spillways, irrigation systems [3], pipelines and industrial spillways [4] can be used. Small hydropower plants can be installed at low cost on existing reservoirs. Small hydropower is probably one of the most clean technology to produce electricity, because small hydropower plants do not pollute the atmosphere with harmful emissions, do not block the migration ways of fish, and do not need creation of reservoirs for their work that flood large areas of land. Small HPPs do not pose a serious danger in the event of emergency situations on the plant and are characterized by short commissioning times and low operating costs. Modern equipment for micro hydro power plants can be made quite compact with automatic control system, which allows the station to operate in an automatic mode, without the involvement of staff on duty.

To develop recommendations on the organization of optimal geometric boundary conditions and operating modes of a micro-hydro turbine in terms of flow stability, minimal energy losses in a wide range of load control of a hydro-turbine apparatus, detailed studies of flow characteristics in the micro-turbine elements are necessary [5]. In that context, the current work deals with an LDA characterization of the velocity distributions and pressure pulsation map in an axisymmetric draft tube.
model for the flow conditions corresponding to wide range of the operating regimes of the micro-hydro turbine. In particular, the study focus was on determining regimes with generation of powerful flow pulsations in form of precessing vortex core (PVC). To capture spatial characteristics of the unsteady flow an ingenious phase averaging procedure for the LDA data has been employed.

Figure 1. Scheme of experimental setup (measuring cross-section shifted 4 mm down).

2. Experimental setup
A concept based on a propeller-type turbine has been chosen as a prototype microhydroturbine device [6-10]. This turbine consist of sequentially installed stationary and rotating blade elements (figure 1). As a reference case, the geometry of the axial swirlers simulating velocity distribution at the exit of a real hydroturbine [11] has been used. In particular, the geometry used was calculated for the turbine operation at the best efficiency point (BEP) for the flow rate \( Q_c = 48.5 \) l/s and the runner rotation frequency \( n_c = 40.5 \) Hz of the laboratory scale model. All the parts of the model test section were manufactured making use of a rapid prototyping technique. By applying a sophisticated software, it was possible to maintain the specified flow regime parameters within the required time with an uncertainty of 1.5 and 0.5% for setting a discharge \( Q \) and the rotation frequency of the runner \( n \), respectively. The inlet diameter of the cone draft tube was \( D = 100 \) mm. The length of the cone was 280 mm; the cone angle was 4°.

To characterize the various regimes of the hydro turbine operation, pressure pulsations were measured using two acoustic probes with the same procedure as described in [12]. Acoustic probes included measuring microphones Behringer ECM8000, which were connected to a pressure wave transmitter in the form of thin capillary. Acoustic measurements were performed on diametrically opposed sides of the draft tube cone. The acoustic probe ends were installed in the holes drilled in the cone wall at a distance of 50 mm from the cone inlet.

The averaged and phase-averaged velocity distributions of the flow were measured using a laser Doppler anemometer "LAD-06i" in the selected central cross-section as showed in figure 1. As tracers we used particles of paraffin oil aerosol, produced by Laskin atomizer, which allows obtaining droplets with a characteristic size of 1-3 \( \mu \)m [13].
3. Results

3.1. Characteristics of the flow

Figure 2 (a) shows the maximum amplitudes in the spectra of the differential signal of two sensors as a function of the flow rate and rotation speed of the impeller. This procedure allows retrieving the fluctuating signal component corresponding to the PVC and eliminate the in-phase component of pulsations [12]. It can be noticed that a shift away from the BEP, for example by reducing the flow rate below $Q_c$ at a constant rotor frequency $n_c$ (partial load) results in a rise of the pressure pulsation intensity as can be seen in the upper left area of the plot.

The figure 2 (b) shows frequencies of the maximum amplitudes in the spectra of differential signals as a function of the volumetric flow rate and the impeller rotation frequency. The diagram evidences a linear growth of the frequency with increasing of the parameters $Q$ and $n$.

To survey the velocity profiles over the full space of investigated operating parameters we have chosen the flow rates corresponding to $0.51 Q_c$, $Q_c$, and $1.51 Q_c$ at a constant rotation speed of the impeller equal to $n_c$. These three distinctive regimes correspond to part-load regime with PVC formation, BEP regime and overload regime, respectively. In figure 3, the time-averaged velocity field in the central cross-section of the draft tube cone is presented. It can be noted inspecting the velocity field plots that main features of the flow structure are very similar to those observed for the draft tube model with an elbow part [12]. For the optimal regime (figure 3 (a)) attributed to a subtle angular-to-axial momentum ratio, the axial velocity is invariably directed along the $z$-axis throughout the overall surveyed region except for the insignificant backward flow area under the cowl, which ends at a distance $z < 10$ mm. The tangential velocity distribution at the optimal conditions with flowrate $Q_c$ shows a flow pattern consisting of two concentric counter-rotating swirling flows (see two white dot lines at figure 3 (b)). The inner part of swirling flow with a transversal size of about 20 mm, slightly shifted from the cone central axes, rotates in the counterclockwise direction following the runner exit angle, but opposite to the impeller rotation direction. The external rode type flow area is unwrapped in a clockwise direction superimposed by guide vanes of the stationary swirler.

In the case of over load at flowrate $1.51 Q_c$ (figure 4), the axial velocity distribution shows that the structure of the flow significantly changed (figure 4 (a)). In the bottom part of the cone, it can be seen that there is a reducing of the flow velocity in the center of the cone. This region is associated with the formation of a PVC at the cone exit. As can be seen from the tangential velocity distribution, an axisymmetric concentrated vortex core appears in the centerline of the cone (size of vortex $\approx 10$ mm), and the flow on the periphery of the cone occupied by free vortex (figure 4 (b)). In the bottom part of the cone, PVC forms without observation of strong pressure pulsations.
Figure 3. The time-averaged velocity field in the central cross-section of the draft tube cone: axial (a) and tangential velocity (b) at flowrate $Q_c$.

Figure 4. The time-averaged velocity field in the central cross-section of the draft tube cone: axial (a) and tangential velocity (b) at flowrate $1.51 \cdot Q_c$.

In the case of part load conditions at flowrate $0.51 \cdot Q_c$ (figure 5), the axial momentum is much weaker than the angular one and the flow is forced to squeeze along the cone wall where the axial velocity attains its maximum (figure 5 (a)). The much wider central area, progressively increasing in transversal size when moving downstream, is near a stagnant flow. The tangential velocity shows that
the vortex deviates from the central position in the cone, i.e. strong PVC motion observed in the cone (figure 5 (b)).

![Figure 5. The time-averaged velocity field in the central cross-section of the draft tube cone: axial (a) and tangential velocity (b) at 0.51Qc.](image)

To understand the three-dimensional structure of the PVC, a phase averaging of the velocity field was constructed with applying the reference signal from the acoustic probe following to procedure outlined in [14]. Figure 6 presents a sample result on the phase-averaged of three components of velocity over an x-y cross-section. It can be noticed that the recirculation zone (area with negative axial velocity) and the PVC are shifted apart from the geometric centre of the draft tube cone.

![Figure 6. Phase-averaging velocity distribution at z = 4 mm cross-section.](image)
4. Summary
Current work deals with an LDA characterization of the velocity distributions and pressure pulsation map in the axisymmetric draft tube of a model micro-hydro turbine for the flow conditions corresponding to wide range of the operating regimes of the hydro turbine unit. To survey the velocity profiles over the full space of investigated operating parameters the three characteristic regimes correspond to part-load regime with PVC formation, BEP regime and overload regime of hydro turbine operation were selected. To capture spatial characteristics of PVC for part-load regime a phase averaging procedure for the LDA data has been employed. In particular, it was shown that a shift away from the BEP, for example, by reducing the flow rate below \( Q \), at a constant rotor frequency \( n_r \) (partial load) results in a rise of the intensity of pressure pulsations superimposed by the PVC. At these conditions, the axial momentum is much weaker than the angular one and the flow is drastically pushed towards the cone periphery where the axial velocity reaches rather high maximum. While the overly broad central region is occupied by a stagnant flow. Therefore, the overall flow is forced to squeeze through the narrow annulus area along the cone wall. The revealed heavy unsteadiness and nonuniformity of the flow at overload conditions would naturally lead to energy losses and reducing the hydroturbine efficiency. Thus, the problem of extending range of the stable and efficient operation of the microhydroturbine device demands for discovering ways to suppress the PVC and to perform levelling of the axial flow distribution.

Acknowledgments
The study of pressure pulsation map was carried out under state contract with IT SB RAS (AAAA-A17- 117030910025-7), the measurements of time-mean and phase-averaged velocity fields were funded by Russian Foundation for Basic Research and Government of the Novosibirsk Region of the Russian Federation according to the research project No. 18-48-540033.

References
[1] Sobolin G V, Satarkin I V and Korovin Yu I 2004 Problems of using small rivers and canals of irrigation systems for the development of small hydropower News of the Orenburg State Agrarian University 2 (2-1) 32-35 [In Russian]
[2] Jain S V and Patel R N 2014 Investigations on pump running in turbine mode: A review of the state-of-the-art Renewable and Sustainable Energy Reviews 30 841–68
[3] Shchedrin V N, Baklanova D V, Bondarenko V L and Lobanov G L 2017 Assessment of the prospects for the use of small hydropower on irrigation systems to meet the internal needs of electricity Scientific Journal of the Russian Research Institute of the Land Reclamation Problems 3 (27) 160–78 [In Russian]
[4] Popelyukh I A and Zhdanovich A A 2013 Analysis of the installation sites of micro-hydropower plants in industrial effluents of Novosibirsk In: Science, Technology, and Innovation Materials of the All-Russian Scientific Conference of Young Scientists: in 10 parts - Novosibirsk State Technical University 191-94 [In Russian]
[5] Zhang Y, Liu K, Xian H and Du X 2018 A review of methods for vortex identification in hydroturbines Renewable and Sustainable Energy Reviews 81 1269–85
[6] Ivanov V M, Ivanova T Yu, Zhdanov E P, Blinov A A and Pchelintsev S G 2010 Hydropower plant with axial hydraulic turbine of a new original design and hydraulic stand for complex modeling of flow parts of hydroturbines Polzunovskiy Vestnik 4 (2) 54-60. [In Russian]
[7] Yassi Y and Hashemloo S 2010 Improvement of the efficiency of the Agnew micro hydroturbine at part loads due to installing guide vanes mechanism Energy Conversion and Management 51 1970–75
[8] [8] ShojaeeFard M H, Mirzaei A and Babaei A 2014 Shape optimization of draft tubes for Agnew microhydro turbines Energy Conversion and Management 79 681–89
[9] [9] Nishi Ya, Kobayashi Yu, Inagaki T and Kikuchi N 2016 The design method of axial flow runners focusing on axial flow velocity uniformization and its application to an ultra-small
axial flow hydraulic turbine *International Journal of Rotating Machinery* 2016 5390360

[10] Kaunda Ch S, Kimambo C Z and Nielsen T K 2014 A technical discussion on microhydropower technology and its turbines *Renewable and Sustainable Energy Reviews* 35 445–59

[11] Sonin V, Ustimenko A, Kuibin P, Litvinov I and Shtork S 2016 Study of the velocity distribution influence upon the pressure pulsations in draft tube model of hydro-turbine *IOP Conference Series: Earth and Environmental Science* vol 49 (IOP Publishing) p 82020

[12] Litvinov I, Shtork S, Gorelikov E, Mitryakov A and Hanjalic K 2018 Unsteady regimes and pressure pulsations in draft tube of a model hydro turbine in a range of off-design conditions *Experimental Thermal and Fluid Science* 91 410–22

[13] Echols W H and Young J A 1963 Studies of portable air-operated aerosol generators *Naval research laboratory report* 16–16

[14] Litvinov I V, Sharaborin D K and Shtork S I 2015 Finding of parameters of helical symmetry for unsteady vortex flow based on phase-averaged PIV measurement data *Thermophysics and Aeromechanics* 22 647–50