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Application of the Scully model to determine the vortex core parameters in the Francis hydro turbine

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This study investigated spatial characteristics of the precessing vortex core (PVC) by using the Scully vortex model; the focus was made on the effects of additional jet injection through streamlined bodies in the center of the runner within the Francis hydraulic turbine model. The study was conducted under the partial-load conditions when intense precessing vortices developed and contributed to high-amplitude flow pulsations. The findings demonstrate that injection configurations leading to significant PVC suppression are associated with an increase in both the vortex radius and its precession radius. The results provide valuable insights for enhancing the range of stable and safe operation of hydraulic turbines.

Keywords: Scully vortex model, precessing vortex core (PVC), Francis turbine.

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Hydroelectric power plants (HPPs) provide significant power output and act as a key energy regulator in the power consumption system. In a wide range (in terms of the flowrate) of hydro turbine partial-load modes, the runner outlet flow is swirling. This leads to formation of a recirculation zone, which is accompanied by emergence of a concentrated vortex in the expanding flow [1].

While deviating from the axisymmetric position, this vortex begins to precess around the chamber geometric axis thus forming the so-called precessing vortex core (PVC). This phenomenon is accompanied by generation of intense low-frequency pressure pulsations propagating throughout the entire water duct [2], which significantly reduces the HPP operational reliability and limits the range of permissible operating modes. In this regard, development of efficient methods for actively controlling the dynamics of non-stationary vortex structures is a pressing scientific and technological task.

The goal of this study was to analyze the PVC spatial characteristics by using the Scully vortex model under different flow control strategies. The most common method for suppressing vortex structures in hydro turbines is axial injection of a constant-flowrate jet through the central part of the runner's streamlined body [3]. However, such approaches lead to a decrease in the turbine efficiency due to that a significant flow portion bypasses the runner and is considered lost. Attempts to minimize the control flow did not yield significant results, since the control methods used were based on empirical data and physical intuition rather than on systemic analysis of the pressure pulsation sources.

In the context of linear analysis of the flow resistance to disturbances, PVC gets formed in the region of instability in the wake recirculation zone and represents a global instability mode that initiates internal coupling of the swirling flow [4]. In [5], analysis of the mean flow sensitivity to disturbances was performed, which allowed revealing the influence of flow variations on the PVC dynamics. The region of maximum sensitivity was found to be near the recirculation zone in the runner central part where in this study the control jets were injected. We assume that application of a strict theoretical formalism will allow minimizing the energy consumption for the flow control.

The experimental procedure was based on studies conducted on the aerodynamic rig that was previously successfully tested in modeling flows in the Francis hydro turbine flow path [6]. Correlation of the results obtained on aerodynamic and hydrodynamic facilities confirms the possibility of transferring data from the air medium to aqueous one with observing criteria of dynamic similarity [6]. The PVC-containing swirling flow is being created by reproducing the velocity distributions typical of real hydro turbines by using two coaxial swirlers. This technique [6,7] ensures generation of flows similar to those in operating modes of a full-scale Francis hydro turbine. Configuration of the experimental facility and injection system are described in detail in [7,8].

The PVC parameters' control system is based on injecting air jets into the main flow through an additional air duct; the medium is single-phase everywhere. To create jets with different spatial orientations, a model actuator was used [7], which was a replaceable cylindrical streamlined body with holes for injection into the region of maximum flow sensitivity to disturbances. To assess the influence of jet parameters on the efficiency of impact on characteristics of PVC and flow as a whole, four actuator versions with

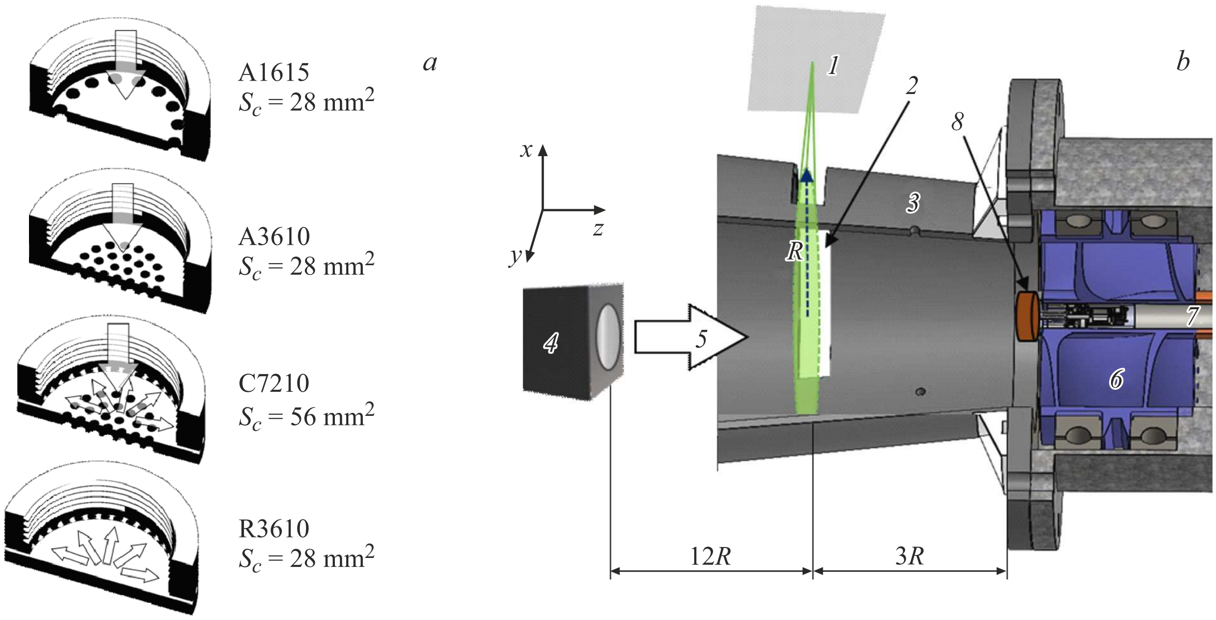

Figure 1. *a* — actuators and their parameters; the arrows indicate the direction of injection. *b* — schematic diagram of the aerodynamic rig section. *1* — PIV-laser, *2* — transparent glass (optical access), *3* — conical part of the draft tube model, *4* — CCD camera, *5* — camera shooting direction, *6* — rotating swirler (runner), *7* — supply pipe for the control air flow, *8* — actuator.

different hole configurations (Fig. 1) and total hole area S_c were used.

Variable parameters were the jets' relative flowrate Q_c/Q (where Q is the main flow rate) and injection direction: radial (R) — along the runner, axial (A) — along the axis of the draft tube conical part, combined (C) — a combination of radial and axial injection. The first two digits in the actuator model designation, after the injection direction, represent the number of holes; the next two digits are the hole diameter in millimeters multiplied by 10.

To analyze the effect of injection on the PVC parameters, a planar PIV (Particle Image Velocimetry) experiment was conducted; it provided instantaneous velocity fields in the axial cross-section with the circle radius $R = 55$ mm at the distance of $3R$ from the actuator. Specific features and procedures of the PIV-experiment in the aerodynamic flow may be found in [9,10]. Schematic diagram of the experimental setup is presented in Fig. 1. Shooting frequency of CCD-camera „JAI SP-5000M-CXP2“ was 91 Hz at the PVC characteristic frequency of 12 Hz [7]. Spatial resolution was 1.2 velocity vectors per 1 mm with the field of shot of 1850×1850 pixels. In each mode, 5000 pairs of frames were obtained. Tracer particles, namely tiny droplets of vaseline oil (Stokes numbers of the order of 10^{-4}), are mixed into the flow with the aid of an aerosol generator (Laskin atomizer). The laser sheet plane formed by double-pulsed Nd:YAG laser VLITE-HI-100 Beamtech with the wavelength of 532 nm was located in the axial cross-section at the distance of $3R$ from the runner. The velocity field was reconstructed from tracer images by using cross-correlation adaptive algorithms with continuous shifting of the window 64×64 and 32×32 pixels in size in two passes, which enabled significant expansion of the dynamic range of detected velocities.

All the experiments were conducted in the mode of hydraulic turbine partial load at the runner rotation speed of 2100 rpm and main fluid flowrate of $Q = 80$ m^3/h in the mode with the highest pressure pulsations from PVC on the draft tube walls [7]. In this mode, the Reynolds number is 19 000 which complies with the mode of developed turbulent flow. Air was supplied via the actuators through a separate duct along the runner axis (Fig. 1); its flowrate was $Q_c = 1.2$ and 2.4 m^3/h (1.5 and 3.0 % of Q). The „base case“ with the zero control flow rate and closed actuator was studied separately. A total of nine modes were analyzed. The obtained instantaneous velocity fields were averaged in every case. To perform averaging for each pair of instantaneous fields of velocity components, the instantaneous vorticity field (velocity curl) was calculated, and spatial position of its maximum was determined. For the sake of certainty, we selected the vorticity fields with the distance from the vorticity maximum to straight line $y = 0$ not exceeding $0.05R$. In this case, the maximum vorticity along axis x in different vortex passages deviated from the precession radius by no more than $0.003R$, while the vortex radius variation did not exceed 0.7 %. Based on the averaged vorticity fields, vorticity profiles were constructed in the $y = 0$ cross-section (Fig. 2). Point $x/R = 0$ corresponds to the cone axis, $x/R = 1$ corresponds to the cone wall. Since the fields are two-dimensional, there is only one non-zero vorticity component ω_z which is perpendicular to the axial cross-section plane (the laser sheet plane). Strong vorticity localization in the metering cross-section, jointly with its uneven spatial distribution (Fig. 2), evidences that

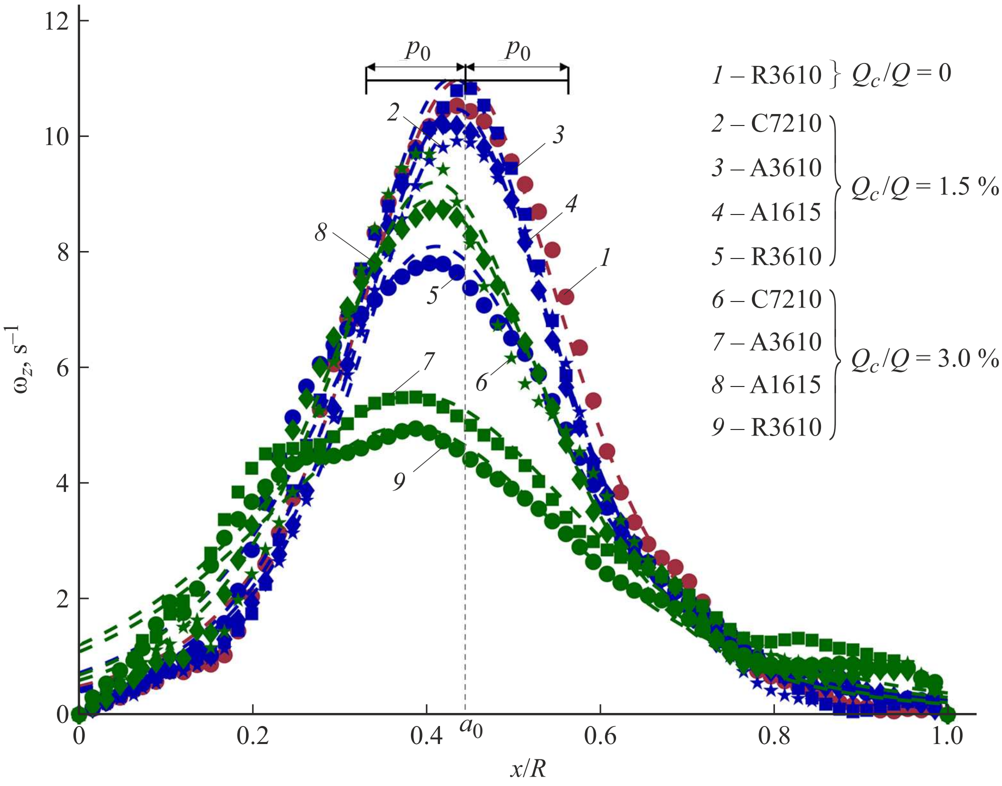

Figure 2. Profiles of the vorticity z-component with approximation by the Scully vortex model (dashed lines).

the PVC spatial parameters may be modeled either by the Lamb–Oseen vortex whose vorticity is Gaussian-distributed or by the Scully vortex whose vorticity is expressed as a fractional-power function of a coordinate. For turbulent flows, preferable is the Scully vortex, since the fractional-power vorticity distribution is more „smeared" over the distance from the axis than the Gaussian one and more accurately describes turbulent flows where vorticity more intensely passes from the flow core to periphery [11].

The vorticity distribution for the Scully vortex in the 2D velocity field has the following form [11]:

$$\omega_{z,Skulli} = \frac{Gp^2}{\pi}\frac{1}{\left((x-a)^2+p^2\right)^2}, \quad (1)$$

where G is the vortex structure intensity (circulation), p is the vortex core radius, a is the helical-vortex structure radius. The PVC spatial parameters, namely a, p, G, will be found from the condition of the best least-square fit of the Scully vortex model to the measured vorticity profile. Fig. 2 shows that experimental data on the vorticity distribution along straight line $y = 0$ are well describable by vorticity for Scully vortex (1); average determination coefficient for all the nine cases is 0.978 ± 0.018.

The Scully vortex model allows determining the precession radius and vortex core radius, which are represented in the form of histograms in Fig. 3. All the experimental results are normalized to the respective parameters (a_0, p_0) in the „base case". One can see that injection of an additional flow leads to an increase in the vortex precession radius a/a_0 proportionally to flowrate fraction Q_c/Q. The maximum increase in the dimensionless precession radius is observed for the radial (R3610) and axial (A3610) injections. A similar effect is observed for dimensionless vortex core radius p/p_0.

Comparison of the vortex core and precession radii in the case of the control flow rate $Q_c/Q = 1.5\,\%$ shows that a significantly greater increase in the core and precession radii is provided by radial injection (R3610). This means that radial injection is preferable for suppressing PVC, since even at low flowrates it allows reducing the maximum flow vorticity in the near-axial region. A further increase in flowrate Q_c/Q to $3\,\%$ allows the axial injection to become comparable with radial injection in terms of impact on the PVC parameters. Thus, the flow is more sensitive to the radial impact than to the axial one.

Actuator A1615 exhibits a weaker impact on the PVC parameters than A3610. This is associated with the holes' distribution in actuator A1615 (Fig. 1): they are concentrated on the actuator periphery, and, presumably, a part of injected jets do not get in the region of the maximum flow sensitivity to disturbances. The combination of two injection directions (C7210) has the minimum effect on the PVC characteristics; this is due to that the pulse flow is low because total area of holes S_c is larger than that of other actuators, and also due to competition of two mechanisms of impact on the recirculation zone: radial injection expands it thus promoting reduction of the

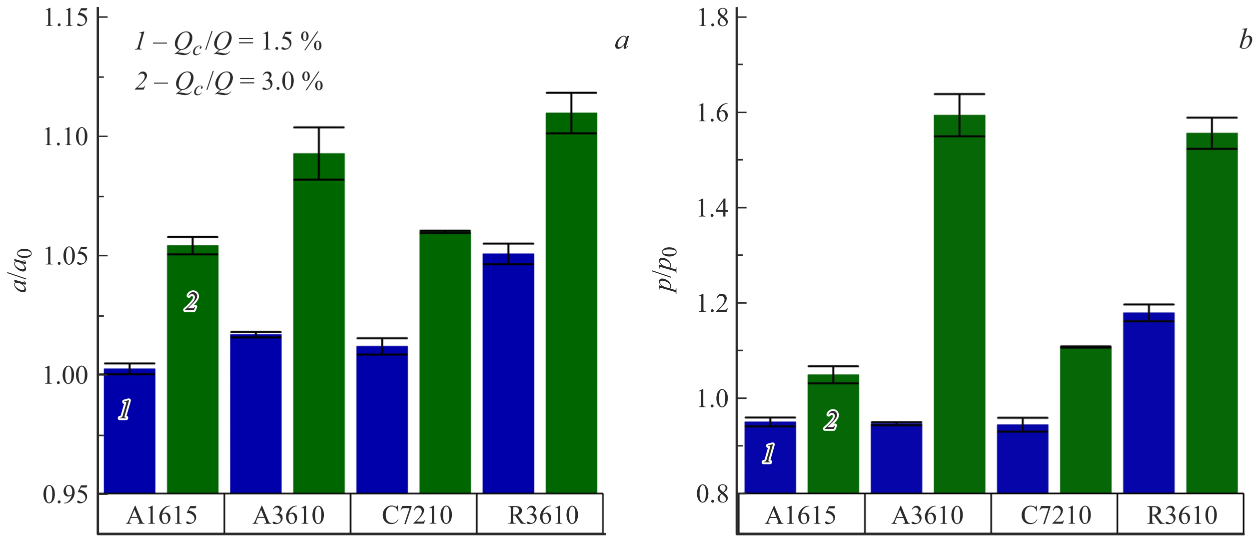

Figure 3. *a* — variation in the precession radius; *b* — variation in the vortex core radius. Variable parameters are the control flow rate and actuator. The data were normalized to the reference case (a_0, p_0) in the absence of injection.

localized core circulation, while axial injection suppresses PVC by reducing the velocity deficit near the cone axis.

The vorticity distributions (Fig. 2) demonstrate that only the axial and radial injections are capable of efficiently reducing the vorticity by about 2 times with respect to the „base case“. The decrease in vorticity indicates redistribution of the flow velocity tangential component; the flow becomes closer to the potential one. This leads to a pressure increase in the near-axial region and in the vicinity of the vortex core, i. e. the pressure difference between the axial and peripheral regions decreases and, hence, reduction of the PVC-induced pressure pulsations on the draft tube wall takes place. The simultaneous increase in the precession and vortex core radii under smoothing the vorticity profiles characterizes the general mechanism of PVC suppression in the Francis hydro turbine model: the vortex loses its coherence due to the vortex core expansion, while an increase in the precession radius may, in addition, enhance the cone-wall pressure pulsations. However, a further increase in the injected flow rate and selection of the optimal actuator geometry will promote a significant suppression of PVC-induced pressure pulsations [7]. The vortex structure disintegration associated with the PVC suppression for the most efficient injection configurations stimulates significant deviations of the vorticity distributions from the Scully distribution (Fig. 2) which is designed for modeling structures with localized vorticity.

Note that the obtained results unravel physical mechanisms of the effects and thus supplement previous studies devoted to controlling PVC within the Francis hydro turbine model by using acoustic measurements of the cone-wall pressure pulsations [7] and laser Doppler anemometry [8]. Thus, this research has shown that injection configurations providing significant PVC suppression are characterized by an increase in the radii of vortex and its precession. The Scully vortex model used to analyze spatial characteristics of large-scale vortex structures based on velocity fields has proven its adequacy for determining a number of important vortex core parameters. Data on the key spatial characteristics of the vortex may be used in further calculations of the flow and dynamics of large-scale vortex structures. The study results provide valuable insights for enhancing the range of stable and safe hydro turbine operation.

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Conflict of interests

The authors declare that they have no conflict of interests.

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