

## Connection between the spatial characteristics of a precessing vortex and pressure pulsations in a swirling expanding flow

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An experimental study was conducted on the control of a precessing vortex core in a highly swirling flow by using jet injection. It is shown that the effectiveness of suppressing strong low-frequency pressure pulsations induced by the vortex is determined not so much by the amplitude of the control action, but by its influence on the spatial structure of the vortex. It was found that radial injection affecting the global instability mechanism most effectively alters the vortex spatial parameters. The connection between the reduction of pressure pulsations and changes in vortex parameters is demonstrated.

**Keywords:** precessing vortex core (PVC), swirling flow, jet injection.

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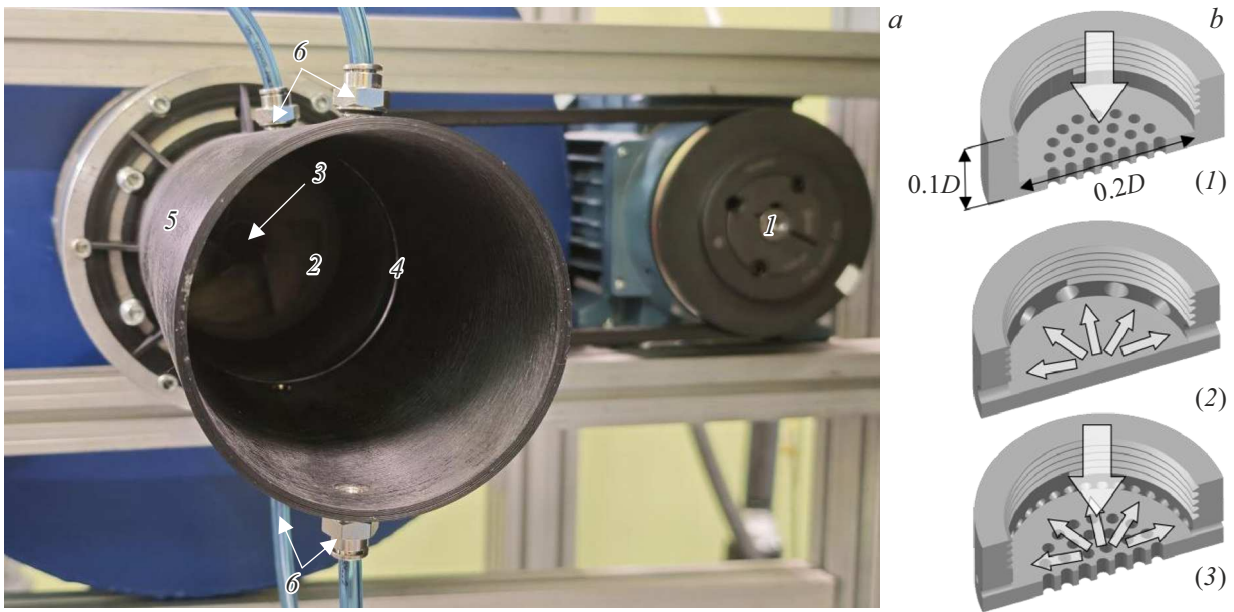
Swirling flows widely used in technical applications are characterized by formation of coherent structures, one of which is the precessing vortex core (PVC) [1–3]. PVC is a manifestation of global hydrodynamic instability arising as a result of supercritical Hopf bifurcation of a flow that is linearly unstable to small perturbations under significant swirling [4]. PVC gives rise to powerful low-frequency pressure pulsations, which is a pressing problem in, e.g., operation of hydraulic turbines [5]. In the latter, PVC generates powerful pressure pulsations inducing resonance phenomena, vibrations, and fatigue damage of structural components.

Available PVC control strategies, e.g. control via liquid injection, still remain energy-intensive. This is because the empirical approach is focused on reducing the pressure pulsation amplitudes in local regions [6] rather than on controlling the instability mechanism itself. Moreover, the pressure pulsation amplitude is an insufficient indicator for assessing the control efficiency, since the control system may induce nonlinear changes in the PVC spatial structure [7]. Variations in the PVC spatial characteristics are assumed to be an important mechanism allowing reduction of the pressure pulsations at a lower jet injection rate. However, there are no experimental data establishing correlations between the control action parameters, integral flow characteristics, and variations in the PVC spatial characteristics (such as precession radius, core size, and spatial period of the helical vortex). This work is aimed at bridging this gap. The goal of this study was establishing correlations between pressure pulsations in a swirling flow with the PVC spatial characteristics under additional injection of differently oriented jets.

Experiments were conducted on an air test bench that is able to create intensely swirling flows (Fig. 1, *a*). The swirl generator consists of two coaxial swirlers. The first

one, a stationary swirler, imparts to the flow a fixed angular momentum, while the rotating swirler located downstream additionally modifies the vorticity distribution. Independent regulation of the movable swirler rotation speed and flowrate makes it possible to realize a wide range of hydrodynamic modes, including those favorable for the occurrence of global instability like PVC with intense pressure pulsations. After passing through the swirlers, the flow enters a conical diffuser with the expansion angle of  $4^\circ$  and length of  $3.5D$  ( $D = 100$  mm is the diffuser inlet diameter) where the flow diagnostics is performed. The key parameter characterizing the flow is swirling parameter  $S$  defined as the ratio of axial angular momentum flux to the product of axial momentum flux by diffuser inlet diameter  $D$  [1]. The experiments were performed in the mode corresponding to developed PVC at  $S = 0.75$  which exceeds the critical threshold ( $S > 0.6$ ) for emergence of global instability [8]. The Reynolds number is  $2 \cdot 10^4$ ; it was determined based on the main flow mean-flowrate velocity of 3.2 m/s in the inlet cross-section with diameter  $D$ .

The control concept is based on the results of a linear stability analysis, which pointed to the region near the rotating swirler flow body as the place of maximum susceptibility to external disturbances [9]. To intentionally affect the global instability mechanism, there was developed a system of stationary actuators with diameter  $0.2D$  and length along the channel axis  $0.1D$  (Fig. 1, *b*); the actuators were installed as a replaceable flow body downstream the rotating swirler and coaxially with it at the distance of  $0.01D$ . The actuators have openings through which additional air flow is supplied via a separate independent line. The jet orientation was varied by using different actuator configurations: axial (A), radial (R) and combined axial-radial (AR) for disturbing the flow in different directions relative to the reverse flow region (Fig. 1, *b*). The first two digits in the actuator model



**Figure 1.** *a* — a photo of the aerodynamic test bench working section. 1 — servomotor, 2 — rotating swirler, 3 — actuator, 4 — laser sheet, 5 — diffuser, 6 — pressure taps. *b* — actuators: A3610 (1), R3610 (2), AR7210 (3). Arrows indicate the direction of injection.

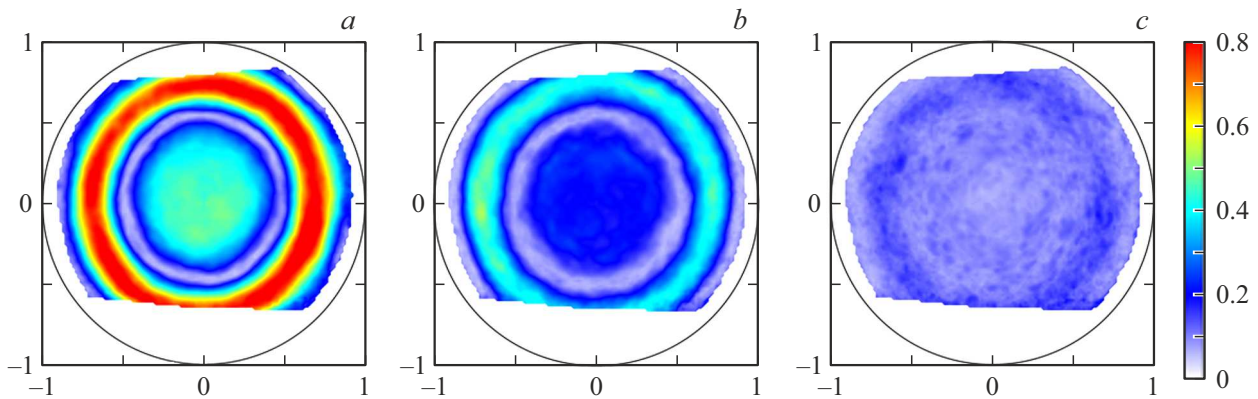
designation after the injection direction are the number of openings, the second two digits are the opening diameter in millimeters multiplied by 10. In addition, the distribution and diameters of the actuator openings were varied to alter the jet spatial distribution and depth of penetration into the main flow. The jet flowrates were 1.5 and 3.0% of that of the main flow. Configuration of the test bench and injection system is described in detail in [10].

To comprehensively characterize the spatial structure of PVC and associated pressure pulsations, a synchronized procedure was used that combined the velocity field measurements by the PIV technique (PIV is the Particle Image Velocimetry) and acoustic measurements. The planar PIV experiment was performed in the plane perpendicular to the channel axis  $1.5D$  apart the actuator. The flow was visualized by using a laser knife and tracer particles. Data were detected with a CCD camera with the frequency of 100 Hz, which provided time resolution sufficient for analyzing the PVC dynamics (characteristic frequency 15 Hz). Spatial resolution was 1 vector/mm. In each mode (21 configurations of the actuator–flowrate pairs), 5000 pairs of frames were made and processed. Total relative error did not exceed 5% due to calibration, large amount of collected statistics, and algorithms for improving the data quality.

Pressure pulsations on the diffuser wall were detected with acoustic sensors installed in two cross-sections at the distances of  $1.5D$  and  $3D$ . The sensor signals were digitized with the frequency of 1 kHz. To reveal the pulsations associated just with PVC, Fourier analysis was applied to the difference signal between diametrically opposed sensors; this is an efficient way of isolating the contribution of external common-mode noise. Besides the pressure

pulsations on the diffuser walls, of interest are pressure pulsations in the flow itself. To solve this problem, pressure fields were reconstructed from the obtained PIV velocity fields by solving the Poisson equation. To reduce the contribution of turbulent noise, the algorithm given in [11] was applied, which allows the pressure field to be reconstructed by integrating the pressure gradient using median averaging. Next, the Fourier transform was applied to each spatial point in order to realize the over-time pressure for obtaining the power spectral density (PSD) of the pressure field pulsations. Fig. 2 demonstrates the pressure PSD normalized to the maximum value in all the experiments for three most representative flow modes. Note that the pressure PSD is directly related to pressure pulsations in the flow.

The base (injection-free) case shows that pressure pulsations are mainly concentrated at the flow periphery and reach minimum in the vortex core. Axial injection (Fig. 2, *b*) demonstrates a result similar to that in radial injection (Fig. 2, *c*), although at the periphery noticeable pressure pulsations are still observed. Radial injection (Fig. 2, *c*) provides almost complete suppression of pressure pulsations as compared to the base case (Fig. 2, *a*). If the injection flowrate increases, axial injection will probably become comparable to radial injection in terms of the pressure pulsation suppression. Combined injection proved to be less efficient in controlling pressure pulsations that, however, decreased with increasing injection flowrate, although to a much lesser extent than in the case of radial or axial injection. Note that all the conclusions are in good agreement with the results of analyzing turbulence kinetic energy in the flow [10].



**Figure 2.** Normalized power spectral density under different conditions. *a* — base (injection-free) mode, *b* — A3610, 3%, *c* — R3610, 3%.

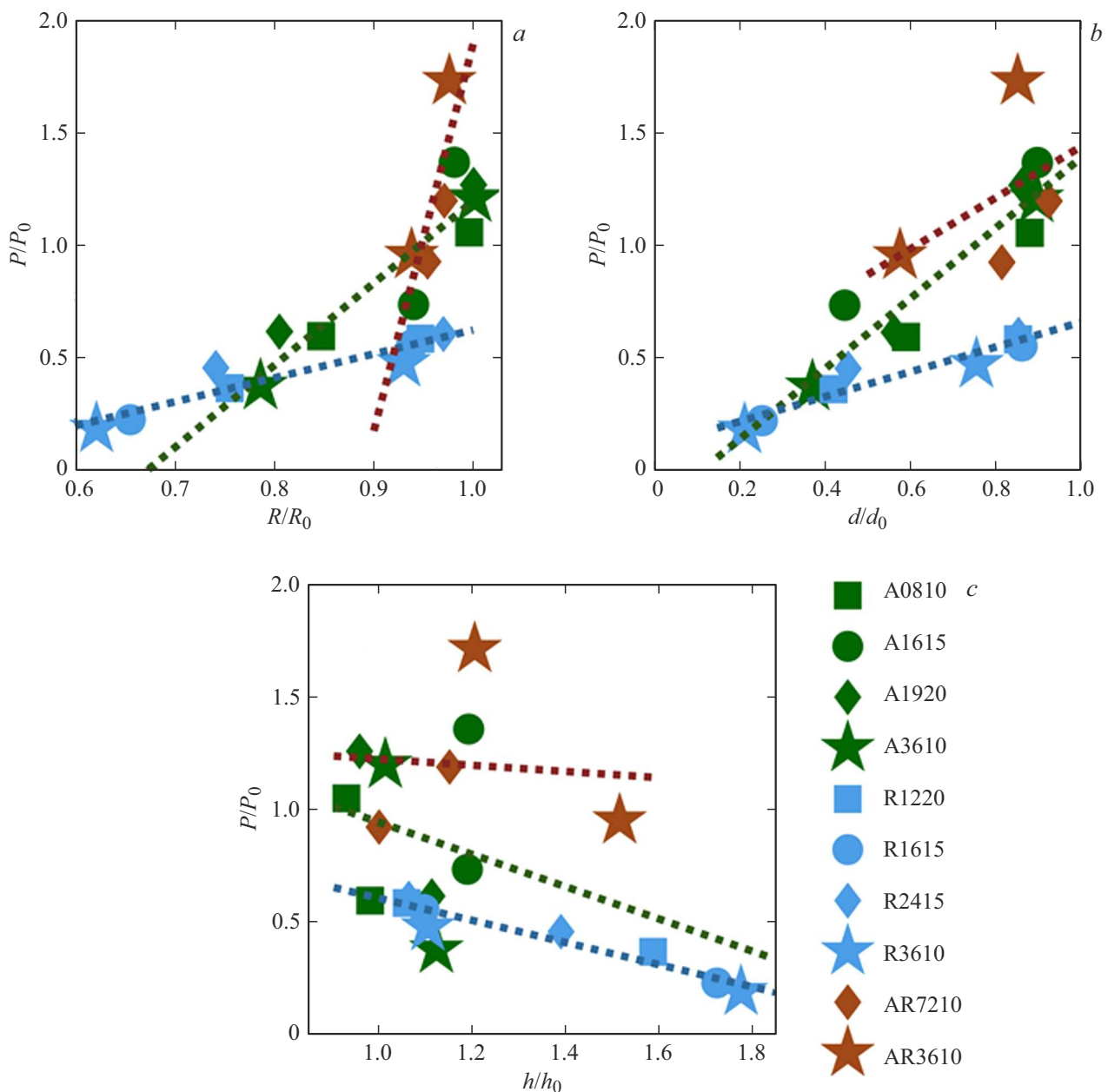
In analyzing the PVC spatial characteristics, we used the  $G$  criterion based on geometric analysis of velocity fields: at each point  $K$ , function  $G$  is calculated, which is equal to the mean sine of the angle between radius vector drawn from  $K$  to surrounding points and velocity vector at these points. Velocity vectors at the vortex center appear to be almost perpendicular to the radius vectors, which leads to the maximum value of  $G$ . This allows reliable vortex core localization even under significant background turbulence [12]. This approach enabled tracking the instantaneous vortex core position and determining the average precession radius and characteristic vortex core size. Synchronous recording, by acoustic sensors, of pressure pulsations on the diffuser walls  $1.5D$  downstream the rotating swirler (Fig. 1, *a*) and PVC velocity fields made it possible to perform phase averaging of the velocity fields, extract averaged vortex characteristics, and reveal correlations between root-mean-square magnitudes of pressure  $P$  pulsations on the walls and variations in precession radius  $R$  (Fig. 3, *a*) and vortex core size  $d$  (Fig. 3, *b*). To determine the pitch of the PVC helical structure (Fig. 3, *c*), acoustic sensors were installed in the form of diametrically opposite pairs in two cross-sections at the distances of  $1.5D$  and  $3D$  downstream the rotating swirler (Fig. 1, *a*). Helix pitch  $h$  was calculated by normalizing the reciprocal phase shift between the signals from microphones located in the near and far wake to the axial distance between them. In Fig. 3, all the parameters are normalized to the corresponding base-case (injection-free) parameters ( $P_0$ ,  $R_0$ ,  $d_0$ ,  $h_0$ ).

Evidently, the decrease in pressure pulsations correlates with reduction in both the vortex precession radius (Fig. 3, *a*) and vortex core size (Fig. 3, *b*). Note that the level of pressure pulsation reduction linearly correlates with respect to the precession radius and vortex core size. Such a linear relationship (determination coefficient 0.95) is especially characteristic of radial actuators which have previously been presented in literature rather poorly in respect to controlling PVCs in swirling flows. The relationship between pressure pulsations and vortex helix

pitch (Fig. 3, *c*) exhibits a more complex character. A clear correlation has been revealed only for radial injection which exhibits a pronounced inverse relationship: reduction of pressure pulsations is accompanied by an increase in the helical vortex pitch.

Note that axial and radial injections differently affect the PVC helix pitch. Axial injection has less impact on PVC as compared to radial injection. This is because axial jets get captured by the vortex with partially preserving its axial coherence, while simultaneous destruction of the recirculation region reduces the vortex intensity and coherence. Radial injection not interacting directly with the far-field PVC affects the fundamental instability mechanism responsible for PVC formation. Jointly with the decrease in precession radius, this leads to an efficient increase in the vortex helix pitch. PVC is subject to spatial restructuring, however, the dominant effect is the rupture of self-sustaining feedback loop resulting in efficient suppression of pressure pulsations (Fig. 2, *c*). Radial injection induced the most significant increase in the PVC helix pitch (up to 80%) simultaneously with reduction of pressure pulsations by 70–80% relative to the base case at the flowrate of 3% of the main-flow one (Fig. 3, *c*); this makes the radial injection most efficient in varying the PVC helix pitch.

The key to efficient controlling of PVC and, hence, PVC-induced pressure pulsations is an intentional impact upon its spatial topology. Correlations have been established between the control injection parameters and integral flow and PVC characteristics: reduction of pressure pulsations linearly correlates with reduction in the precession radius and vortex core size. The highest efficiency was achieved for the radial injection which breaks the feedback loop of global instability and thus initiates spatial restructuring of PVC and significant increase in the helical structure pitch. The obtained results open the way to developing optimized systems for active control of instabilities in hydroturbines and other devices with swirling flows.



**Figure 3.** Correlation of pressure pulsations with variations in the precession radius (a), vortex core radius (b), and vortex helix pitch (c). The colored figure is presented in the article's electronic version.

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### Conflict of interests

The authors declare that they have no conflict of interests.

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