Experimental investigation of vortex ring formation as a consequence of spiral vortex re-connection

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Abstract. The unsteady shape variation of a cavitating spiral vortex is experimentally studied pointing out the repetitive creation of vortex ring (or vortex loop). To generate the spiral vortex structure, a newly designed vortex generator is employed. This generator is used to study the decelerated swirling flow leading to the spiral vortex formation as a consequence of spiral vortex breakdown, which is considered to be the main triggering mechanism for the occurrence of the coherent vortex rope structure in the Francis turbine draft tube operated at part load conditions. Thanks to its design, the vortex generator enables to change the ratio between fluxes of axial momentum and tangential moment of momentum of generated swirl. Using this set-up, the behavior of the vortex structure changes in a similar way as the flow rate variation in the draft tube of Francis turbine. At certain flow conditions, the spiral vortex movement is characterized by sudden spiral entanglement leading to disconnection of a vortex ring and followed by spiral re-connection. Thanks to the transparent diffuser of the swirl generator apparatus, both high-speed camera recording of the cavitating vortex and PIV measurements of velocity fields at cavitation-free conditions are employed. The main aim of this paper is to link the visual observation of the above described vortex dynamics with the velocity fields measured in one longitudinal and one cross-sectional planes.

1. Introduction
The spiral vortex (special form of so called "vortex rope" in hydro-turbine terminology) is one of the main flow structures found in the draft tube (outlet diffuser) of Francis turbine operated at part load. At part load the flow rate \( Q \) is lower than one at the best efficiency point \( Q_{BEP} \) and the high residual swirl exits the turbine outlet and enters the draft tube where the remaining kinetic energy is transformed to the static pressure. This decelerated swirling flow tends to be unstable, thus the highly unsteady pressure field with the spiral vortex rotating within 30-50% of the runner speed is formed. The resulting high pressure amplitudes strain the mechanical parts of the turbine (e.g. blades, bearings) [1], cause power swing in electricity generation [2, 3, 4] and produce significant mechanical noise. For this reason it is important to understand the main source of dominant frequencies which could also cause resonance of some parts in hydraulic system. In order to study dynamical behavior of such vortex structure the simplified approach consisting of swirling apparatus was employed in several researchers’ studies [5, 6, 7, 8, 9, 10] and various spiral vortex behaviors were reported: transition from single to twin spiral vortex
[11, 12], self-oscillating vortex rope dynamic of synchronous character [13, 14] and finally the vortex re-connection with formation of vortex rings [15, 16, 17]. It is important to understand all these mentioned instabilities since they might be linked to the vortex rope observed in the upper limit of the range of the partial-load vortex at $Q = 0.8 - 0.9Q_{BEP}$ where the transition between different vortex structures can be found [18, 19]. This is also the case of ongoing research at Viktor Kaplan Department of Fluid Engineering, where the next evolution of swirl generator apparatus was developed. With the spiral vortex breakdown as the main motivation, the study also presents the vortex phenomenon leading to the formation of vortex ring as a consequence of spiral vortex re-connection. This phenomenon was already partly observed in flow field generated by the previous design of our swirl generator and was linked to be a side effect of vortex shape transition producing the significant synchronous pressure pulsations and decrease in frequency of asynchronous pressure pulsations alongside the diffuser cone [20].

2. Swirl generator

The vortex generator presented in this study is the next generation of previous type used for several research studies of spiral vortex breakdown [8, 21, 20, 22]. Contrary to previous one the new geometry enables to change ratio between fluxes of axial momentum and tangential moment of momentum of generated swirl. The motivation was to change the swirl parameters while keeping the simple design for manufacturing and operation. Thus preferably without any rotating part. This was ensured by the inflow separated to axial and tangential entrance. The tangential inflow is mixed with axial one using the spiral geometry without any blade cascade. The swirl generator geometry and its main dimensions are shown in figure 1.

![Figure 1. Dimensions of swirl generator.](image)

3. Measurements

Measurements were performed using the closed loop hydraulic circuit where the water is supplied by the pump situated in the basement of laboratory. While the main pipeline system together with the suction tank are made of stainless steel, the rest of the circuit can be easily reconfigured using plastic pipes. For both axial $Q_a$ and tangential $Q_t$ inflow the static pressure level and flow rate were measured. The photo of test-rig with installed swirl generator is shown in figure 2. The flow regime investigated in this study was selected according the most often occurring appearance of the vortex ring onset. This phenomenon was most significant at swirl regime 50:50 of axial to tangential flow rate considering the nominal flow rate of $Q = 10 \text{ l/s}$. 
3.1. High speed camera recording
For the image recording of cavitating vortex the high speed camera Ximea CB120MG-CM-X8G3 was used. This camera, consisting of 12 MPx monochrome CMOSIS sensor, was equipped with Canon EF 50 mm f/1.4 USM lens characterized by a very good aperture and focal length without image distortion. For the scene illumination the 238 x 190 mm large LED lightening panel Aputure Amaran HR consisting of 672 LED bulbs was used. In order to record vortex structure filled with the water vapors, the so called back-light method was employed as suitable and previously proved technique. According to the layout shown in figure 3 the camera, light and recorded object are situated inline. While the camera is heading towards the light source, the recorded object is in the middle of the scene. In our case the diffuser was manufactured from acrylic glass, thus it is fully transparent. The LED panel was placed just aside the diffuser wall and camera was placed approximately in distance of 0.5 m. The final record was done with aperture F2.5 and frame rate 1487.5 fps.

![Figure 2. Test rig overview.](image1)

![Figure 3. Layout of HSC recording.](image2)

3.2. PIV measurements
PIV measurements in one longitudinal and one cross-sectional plane was carried out with stereoscopic layout employing two NanoSense Mk III cameras from Dantec Dynamic A/S. Cameras were equipped with Nikon lenses. The Pegasus PIV laser from New Wave Research was used as the light source. As shown in figures 4 - 5, for calibration purpose the multi-level targets were designed and 3D printed exclusively for this application.

![Figure 4. Calibration arrangement for longitudinal target.](image3)

![Figure 5. Calibration arrangement for cross-sectional target.](image4)

Since the calibration target has multi-level layout the white calibration dots are alternately distributed on the front and back planes. The measured plane is the one where the central
(zero) calibration marker is placed, thus the one with raised dots. Consequently the laser sheet must match this plane location. The water was saturated by a borosilicate silver coated glass particles from Dantec. Diameter of particle is $10 \mu m$ with spherical shape and smooth surface. Totally 1636 snapshots were acquired with record length $t = 3.27$ s.

4. Results
The vortex ring creation for 50:50 of axial to tangential flow ratio is shown in figure 6. The time interval between consecutive snapshots is $\Delta t = 6.7 \times 10^{-4}$ s. Spiral vortex re-connection was observed randomly, without any periodicity and at various locations. This is in agreement with other studies thoroughly examining the exact mechanism of this phenomenon [23, 16].

![Figure 6. Vortex ring creation for 50:50 of axial to tangential flow ratio.](image)

Skripkin et al. found that vortex ring formation scales at high flow rates within the boundaries of the swirl number from $S = 0.4$ to 0.5 [17]. From CFD analysis it was found that for the 50:50 flow ratio the swirl number at the diffuser entrance is $S = 0.52$, which is very close to above mentioned range.

![Figure 7. Vortex ring creation visualized by contours of $\Omega_z$, (consecutive snapshots).](image)
Since it was technically impossible to simultaneously perform PIV measurements together with the HSC recording, the exact identification of vortex ring formation from PIV velocity fields is rather difficult. Therefore the main aim was to plot the velocity field pointing out the spiral vortex instability which is consequently reflected in vortex ring formation. For this purpose the vorticity component $\Omega_x$ perpendicular to longitudinal $Z-Y$ plane was calculated. Considering that the vortex ring heading towards the upper or lower diffuser wall creates nearby local vorticity minimum and maximum, the possible appearance of vortex ring formation in velocity fields might be identified as shown in figure 7. Nevertheless, even from the contours of $\Omega_x$, identification of exact snapshot where the vortex ring passes the measuring plane might be only guessed. The standard deviation (RMS) of all three velocity components is relatively high compared to the mean values. Especially in case of radial velocity where the $v_r\text{RMS} = 2 \text{ m/s}$ is almost in order of its mean value. Only the small back-flow area was identified for this flow ratio confirming that the vortex structure is strongly inconsistent in time. The time-averaged velocity and vorticity fields are shown in figures 8 - 11. One can see that either small or large non-axisymmetrical character might be found. Especially the radial velocity field at the diffuser inlet is far from being axisymmetric. The radial velocity is rarely measured by either LDV or PIV at the turbine runner outlet. Nevertheless, as Tridon et al. shown the non-axisymmetrical character in velocity fields might be found at the draft tube inlet of Francis turbine [24]. Since the radial velocity is good measure of flow field unsteadiness, this non-axisymmetrical flow might be responsible for the various vortex shape transitions, e.g. twin vortex, spiral entanglement and vortex re-connection. In our case most likely we might link the non-axisymmetrical flow fields to the way how the axial and tangential inflow is mixed in the spiral part of our swirl generator.

5. Conclusions
The unsteady spiral vortex structure was studied using simple device of newly designed swirl generator apparatus. The experimental results of cavitating vortex record pointed out the random character of vortex ring formation. Several occurrences of this phenomenon in swirl apparatus with different geometry lead to conclusion, that the vortex ring formation as a spiral
vortex re-connection is independent of the geometrical features, but rather linked to the flow field unsteadiness itself. From analysis of experimental data, the dominant vortex frequency at 50:50 axial to tangential flow regime was found in range of 25 - 30 Hz. The statistically estimated frequency of vortex ring formation is approximately one third lower than vortex rotational frequency. This is in agreement with findings of Skripkin et al.\cite{16}. Nevertheless, since the vortex structure is strongly inconsistent in time and the PIV measurements were done separately from the video record, the exact link between measured velocity fields and visual observation of vortex ring creation is rather difficult. For this reason the further investigation will consist of CFD simulation in order to capture this vortex phenomenon and preferably the exact swirl ratio which bounds the regimes with and without vortex ring formation. Probably the scale resolving simulations, employing SAS or SBES models, or large eddy simulations will be necessary for this purpose\cite{25}.

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### References

[1] Frunzˇaverde D, Muntean S, Mǘrginean G, Cǎmpian V, Marşavinina L, Terzi R and Şerban V 2010 IOP Conference Series: Earth and Environmental Science 12 012115 URL
[2] Rheingans W J 1940 Transactions of the ASME 62 14
[3] Silva P C O, Nicolet C, Grillot P, Drommi J L and Kawababini B 2017 IEEE Transactions on Industry Applications 53 3345–3354
[4] Valentín D, Presas A, Eguquisqua E, Valero C, Eguquisqua M and Bossio M 2017 Energies 10
[5] Susan-Resiga R, Muntean S, Tanasa C and Bosioc A 2008 4th German–Romanian Workshop on Turbomachinery Hydodynamics (Stuttgart, Germany) pp 1 – 16
[6] Gramlich M 2012 Numerical Investigations of the Unsteady Flow in the Stuttgart Swirl Generator with OpenFOAM Master’s thesis Chalmers University of Technology Gothenburg, Sweden
[7] Bosioc A I, Susan-Resiga R, Muntean S and Tanasa C 2012 J. Fluids Eng. 134 11
[8] Stefan D, Rudolf P, Muntean S and Susan-Resiga R 2013 Engineering MECHANICS 20 339–353
[9] Javadi A and Nilsson H 2017 Engineering Applications of Computational Fluid Mechanics 11 30–41
[10] Litvinov I, Shotork S, Gorelikov E, Mitryakov A and Hanjalić K 2018 Experimental Thermal and Fluid Science 91 410 – 422
[11] Tsyov M A, Skripkin S G and Shotork S I 2015 2015 5th International Youth Conference on Energy (IYCE) pp 1–5
[12] Skripkin S, Tsyov M, Shotork S and Hanjalić K 2016 Journal of Hydraulic Research 54 450–460
[13] Müller A, Yamamoto K, Alliguë S, Yonezawa K, Tsuchimoto Y and F F A 2015 J. Fluids Eng. 138 8
[14] Stuparu A and Susan-Resiga R 2015 6th IAHR International Meeting of the Workgroup on Cavititation and Dynamic Problems in Hydraulic Machinery and Systems (Ljubljana, Slovenia) p 8
[15] Alekseenko S V, Kuibin P A, Skripkin S G, Sonin V I, Tsyov M A and Ustimenko A S 2016 IOP Conference Series: Earth and Environmental Science 49 082025 URL
[16] Skripkin S G, Tsyov M A, Kuibin P A and Shotork S I 2017 Journal of Fluids Engineering 139
[17] Skripkin S, Tsyov M, Kuibin P and Shotork S 2019 Experimental Thermal and Fluid Science 100 349 – 359
[18] Dörfler P, Sick M and Coutu A 2013 Basic Concepts (London: Springer London) pp 1–31
[19] Nishi M and Liu S 2013 International Journal of Fluid Machinery and Systems 6 33 – 48
[20] Stefan D, Rudolf P, Hudec M and Habán V 2015 6th IAHR International Meeting of the Workgroup on Cavititation and Dynamic Problems in Hydraulic Machinery and Systems (Ljubljana, Slovenia) p 8
[21] Stefan D, Zubik P, Hudec M and Rudolf P 2015 EPJ Web of Conferences vol 92
[22] Kozák J, Rudolf P, Hudec M, Stefan D and Forman M 2018 J. Fluids Eng. 141 11
[23] Alekseenko S V, Kuibin P A, Shotork S I, Skripkin S G and Tsyov M A 2016 JETP Letters 103 455–459
[24] Tridon S, Barre S, Ciocan G D and Tomas L 2010 European Journal of Mechanics - B/Fluids 29 321 – 335
[25] Minakov A V, Platonov D V, Litvinov I V, Shotork S I and Hanjalić K 2017 Journal of Hydraulic Research 55 668–685