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EFFICIENT RADIAL-AXIAL JET FOR IMPROVING THE FLEXIBILITY IN OPERATION OF HYDRAULIC TURBINES

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ABSTRACT

In industrialized nations, the prevailing mandates necessitate the adoption of renewable energy to the maximum extent practicable. A substantial challenge associated with renewable energy is the intrinsic variability in power generation. The exclusive mechanism currently available for rapid compensation of energy is facilitated by hydroelectric power plants. Notably, hydroelectric power plants, particularly those with hydraulic turbines featuring fixed blades (e.g., Francis turbines), are designed to operate near the optimal operating point with an allowable deviation of up to ±10%. The conventional configuration of a Francis turbine consists of stationary stay vanes, guide vanes, and a radial-axial runner with fixed pitch blades. The swirling flow emerging from the runner blades is typically optimized for peak overall efficiency, thereby reducing losses in the draft tube cone. However, at off-design operating points, there is a sudden increase in draft tube cone losses, alongside pronounced flow instabilities.

This paper introduces a novel approach involving the injection of a radial-axial water jet into the draft tube cone. The radial-axial jet injection necessitates a lower flow rate compared to traditional axial water injection, while effectively mitigating hydraulic instabilities (such as the vortex rope) within the draft tube cone. The investigations will be conducted numerically by examining the flow dynamics and analysing the unsteady static pressure from the walls within the draft tube cone. Ultimately, the paper will assess the ratio between the draft tube pressure amplitude and the requisite flow rate to alleviate these instabilities.

Keywords: Hydraulic Turbines, LDA, Numerical Simulation, Part Load Operation, Radial-Axial Water Jet.

NOMENCLATURE

D_h	[m]	main runner hub diameter
D_t	[m]	main runner tip diameter
n	[rpm]	rotational speed
Q_n	[m^3/sec]	nominal flow rate discharge
V_m	[m/sec]	meridional velocity
V_m	[m/sec]	meridional velocity
V_u	[m/sec]	circumferential velocity
V_{ref}	[m/sec]	reference velocity

1. INTRODUCTION

In the last decades the renewable energy experienced a spectacular development all over the globe. The same trend was observed in Europe and also in Romania, where the renewable energy was developed especially on solar and wind energy generation. Accordingly, the amount of renewable energy in the electricity generation in Romania increase with approximately 10% in less than 8 years, and this trend is increasing constantly. A significant challenge associated with renewable energy is the variability of the produced power. At present, the sole method available for prompt energy compensation is provided by hydroelectric power plants, [1].

Hydroelectric power plants, particularly those equipped with hydraulic turbines featuring fixed blades, such as Francis turbines, are engineered to function near the optimal operating point, allowing for a deviation of up to ±10%. The classical Francis turbines design includes the stationary stay vanes and guide vanes and a radial-axial runner with fixed pitch blades. The swirling flow exiting the runner blades, usually optimised for a peak overall efficiency with corresponding minimum draft tube cone losses. At off-design operating point, the draft tube cone losses abruptly increase, with severe flow instabilities, [1], [2].

The energy market necessitates that hydraulic turbines operate within an increasingly expansive range, between -35% and 20% from the optimum operational point [2]. Operating hydraulic turbines far from their optimal point results in the emergence of a decelerated swirling flow with instabilities downstream from the turbine, a phenomenon referred to in the literature as the vortex rope. Hydraulic instabilities form at the boundary between the main flow zone—when operating at partial flow near the cone wall—and the stalled area situated at the center of the conical diffuser [3][4][5]. The primary objective of the draft tube cone is to convert the surplus kinetic energy into static pressure, thereby recovering a significant portion of the hydraulic energy and enhancing turbine efficiency. Typically, hydraulic instability originating from the draft tube cone is accompanied by high-pressure pulsations that propagate throughout the hydraulic system, diminishing hydraulic losses and subsequently reducing turbine efficiency. Operating at partial flow rates often results in cracks on the runner blades or the removal of the ogive from the crown type of the runner. These adverse effects and incidents necessitate the cessation of the hydroelectric power plant's operations, leading to substantial economic losses due to repairs and its withdrawal from electricity production, as noted by Casanova et al. [6]. Generally, mitigating the effects of pressure fluctuations induced by hydraulic instabilities involves constraining the turbine's operating range. Consequently, the hydroelectric power plant's function as an energy compensator within the national electrical system remains unfulfilled. Numerous methods have been developed over the years to extend operating regimes while moderately developing hydraulic instabilities. Most solutions are related primarily to the effects, rather than addressing the root cause of hydrodynamic instability. Among the most prevalent solutions are filling the stalled region within the middle of the draft tube cone with air or solid bodies [8][9], or reducing decelerated swirling flow near the conical diffuser wall by installing different fins or channels [10]. Nonetheless, all these methods focus on the effects of hydraulic instabilities rather than addressing the root cause, which, in this context, is the decelerated swirling flow emanating from the runner turbine's outlet. The Laboratory of Hydraulic Machinery and the Research Centre for Engineering of Systems with Complex Fluids (RCESCF) at the Politehnica University Timișoara (UPT) focusses on the investigation of hydraulic machines. An experimental test rig has been developed to study the decelerated swirling flow from the conical diffuser of hydraulic turbines, as depicted in Fig. 1.. The vortex rope is developed in the draft tube cone (or conical diffuser) with higher pressure fluctuations and vibrations, Fig. 1.

In the last decade, a new active control method has been proposed and patented by Resiga et al. [11][12], axial water injected through the runner’s crown along the draft tube cone. The method was intensively experimented by Bosioc et al. [13][14] in the laboratory, where the control method proved the efficiency and diminish the flow instabilities from the draft tube cone. The method addresses directly to the cause of flow instabilities, and it acts on dynamic behaviour (by reducing the pressure fluctuations and vibrations) and flow behaviour (modifies the structure of the flow, by eliminating the formation of the vortex rope). As a result, the water jet injection trough the runner crown has been tested in other laboratories on model turbines and has been implemented in real hydropower plants, [15] [16]. Anyway, the major obstacle on implementing this control method in the power plants on large scale, is related by the higher volume of water (more than 15% from the main flow rate) necessary to be axially injected through the ogive in the draft tube cone.

2. METHOD FOR REDUCING THE HYDRAULIC INSTABILITIES AND THE EXPERIMENTAL SETUP

Recently a series of numerical investigations, reheated the idea of water injection in the draft tube cone, [16][17] with similar results in diminishing the flow instabilities from the draft tube cone at part load operation. The investigations performed by two different research collectives [17][18] concentrated on ogive or nozzle modification with the purpose to reduce the amount of water necessary for injection. The results show that a radial-axial water jet can reduce the effects of the vortex rope while using a water jet flow rate of approximately 10% from the main operating flow rate or even less.

The main goal of the paper is to investigate a new concept by using an actuator mounted at the end of the ogive. The actuator will provide a radial-axial water jet in the draft tube cone. According with Fig. 2, the swirl generator which consist by the fixed stay vanes and the runner and continues with the ogive, has an actuator (shown in red) with the possibility to move and positioning at the inlet in the draft tube cone. In comparison with the axial water jet control technique already validated in the laboratory, the concept for radial-axial water jet it comes with the following advantages: 1) efficient jet - reduces the amount of flow rate for water injection from 14% up to 10%; 2) efficient jet - the displacement system has the possibility to provide axial or radial-axial or radial jets, depending by the hydrodynamic instability developed in the drat tube cone.

The main purpose of the new concept of efficient jet is to add flexibility in operation for the hydraulic turbines to avoid the draft tube performance deterioration at off-design operating conditions. Moreover, the main runner operation is not influenced, and the radial-axial water jet will function only when the machine is operated at part load or full load with the development of the vortex rope.

The principle of modulating the decelerated swirling flow within the conical diffuser has been investigated through numerical analysis [18]. In alignment with this theoretical framework, the research objective is to provide an optimal configuration at the draft tube cone inlet. To achieve this optimum configuration, three conditions must be addressed: minimizing hydraulic losses, maximizing pressure recovery, and minimizing pressure pulsations within the draft tube cone. The implementation of a radial-axial water jet facilitates the fulfilment of these conditions with the least energy required for radial-axial water injection.

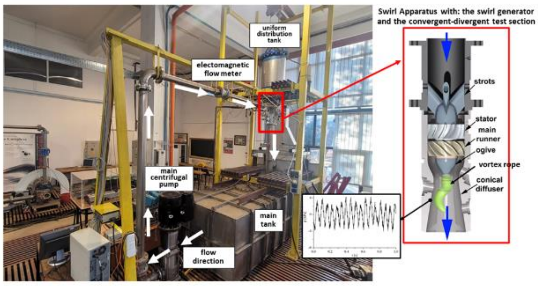


Figure 1. The test rig from the laboratory similar with the numerical model employed in this paper.

The computational model utilized for evaluating the radial axial jet within the discharge cone of hydraulic turbines is linked to the swirl apparatus present within the laboratory environment. This swirl apparatus facilitates the investigation of various control methodologies aimed at alleviating flow instabilities associated with the vortex rope phenomenon. The apparatus, integrated into the primary hydraulic circuit of the test rig, comprises two principal components: the swirl generator and the test section. The swirl generator itself is composed of three parts: the ogive, the stator, and the main runner, which are installed within a cylindrical Plexiglas section with an internal diameter of 0.150 m, as illustrated in Figure 1. At the inlet of the conical diffuser, the stator and main runner generate a rotating flow analogous to that observed downstream of a Francis runner operating at 70% of the nominal flow rate, [13].

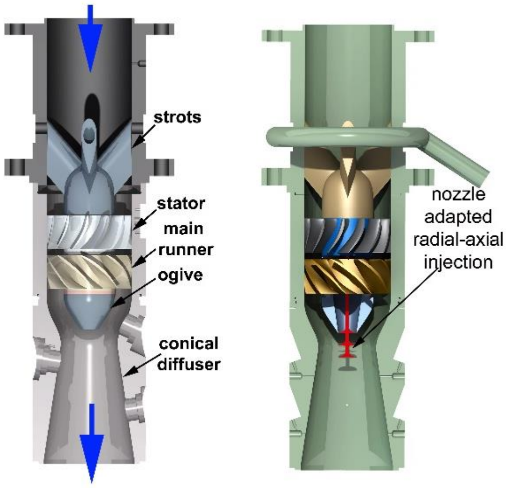
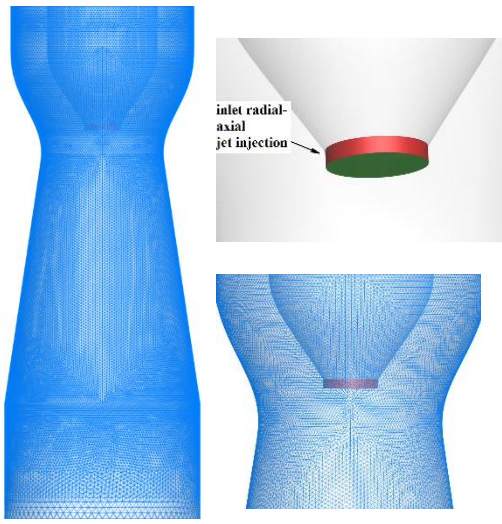


Figure 2. The swirl apparatus and test section from the experimental test rig are illustrated. The left image depicts the original configuration, whereas the right image displays the setup with the device designed to facilitate a radial axial jet rig.

The main dimensions of the components from the swirl apparatus together with the dimensions of the radial axial concept are presented in Table 1.

3. NUMERICAL SETUP

The computational domain pertains to the convergent-divergent segment of the swirling flow apparatus developed at Politehnica University Timisoara (UPT) [19]. The convergent segment is delineated by the annular inlet section and the throat, as depicted in Figure 2. Figure 3 illustrates the computational domain inclusive of the jet injection device. A mixed mesh, comprising approximately 2.8 million cells, has been generated.



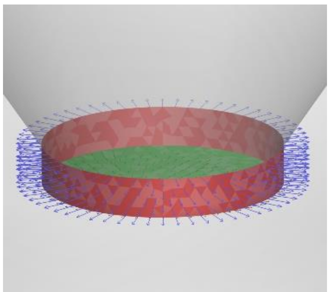


Figure 3. Mesh domain for the convergent-divergent test section and the detail of the inlet for radial-axial jet injection.

For each scenario, boundary conditions are prescribed utilizing a velocity profile at the domain's inlet and an outflow condition at the outlet section. The inflow boundary conditions are derived by computing the flow upstream of the numerical domain from our preceding research work. Consequently, the inlet velocity profile (covering axial, radial, and circumferential velocity components) in addition to the turbulent quantities (kinetic energy and turbulence dissipation rate) corresponding to a runner speed of 920 rpm are applied to the annular inlet section. Figure 5 shows the velocity profiles from the inlet test section. Two flow rates values were tested for the jet injection device: 1.5 l/s and 3 l/s. For the two values of the flow rate of the jet, corresponding constant velocity values were imposed on the outer section of the jet injection device.

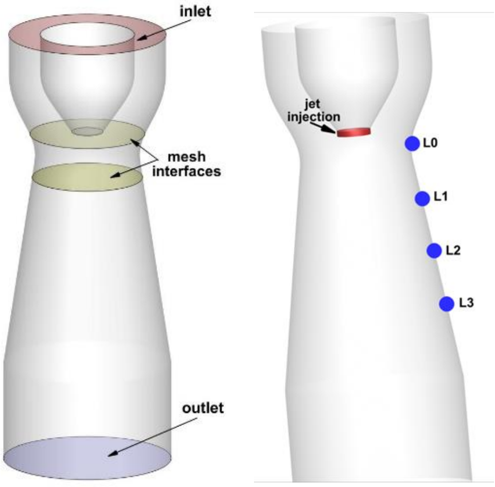


Figure 4. Full 3D domain: with the development of the vortex rope (left), with nozzle for radial axial jet injection (right)

Three-dimensional unsteady numerical simulations, both with and without jet injection, were undertaken utilizing Ansys FLUENT 2023 R2 software to evaluate the efficacy of the novel approach in mitigating the vortex rope. In modelling the turbulent flow within the domain, the k-ω GEKO turbulence model was employed. This turbulence model has been recently introduced into Ansys FLUENT and is more adept at accurately capturing the flow characteristics specific to hydraulic machines. The advantage of this turbulence model lies in its flexibility to encompass a wide array of applications. The model offers free parameters that may be adjusted for specific application types, without adversely affecting its fundamental calibration. This attribute constitutes a potent tool for model optimization; however, it necessitates a thorough understanding of the coefficients' impact to prevent mistuning. It is vital to underscore that the model possesses strong default settings, enabling its application without modification, although any adjustments should be substantiated by high-quality experimental data. The time step applied for the unsteady simulation for all the investigated cases was t = 0.002 s. All numerical solutions were converged down to residuals as low as 10^{-4}. Pressure monitors, L0…L3, have been placed on 4 levels on the cone wall, at 50 mm on each other, in order to acquire the pressure evolution of the flow phenomena.

Table 1. Hydraulic parameters for the numerical setup.

Parameters	Value	Unit
Nominal discharge Qn	0,03	[m^3/s]
Main runner - rotational speed n	920	[rpm]
Main runner - tip diameter D_t	0,150	[m]
Main runner - hub diameter D_h	0,09	[m]
Main runner - blade number z	10	[-]
Nozzle opening	5	[mm]
Control 1 - Flow rate injection	1.5	[l/s]
Control 1 – Procent from main flow	5	[%]
Control 2 - Flow rate injection	3	[l/s]
Control 2 – Procent from main flow	10	[%]

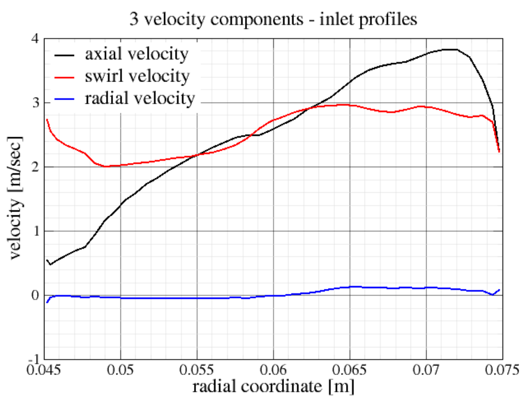


Figure 5. Velocity profiles imposed at the inlet test section

4. VALIDATION, RESULTS AND ANALYSIS

First, the standard case with the development of the vortex rope it was validated with the experimental results, and after the boundary conditions will be replicated for the flowing two investigated cases. The validation results are presented in Figure 6, for the two velocity profiles corresponding to the minimum radius of the test section and for unsteady wall pressure corresponding at the L0 level. Both, the velocity profiles validation and the unsteady pressure are presented in non-dimensional parameters. The paper was concentrated on the validation of numerical against experimental results and the analysis of the new concept of radial-axial jet concept only. The velocity was validated for two velocity components: the meridian component v_m (composed from axial and radial velocity component) and the swirl velocity component v_u. From Figure 6 the velocity profiles obtained from the numerical simulation with the turbulence k-ω GEKO model surprise quite well the velocity measurements, the numerical results being fitted in the error band of the experimental measurements. In case of unsteady pressure validation, the wall point is in L0 level, presented in Figure 5.

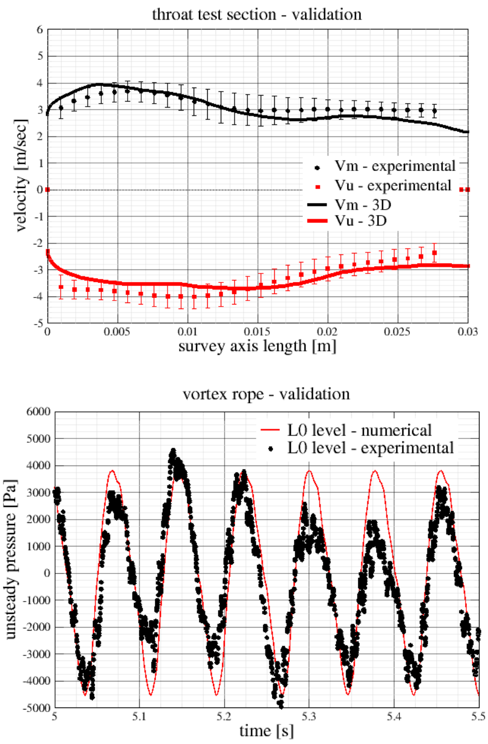


Figure 6. Validation of the vortex rope in case of velocity profiles (close to the throat of the test section) at the inlet in the conical diffuser and in case of unsteady pressure at the wall in L0 level

As it observed in the figure, the numerical validation was registered after 5 seconds iteration, after the case was stabilised, the numerical result having a similar signal as the experiment. The subsequent step involves the analysis of the flow and pressure obtained from the numerical simulation for the scenarios investigated: the vortex rope and two cases for the control: 5% and 10% axial radial injection.

Figure 7 illustrates the flow evaluation within the conical diffuser for all scenarios, focussing on the formation of the vortex rope. To visualise the vortex rope, a constant pressure isosurface was plotted, represented in green, and the vortex cores of the flow field were calculated and depicted as grey. The images show that the vortex rope is present in the conical diffuser in the context of all cases. It forms near the ogive and extends over two-thirds of the conical diffuser's length. When the radial axial jet is introduced into the extension of the ogive, the vortex rope begins to increase in both length and thickness for a flow rate of 5% and begins to decrease for 10%.

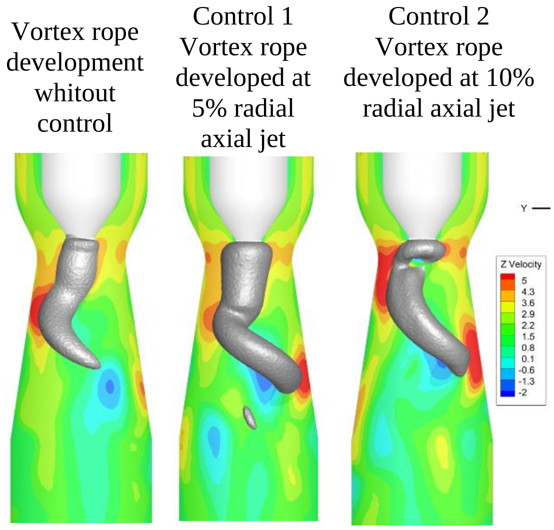


Figure 7. Visualisation of the vortex rope for the case: without and with radial axial jet.

To enhance the understanding of flow dynamics within the conical diffuser, Figure 8 presents a contour plot displaying axial and swirl velocities superimposed with streamlines. It is observed that in the case of the vortex rope, the form is distinctly delineated and extends over more than 50% of the length of the conical diffuser. Upon the introduction of the radial-axial water jet through the ogive inlet, the vortex rope elongates and its angle increases. This augmentation in angle results in the fragmentation of the vortex rope, initiating from the ogive.

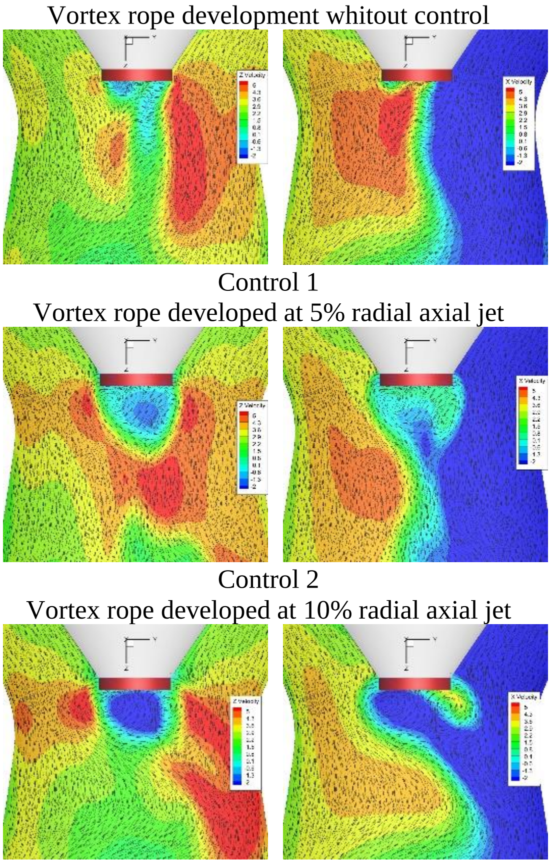
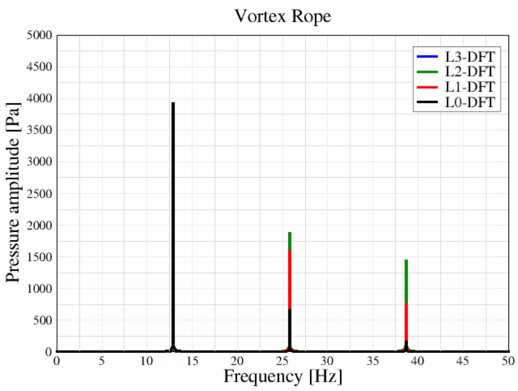


Figure 8. Contour of the axial velocity (left) and of the swirl velocity (right) for the investigated cases where are overlapped the streamlines.

An additional analysis involves the assessment of unsteady pressure recorded on levels L0, L1, L2 and L3 downstream from the inlet within the conical diffuser, as depicted in Figure 9. The unsteady pressure data is obtained from numerical simulation, followed by the execution of FFT. The FFT analysis identifies the primary frequency of the vortex rope of approximately 14 Hz. In the absence of control with axial radial jet, the maximum amplitude attains a value of 4000 Pa. Upon the introduction of the radial axial jet, the maximum amplitude is, and the frequency does not change for 5% flow rate injection. At the maximum flow jet injection of 10% the amplitudes and the frequency in the draft tube cone are diminished completely.



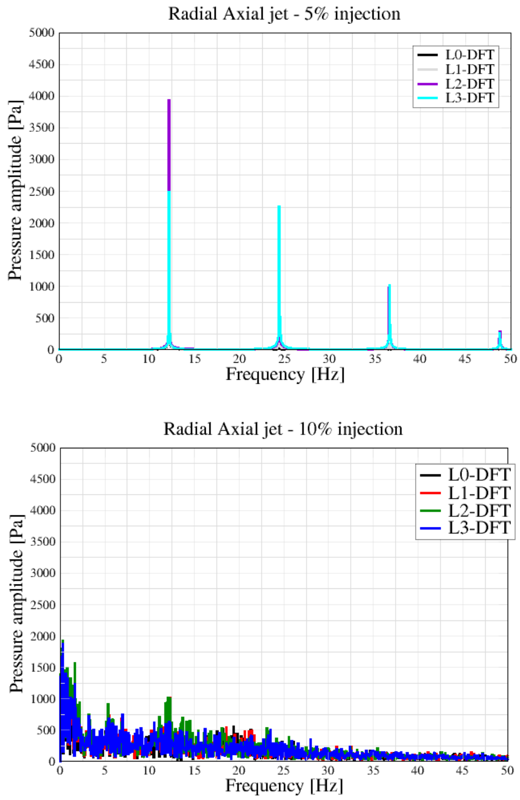


Figure 9. Evaluation of the Fourier transform on the levels L0-L3, downstream of the inlet in the conical diffuser, for the vortex rope case and with radial axial jet from the numerical simulation.

The analysis of the pressure pulsations validates the velocity contours, which means that once the radial axial jet is introduced in the draft tube cone, the vortex rope starts to defragment due to changing the angle. This leads to decrease of frequency and changing the shape of pressure amplitude. Accordingly, the Fourier pressure signal is transforming from a narrowband signal (vortex rope case) to a broadband signal (control with radial axial jet). In practice the defragmentation of the vortex rope into small pieces will lead to a more flexible operation with small pressure amplitudes and without a dominant frequency of the pressure pulsations in the draft tube cone.

5. CONCLUSIONS

The paper explores a method to reduce hydraulic instabilities in draft tube cones by utilizing a radial-axial water jet. Recent numerical investigations have shown that water injection, especially with modifications to the nozzle, can diminish flow instabilities at part load operations, reducing the flow rate required from 14% to about 10%. The study introduces a new concept using an actuator mounted on the ogive to provide a flexible radial-axial water jet that adjusts to different hydrodynamic conditions.

This approach aims to prevent performance deterioration in hydraulic turbines at off-design conditions without affecting the main runner's operation. Numerical simulations with the swirl apparatus and the radial-axial jet injection device were conducted. The Ansys FLUENT 2023 R2 software, employing the k-ω GEKO turbulence model, was used for the simulations, offering flexibility and accuracy for hydraulic machine flows. The study tested two flow rates (1.5 l/s and 3 l/s) for the jet injection, which account for 5% and 10% of the main flow, respectively. Results indicated that radial-axial jet introduction changes the vortex rope characteristics within the draft tube, with increased length and thickness at 5% flow rate and reduced presence at 10%. Unsteady pressure analysis showed that the maximum amplitude of vortex-induced pressure pulsations was significantly reduced with higher flow rate injections, indicating improved hydraulic stability.

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