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Review

An Overview of Active Control Techniques for Vortex Rope Mitigation in Hydraulic Turbines

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Abstract: This review addresses the current state of research into active control and suppression of vortex rope in hydroturbines under off-design operating conditions. Only active control methods that can be “switched on” when required under off-design operating conditions are considered in this work. The review focuses on air addition into the flow, as well as various auxiliary fluid jets. It includes all the best practices for vortex rope suppression in numerical and experimental studies. It can be inferred from the review that a modern flow control system should be comprehensive, designed for a specific hydroturbine geometry, and obtain feedback from the flow. Injecting ~2% of air from the impeller fairing cone appears optimal for suppressing pressure pulsations without significant efficiency loss. The cost of air injection is rarely estimated, but the use of an automatic venting system can minimize overheads and potentially improve efficiencies at low gas contents. Fluid jets ranging from 3% to 12% of the main flow rate can efficiently suppress pressure pulsations, but their high energy requirements limit their use. Azimuthal perturbation of the flow appears promising as it does not require significant energy loss, but practical implementation remains challenging as one needs to accurately know the system dynamics and be capable of real-time manipulation of the flow.

Keywords: swirl flow; precessing vortex core (PVC); rotating vortex rope (RVR); active flow control; air addition; axial jet; injection; actuation

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1. Introduction

The use of hydropower is rapidly increasing worldwide, with different-range-scale hydropower plants being utilized to meet the growing demand for energy while taking advantage of the numerous benefits offered by this technology [1]. These benefits include sustainability, reliable storage, environmental friendliness, regulation flexibility, and high efficiency. However, achieving maximum efficiency in hydraulic turbines requires operating at the best efficiency point (Q_{BEP}), which is rarely feasible because flexible regulation and adjustments to accommodate changing power grid loads are needed.

Turbine operating conditions are divided into ranges based on flow rate with respect to Q_{BEP}. Under part load conditions, where the flow rate is lower than Q_{BEP}, the tangential velocity component is codirectional to the peripheral runner revolution velocity. The resulting tangential velocity cannot be fully transformed into runner torque, and flow in the draft tube remains swirled. Under high-load conditions, where the flow rate is higher than Q_{BEP}, the tangential velocity component is oppositely directed to runner rotation, resulting in excessive swirl and uneven velocity distribution. During partial-load conditions, an excess of swirling can result in flow separation. This can cause a stationary area, flow reversal, and formation of a helical rotating vortex rope (RVR) in the center of the draft tube [2,3]. RVR is helical vortex breakdown [4], which is also called a precessing vortex core (PVC) [5]. The RVR rotates in the same direction as the runner, and its precessing frequency is roughly 30% of the runner's rotational frequency. When operating at high loads, the swirling flow would rotate in the opposite direction to the runner, forming an axisymmetric vortex rope that resembles a torch and precesses in the opposite direction of the runner's rotation. The high load vortex produces synchronous pressure pulsations associated with cavity volume oscillations, while the part load vortex is a source of asynchronous pulsations associated with rotation of the helix around the axis. The resulting pressure pulsations and, in general, the existing vibrations have a negative impact on hydropower equipment [6].

The problem of pulsation mitigation under non-optimal operating conditions associated with the presence of a vortex rope started to be addressed [7] almost as soon as the nature of flow surge was identified [8]. By mitigating the vortex phenomenon, one can reduce pressure pulsation amplitudes and therefore expand the range of stable operation of the hydroturbine. The relevance of developing flow control in hydroturbines is evidenced by numerous recent reviews [9–13].

The most capacious requirements for the control of vortex structures in hydropower equipment were formulated by Prof. Susan-Resiga [14]. Addressing the primary source of excitation is of utmost importance for ensuring optimal turbine performance. The vortex rope, a phenomenon of vortex breakdown in the swirling flow in the draft tube behind the runner, has been identified as the root cause of excitation. Therefore, it is imperative to modify its precessing frequency or entirely eliminate the unsteady vortex breakdown to prevent the detrimental effects on the turbine. In addition to addressing the primary source of excitation, it is crucial to ensure that the control device does not interfere with the turbine operation when it is not required. This is particularly important when operating at or near the optimal efficiency. Per se, the vortex rope control should be switchable on/off or continuously adjusted based on the operating regime to prevent any adverse effects on turbine efficiency.

It is also essential to note that any control method implemented must not significantly reduce turbine efficiency while reducing or eliminating pressure fluctuations. Therefore, it is necessary to strike a balance between controlling the vortex rope and maintaining optimal turbine performance. Finally, to ensure easy acceptance and realization in industrial practice, the practical implementation of the control method should be simple and robust. Any modifications to the current turbine design and costs should be kept minimal to ensure widespread adoption. With these considerations in mind, efficient control over the vortex rope can be achieved, leading to improved turbine performance and reduced maintenance costs.

Nowadays, there are two basic approaches to surge mitigation, which are based on the operation turbine principle. The first one involves modifying the existing geometry through geometric optimization [15,16], seeking to improve performance over a wider range of operations by changing parametric dimensions. This approach mainly involves replacing the draft tube and runner to counteract draft tube surge. Other solutions designed to hold the flow steady by weakening the swirl content include runner cone extensions, modifying the draft tube cone using J-grooves [17,18], finning the inner surface of the draft tube [19], crosspieces [20], runner crown extension [21–23], and the maximum power point tracking control strategy [24]. These devices reduce tangential momentum, i.e., the swirl intensity. In their recent study, Joy et al. [25] described that the vortex rope was significantly suppressed by inserting an "adjustable" special guide vane into the draft tube cone.

The second approach aims to reduce flow swirl and break up stagnant zones by injecting water or air into the flow. The mechanism of impact is different in this case. The air jet, having several orders of magnitude lower density, virtually does not introduce additional momentum to the flow but rather redistributes the low-pressure area, making it more uniform. On the other hand, the water jet can directly affect the rotational momentum of the flow.

Each countermeasure has its own unique benefits and side effects. The most commonly recurring problems include an inability to regulate the frequency of instabilities, which increases the risk of resonance. Additionally, passive elements can contribute to secondary instabilities. Jet injections require additional energy and may be accompanied by hydraulic losses.

This review does not aim to provide an exhaustive list of existing methods for vortex suppression in hydraulic turbines. We will rather focus on the main trend in developing active flow control methods, which are promising due to their ability to use feedback and be switched on or off on demand. Furthermore, we will examine current gaps and problems in implementing specific control methods, with the goal of encouraging researchers to improve existing methods or develop new ones.

Two main concepts for active flow control will be discussed. The first one involves application of air supply in hydraulic turbines, which is a common method for dampening pressure pulsations and has environmental benefits. The second concept involves injecting special water jets to suppress vortices under part-load conditions of hydroturbines. We will assess the potential of this method for flow control.

Drawing on a comprehensive literature review, we will provide recommendations for future research, which is one of the most important goals of current work.

2. Air addition

2.1. Experimental Works

Injecting air into hydraulic turbines to reduce pressure pulsations has a history dating back to the 1950s when it was first introduced in real power plants (refer to [7] for an overview of early work). Initially, the primary objective was to increase the amount of dissolved oxygen at the inlet for environmental reasons and to maintain the required oxygen level at the tailwater depth. However, it was discovered that hydroturbine aeration had other beneficial effects, including reduced vibration and increased efficiency of the turbine per se. Although some studies were performed quite a long time ago, some of them are still of particular interest.

Murakami [26] conducted experiments using a simplified model of a draft tube and a stationary guide vane system to test different levels of swirl. The experiments revealed that at certain levels of swirl, there were powerful pressure pulsations and vibrations in the draft tube. Air was injected through a pipe, 10 mm in diameter, into the center of the draft tube, with the amount of air varied from 0 to 6%. As the ratio between circulating velocity and axial velocity of water increased, more air was required to prevent vibration. When the amount of air was insufficient, vibrations in the draft tube increased, but the draft action was improved. It was found that only 3% or more air injected could suppress pressure pulsation. Although the model was dissimilar to the geometry of a hydraulic turbine, the results of this study were among the first findings demonstrating that the vortex rope can be controlled by air injection.

Further progress has been made by Nakanishi and Ueda [27] in designing and applying air injection to prevent hydraulic turbine surge (Figure 1). Their study examined various parameters that could have the most significant impact on pressure pulsations under different operating conditions. In addition to gas content, they also investigated the optimal position and number of air feed pipes. When the tail race level at a power station is raised to consider runner cavitation characteristics, the static pressure in the draft tube increases, thus impeding natural air admission. Therefore, it is best to find a position of minimal pressure for easy air intake and place the air pipe opening accordingly. However, in some cases, providing enough air to reduce surging may be challenging, and forced air supply from a jet pump may be required.

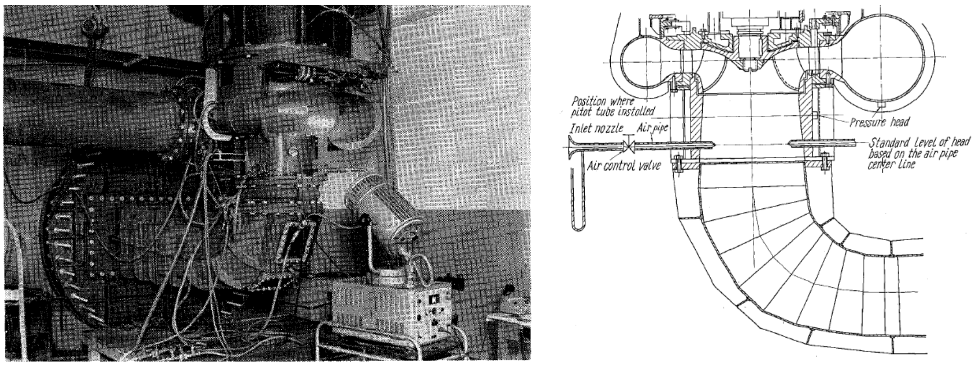

Figure 1. (**Left**)—model turbine test rig [27]; (**Right**)—section of a model turbine test installation [27].

Tests were conducted for three types of Francis turbines with different specific speeds up to *n* = 220 mkW for the high-head cavitation test rig. Two opposing tubes were primarily used to supply air. When air was supplied into the draft tube, air foam gathered in the low-pressure interior of the center cone, breaking the forced vortex core and making it larger. However, the center cone may sometimes tremble more, and the amplitude of water pressure fluctuation may rise. Supplying more air than needed increases draft tube pressure and worsens turbine efficiency. Therefore, it is crucial to obtain the minimal amount of air supply required to stabilize the center cone. Air content changes somewhat when the guide vane opening angle varies, but no noticeable correlation between these values is observed. The optimum airflow rate ranges from 1.5% to 2.5%. When traversing the air pipe opening radially to the draft tube, the optimal air value becomes higher, up to 3–4%, if air is fed from near the draft tube wall. The simple idea is that if the injection site is far enough from the vortex position in terms of radius and the region of low pressure, some air will not reach the vortex core and will be lost. Therefore, air injection from the axis is most promising.

The outcomes of this study remain pertinent to date, since no principally new systems that would be more efficient have been proposed since then. Moreover, the numerous subsequent studies have neglected a crucial air content parameter. Of course, due to the lack of information about the flow structure, no conclusions could be made about the mechanism of pulsation suppression, except for the fact that the vortex rope is transformed into a symmetric vapor–gas cavity. It was not until much later that this issue was considered in studies employing modern methods of computational fluid dynamics. Let us dwell on more recent experimental work. Obviously, research into the prototype turbines is of greatest interest, but simplified experimental rigs will also be considered.

In 2010, García and Viveros [28] conducted field tests at a real hydropower plant equipped with several 95 MW Francis turbines, each with a 3.8 m runner diameter. In order to determine the crucial conditions for the structure, the researchers gauged the pressure within the draft tube and strain exerted on its external wall at different power levels. At partial load between 30 and 50 MW, they observed that the average pressure inside the draft tube and its amplitude increased significantly, leading to elevated stress on the wall, with pressure pulsation exhibiting a low frequency, which was likely due to the vortex rope.

Additionally, they carried out investigations under partial load conditions by infusing air through the stay vanes from a storage tank containing compressed air at 5.45 MPa. The researchers indirectly estimated the amount of air supplied from the pressure in the pressure tank and calculated that air flow was 0.207 m^3/s at a water discharge of 60.8 m^3/s, which corresponded to gas content of 0.34%. Air flow rate as low as 0.34% with respect to water discharge proved to be sufficient for enhancing hydraulic stability and reducing pressure pulsation and wall stress. However, the maximum gas content studied was significantly lower than the threshold values of 2–3% found in previous works by Murakami [26] as well as Nakanishi and Ueda [27]. This difference could be due to inaccurate estimation of the air flow rate, since only pressure in the pressure tank was taken into account, whereas the pressure drop was unknown and could decrease under non-optimal turbine conditions when a large-scale area with vortex rope was formed. Additionally, multiphase effects were notoriously difficult to scale up with increasing turbine size and resulting Reynolds number, and smaller gas contents could have an effect.

Figure 2 shows that air injection slightly reduces pressure pulsation, but the pulsation level subsequently returns to initial values, while pressure in the pressure tank becomes insufficient to ensure the required gas content.

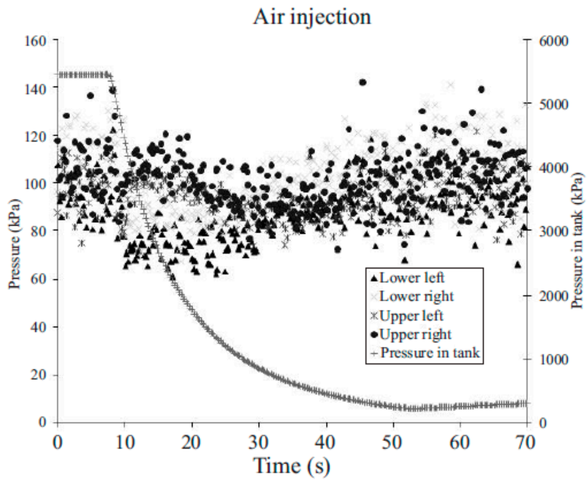

Figure 2. Pressure pulsation amplitude inside the draft tube cone and pressure in the air storage tank as a function of time during air injection [28].

Papillon et al. [29,30] have contributed by developing three different aeration systems: through the runner cone, the peripheral discharge ring aeration system, and aeration by the wicket gate trailing edge. These methods affect turbine performance in terms of flow rate, power output, and efficiency. The central aeration alternatives had a greater impact on efficiency compared to the peripheral aeration system. The introduction of air bubbles into the water changes the fluid density and alters water velocities. Moreover, addition of air affects local pressure, thus reducing the "internal" head observed by the runner. This results in a shift in the runner operating point and drop-in efficiency and output as the internal head decreases (Figure 3). Therefore, air admission alters the entire performance curve of the turbine.

Experimental data obtained from a real hydroelectric power plant are crucial in assessing the efficiency of an air injection system. Türkmenoğlu [31] studied the vibration effects of a vortex in high-head Francis turbines at the Darca-1 hydroelectric power plant in Ordu Province, Turkey. The vortex, caused by oxygen undissolved in water and parallel to the alternator load, resulted in significant vibration within the alternator and turbine bearings, negatively impacting their capacity. To address this issue, an air admission system was added, increasing power production from 44 MW to 49.5 MW (an increase by 11.11%). The air admission rate can be manually adjusted through a valve located on top of the system, which was fully open at Darca-1. After installing the air admission system, the generator can produce power within the safe vibration range at full load. Lowering the vibration amplitude of turbine bearings improves their operating time and safety. At maximum air injection rates, relative radial vibration decreased by up to 40%, indicating promising results for turbine safety.

Muntean et al. [32] went beyond the regimes with the highest turbine efficiency and considered seven different operating conditions in the range Q = 0.29 Q_{BEP}–1.09 Q_{BEP}, where Q_{BEP} is the optimal flow rate. The test case corresponds to a medium specific speed Francis turbine with dimensionless specific speed n = 0.37. An air injection system was installed under the runner cowling whose design can be seen in Figure 4.

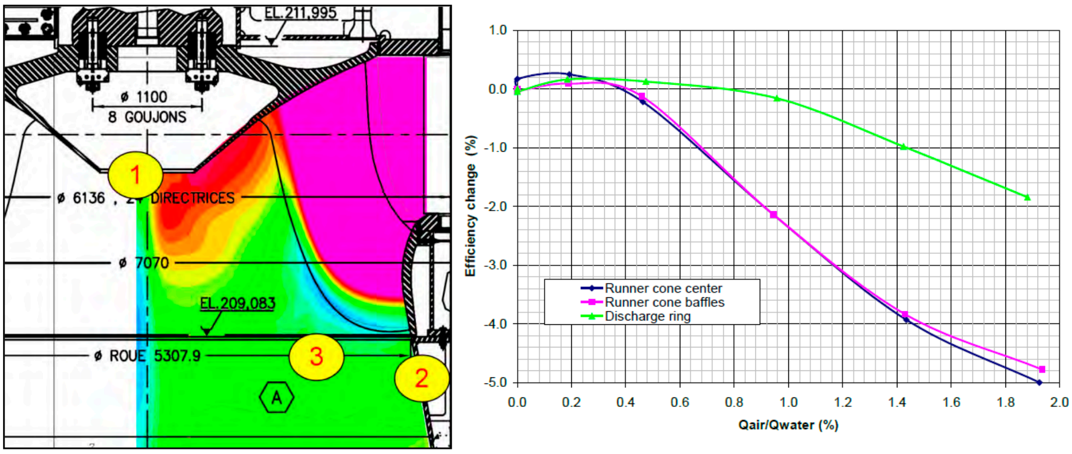

Figure 3. (**Left**)—typical air injection locations and contour plot of static pressure in a turbine water passage near the optimal efficiency point. Location 1 corresponds to central aeration. Location 2 corresponds to peripheral aeration. Location 3 corresponds to the runner outlet. (**Right**)—efficiency changes with air admission as a function of the ratio between air flow and turbine discharge for different aeration devices. Data from a model test of a Francis runner near peak efficiency [29,30].

Figure 4. Photo of an air injection system [32].

In order to register pressure pulsations at different points in the conical part of the draft tube, several pressure transducers were mounted; the signal from them was analyzed using the Fourier spectra in order to identify the fundamental frequency and the associated amplitude. Three operating ranges in which air injection has fundamentally different effects can be distinguished. At high flow rates (>0.81 Q_{BEP}), a small influence of air injection is revealed; when the turbine operates between 0.29 Q_{BEP} and 0.53 Q_{BEP} with air injection, the dynamic behavior is deteriorated. In particular, turbine operation near $Q = 0.42\ Q_{BEP}$ air injection can lead to mechanical problems. The most positive impact was found near the operating point $Q = 0.69\ Q_{BEP}$ at which air injection significantly improved the dynamic behavior. More details can be seen in Figure 5 demonstrating the Fourier spectra for two operating conditions with the opposite air effect. The authors recommended investigating the air control method involving air injection on each individual turbine to identify the dangerous operating regimes.

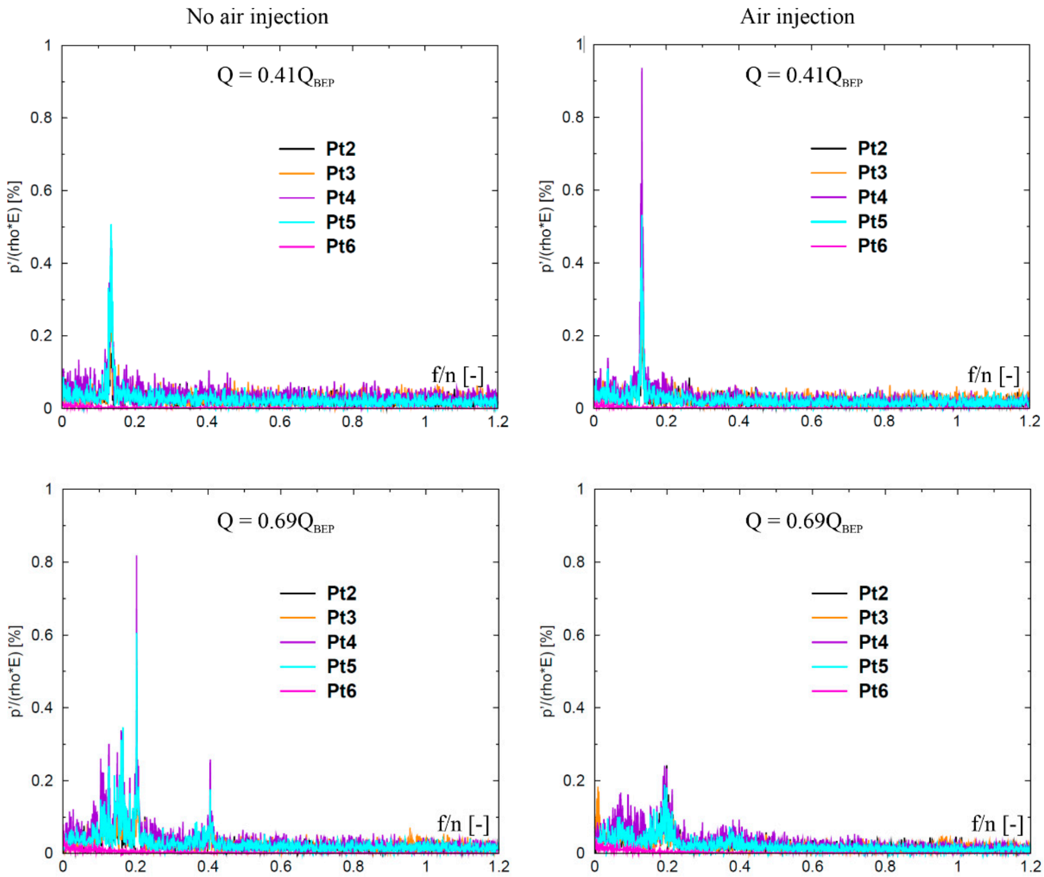

Figure 5. Fourier spectra for two operating conditions with the opposite air effect [32].

Nakashima et al. [33,34] studied the impact of air injection on turbine surge and performance using the Francis turbine model test facility. Forced aeration at Q = 0, 0.5, and 1% was performed downstream of the diffuser inlet at a distance of 0.5 draft tube throat diameter. Pressure pulsations were measured in the cross-section using several transducers so that one could differentiate the frequency associated with cavitation and vortices from the frequency of the unsteady vortex by signal analysis. The aeration suppresses the vortex rope behavior and the cavitation surge by half at Q = 0.5% and fully suppresses at Q = 1%, but the aeration increases the loss in the diffuser and decreases the efficiency of the water turbine by several percent, as shown in Figure 6.

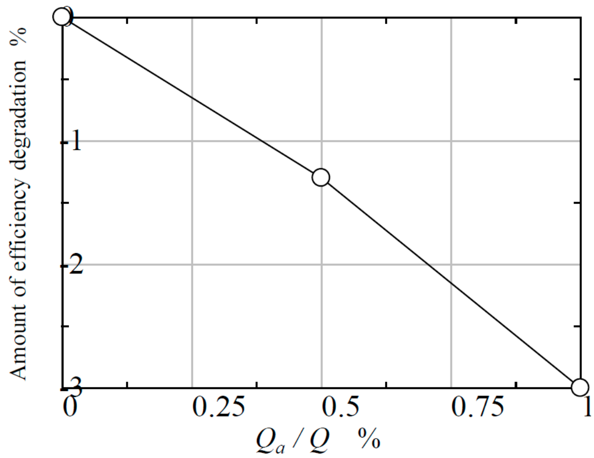

Figure 6. Reduction of water turbine efficiency depending on the flow rate of supplied air [33].

Sometimes studies are conducted not only on the prototypes or Francis turbine models but also on very simplified geometries in order to better focus on one effect and exclude the influence of other factors. The results of experimental modeling of the swirling flow in the simplified Turbine-99 draft tube model are presented by Skripkin et al. [35]. The research was carried out on a single swirl parameter corresponding to the part-load regime provided by a stationary swirler. Dimensional vortex frequency was significantly changed (Figure 7) when the gas content was varied from 0 to 5%. Although no data were presented for vortex rope suppression and pressure pulsations, these results may be useful in terms of flexible control of an unsteady vortex if the precession frequency needs to be changed under the resonance conditions.

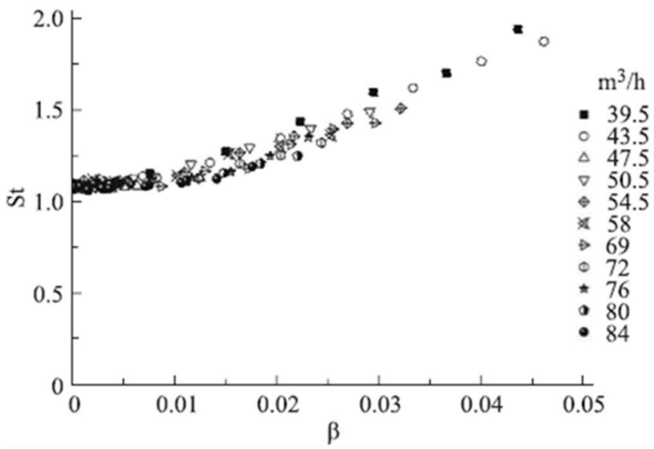

Figure 7. Strouhal number frequency (St) as a function of gas content (β) at fixed simplified turbine flow rates. Reused with permission from [35]. The relative gas content was defined as $\beta = Q_g/(Q_g + Q_l)$, where Q_g and Q_l are the flow rates of injected gas and liquid in the tract, respectively. Copyright © 2015 Springer Nature.

Data on vortex rope control in simplified geometry can be found in the study by Tănasă et al. [36]. The hydraulic system was utilized to produce a flow pattern that mimicked the one experienced by a Francis runner operating at partial discharge. On the other hand, the swirl generator, unlike the turbine runner, featured a stationary and rotating blade annular section generating a swirling flow. The air system was utilized to introduce air into the inlet of the conical diffuser via a nozzle. In order to examine the impact of air admission, the authors installed eight pressure sensors in four different cross-sections. This allowed them to decompose the signal from pressure transducers into two distinct components: the plunging/synchronous and rotating/asynchronous components. The interaction between the helical vortex and the draft tube bend led to asynchronous fluctuation. The amplitude of the rotating component linked to the vortex rope gradually decreased until it reached Q_{air}/Q ratio = 1% and almost disappeared at Q_{air}/Q = 1.7%. The synchronous component behaved in a similar manner but did not disappear completely even at high gas contents. The final pulsation and frequency plots without separation by component are shown in Figure 8. It can be assumed that the frequency jump above 1% in the plot at Q_{air}/Q was related to low-frequency oscillations of the gas cavity rather than to vortex rotation, since the synchronous component should have already been completely suppressed.

Unterluggauer et al. [37], as well as, previously, Türkmenoğlu [31], studied an important parameter such as turbine bearing vibration via the acceleration probes in the Francis turbine prototype with a speed factor n_{ed} = 0.39. Despite the earlier experience showing that supplying air through the runner was most efficient, air is injected upstream of the runner in this study. It was assumed that the unusual location would be advantageous in mitigating the erosive action and reducing the dynamic impact on the entire runner. Operating conditions at p = 63% of the nominal turbine power were chosen for air impact testing. By using the acceleration sensors in two planar (x, y) directions, one can observe the effect of damping and vibration elimination at the hydraulic turbine bearing (Figure 9, left). However, the z-directional vibrations of the runner were not significantly impacted by air admission (Figure 9, right). Reduction of radial bearing vibration could well be due to suppression of the vortex rope whose influence in the radial direction due to its rotation was higher than that in the z direction. Unfortunately, no information about the amount of air supplied was provided.

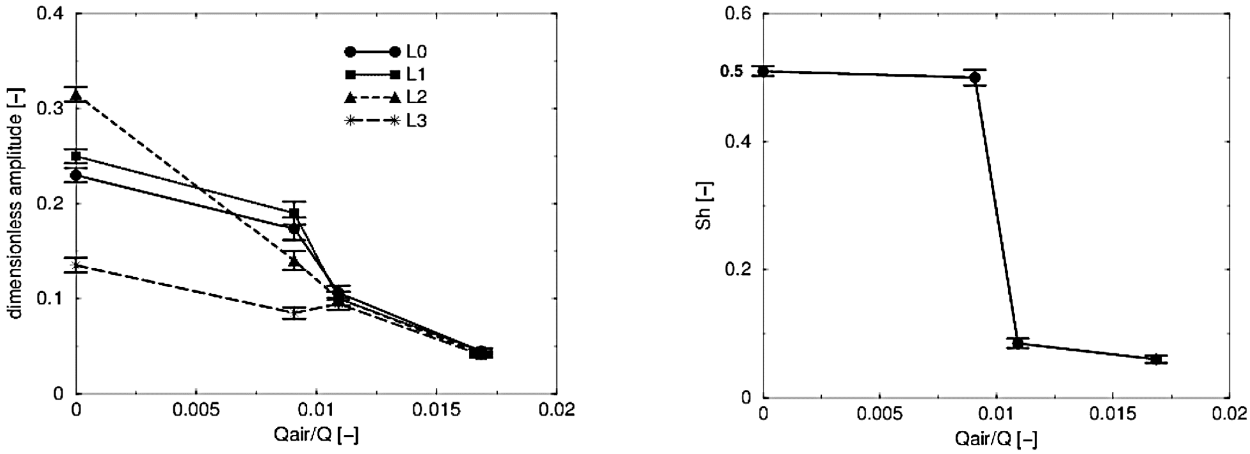

Figure 8. Pulsation amplitudes (**left**) and Strouhal number (**right**) vs. Q_{air}/Q at all pressure sensor positions in the test section [36].

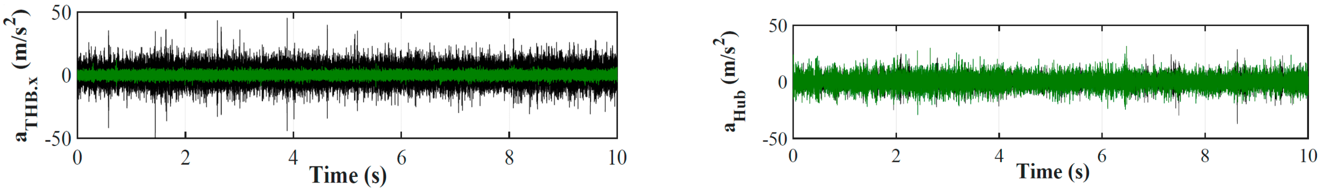

Figure 9. Vibrations with (green) and without (black) air admission: (**left**)—radial vibration; (**right**)—in the axial direction [37].

The findings reported by Platonov et al. [38] demonstrated a significant effect of air injection on the intensity of pressure fluctuations obtained when operating a medium-scale hydrodynamic test bench with a Francis turbine. It was found that when air was injected at operating conditions close to the optimal regimes, a substantial increase in pressure pulsations was observed, while when air was injected under conditions with the maximum pulsations, it could significantly reduce the surge. Experimental results have confirmed that reduction of pressure pulsations was directly related to the amount of air injected into the system. The ideal flow rate of air required to efficiently minimize draft tube pressure pulsations was 1.0% when operating at a guide vane opening of 50% of the optimal value. It was found that this particular flow rate did not affect turbine efficiency, while significantly reducing pressure pulsations in the draft tube. This is clearly illustrated in Figure 10.

Bucur et al. [39] and Bunea et al. [40] proposed an innovative aeration device in a small Francis turbine (Figure 11). Although the main aim of their work was to develop an aeration device to increase the DO level for environmental reasons, the effect of air injection on the turbine's energy and vibration performance was also considered. The development of the aeration system was preceded by numerical calculation to determine the optimal location for air injection, so that air supply would not lead to additional economic costs. Depending on the operating regime of the turbine, aeration can be either natural (without associated energy consumption) or forced (with compressed air). Although no reduction in turbine efficiency was observed when air was supplied, this method is inefficient in terms of suppressing the pulsations associated with the vortex. Air bubbles had little or no interaction with the vortex core that had already been formed and did not converge in the central dead water zone.

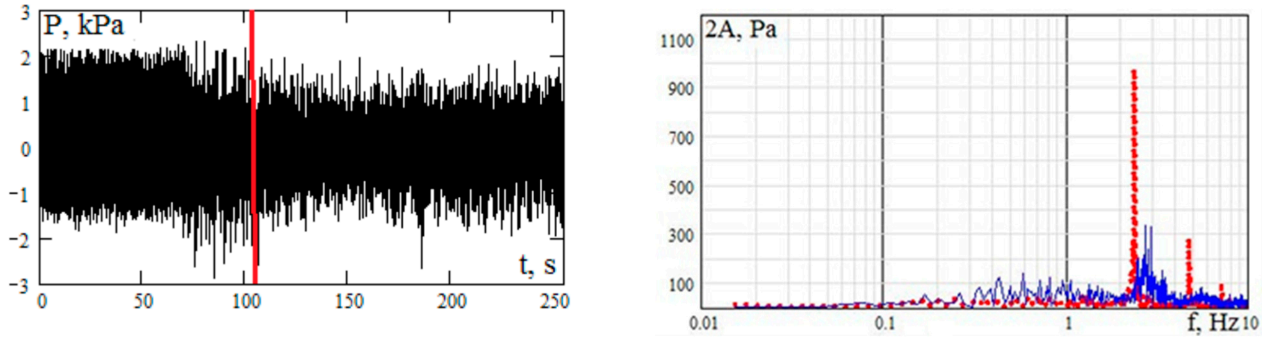

Figure 10. (**Left**)—pressure signal; (**Right**)—FFT; blue line corresponds to 1% air injection [38].

Figure 11. Perforated air inlet system of draft tube [40].

2.2. Numerical Work

Due to the high cost of experimental tests and their inability to provide detailed information on internal flow characteristics, numerical simulations are often utilized to gain a better understanding of the flow mechanisms within turbines. However, research into application of air injection to suppress unsteady vortices in hydraulic turbines using computational fluid dynamics started to emerge later, after a certain level of computational power had been achieved and numerical models describing two-phase flow with acceptable accuracy had been developed. For instance, one can refer to the work by Qian et al. [41] who studied the three-dimensional unsteady multiphase flow in the Francis hydraulic turbine. They observed that the air was directed towards the center of the draft tube cone through a hollow shaft ending at the outlet of the runner cone. The computational results revealed that when air was admitted through the spindle hole, it reduced the pressure difference in the horizontal section of the draft tube, thus decreasing the amplitude of low-frequency pressure pulsation. However, the rotor–stator interaction between the air inlet and the runner increased the blade-frequency pressure pulsation in front of the runner. The researchers also found that air in the draft tube rotated with the vortex rope and its fraction was high in the low-pressure areas. Although air admission did not change the dominating frequency in the draft tube, it significantly decreased its amplitude. The lowest amplitude was observed when the air discharge was 0.5%.

Chirkov et al. [42] analyzed stability issues in electric power stations that were arising when a cavity was formed behind the runner, resulting in self-excited oscillations throughout the flow duct. They found that a symmetrical cavity can appear when a hydropower station operates at high loads, specifically at power equal to 1.175 times its nominal power. Their numerical model considered air as an incompressible fluid with constant density and solved the basic governing equations of the three-phase model using their CADRUN solver. By varying the gas flow rate Q_{air} from 0.1 to 0.4% of the liquid discharge rate Q at the center of the runner hub, they observed that at a maximum air flow rate (0.4%), the recirculation zone at the draft tube center expanded to reach the runner fairing, eliminating cavitation in the flow. The air was accumulated below the runner fairing, resulting in minimal pressure pulsations and reducing cavitation phenomena below the runner. Due to its buoyancy, the air also changed the flow pattern, expanding the flow stagnation zone at the draft tube center, leading to flow stabilization. However, their results differed from the experimental data reported by Muntean et al. [32], which showed that air supply had almost no effect on pressure pulsations under full load conditions. In their subsequent paper, Chirkov et al. [43] tested their numerical model in the part-load regime by comparing the calculated data with the experimental measurements performed at the Laboratory of Hydraulic Turbines, Leningrad Metal Plant. They observed (Figure 12) that their numerical calculations agreed acceptably with the experiment in single-phase flow but failed to adequately describe the unsteady properties of the vortex rope with air injection, making them unreliable to draw any conclusions about the effect of air effect on its frequency and amplitude.

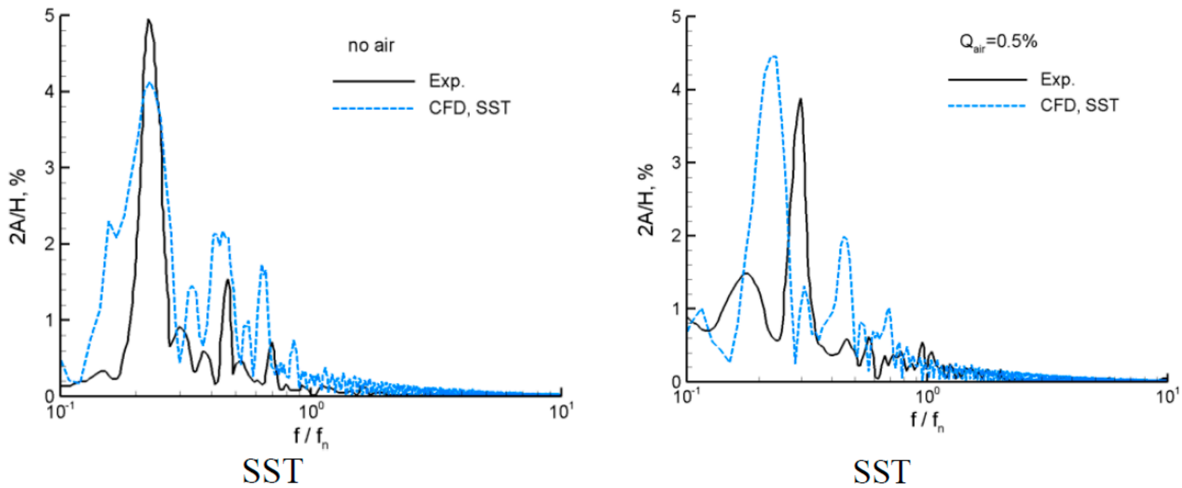

Figure 12. Comparison of numerical simulation with the experimental data for one and two-phase flows [43].

The research by Mohammadi et al. [44], unlike most studies, paid attention to important parameters such as the injection point, number of injection points, and appropriate nozzle diameter in addition to varying the air flow rate. They also considered a combined configuration with an additional water jet from the runner cone. However, the authors neither investigated the influence of injection on unsteady vortex structures nor explained the mechanism of changes in performance. The flow from the spiral case to the end of the draft tube was simulated using the SST k-ω turbulence and two-phase models, which showed the best results. After conducting a parameter search, they selected 72 nozzles with a diameter of 1 cm for 1.5% air injection from the draft tube wall. This configuration increased turbine efficiency up to 4.3% under certain operating conditions and may also be successful in suppressing vortex ropes.

Luo et al. [45] and Zhu et al. [46] made significant progress in suppressing vortex ropes in Francis turbines with a specific speed of 125 mkW. In order to gather empirical information regarding the hydraulic performance and pressure vibration at customary monitoring locations, a series of model trials were carried out on a test apparatus at Harbin Electric

Company Ltd. located in China, Harbin. To simulate the unsteady flow, the Reynolds averaged Navier–Stokes (RANS) procedure was employed in combination with the k-ω SST turbulence model and a homogeneous cavitation model. After conducting mesh independence examination, the computational domain was composed of 3,310,293 mesh elements. Comparisons between the simulation and experiment for the averaged hydraulic performance and instantaneous pressure pulsation showed acceptable agreement [47,48].

Initially, air was supplied through fins on the draft tube wall to reduce pressure pulsations on the draft tube wall downstream by 26.3% with 2% air supply. However, upstream pulsations were not affected by this method. Injecting air through the ventilation hole at the runner hub produced the best results. Zhu et al. [46,48] noted that homogeneous distributions of pressure and pressure gradient due to air admission efficiently suppressed pressure vibration in the draft tube. The ventilation rate Q = 0.04 was found to be very efficient in suppressing pressure vibration due to changes in vortex rope geometry from helical to cylindrical ones, while Q = 0.01 had little effect. Figure 13 clearly illustrates how air admission from the runner hub cone influenced the pulsation intensity.

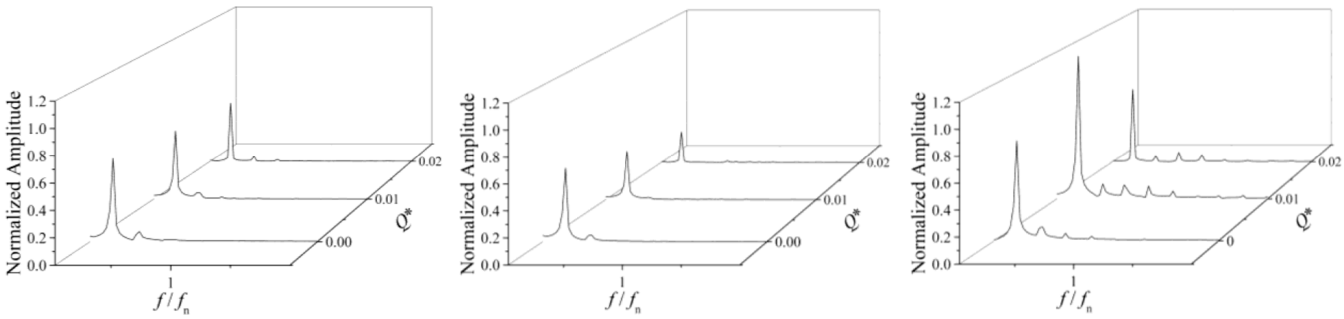

Figure 13. Pressure vibrations in the draft tube at different ventilation rates for three monitoring points along the draft tube [48]. Q* is the ratio of air velocity to working fluid velocity.

The velocity distribution along the diameter shows swirl intensity in the draft tube. The findings suggest that injecting air into the draft tube makes the circumferential velocity distribution more symmetrical and reduces its magnitude, especially at high air flow rates. As aeration volume increases, the backflow area expands and the backflow core moves towards the section center. Since air has lower density than water, the momentum and kinetic energy of the vortex rope decrease rapidly with large aeration volume at the backflow core, as is observed in the case of Q = 4%. It remarkably decreases pressure gradients, and pressure at the vortex core is recovered for the largest aeration volume. Additionally, high-pressure gas contributes to pressure increase in the vortex core and decreases pressure gradients, reducing draft tube wall pulsations in general.

Kim et al. [49] conducted a study using the Francis turbine model with Q_{ed} = 0.33 and n_{ed} = 0.48 to investigate vortex rope suppression using an air supply system from the runner cone and anti-swirl fins. Unsteady-state calculations were performed using the ANSYS CFX software, employing the unsteady-state RANS equations supported by the SAS-SST turbulence model. The working fluid consisted of three-phase flows of water, vapor, and air at 298 K. Part-load conditions at Q = 0.78 Q_{BEP} with well-developed vortex rope were considered.

The results showed that an injection of 0.1% Q resulted in a 14% higher magnitude than that obtained with anti-swirl fins alone. The low flow rate of air injection affected the generation of long vortex rope with high swirl number distribution along the flow direction, leading to highly unsteady pressure characteristics. The magnitude decreased significantly by 55% when injection of 0.5% Q was employed, thus revealing the efficiency of the air injection method utilized in this study. Figure 14 shows an example of a pressure pulsation spectrogram of 0.6D showing the effect of fins and air injections. The authors claimed that reduction in pulsation was due to reduction in swirl strength at this injection level, but the mechanism of changes per se has not been explained. Later, Shahzeret et al. [50] tested mounting air injection holes in anti-swirl fins, but their findings showed this option to be undesirable in terms of turbine efficiency and pressure pulsations.

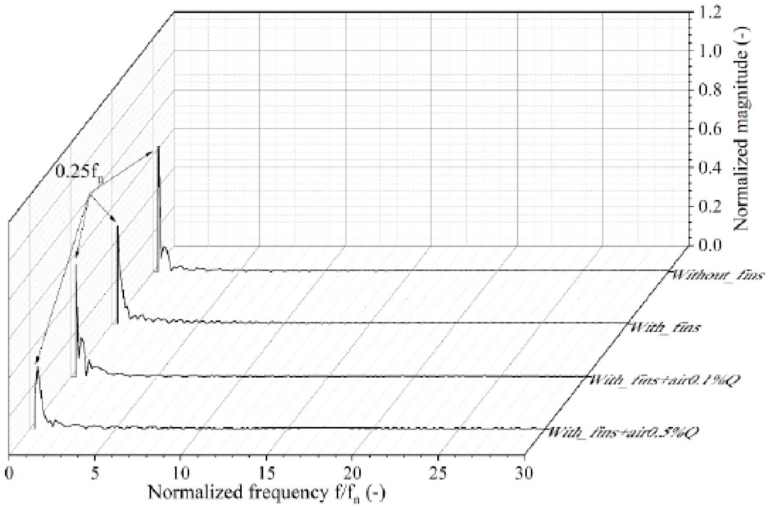

Figure 14. Example of a pressure pulsation spectrogram of 0.6D showing the effect of fins and air injections [49].

One of the more recent numerical studies in which the authors tried to explain the mechanism of vortex rope mitigation and pressure pulsation suppression can be found in the paper by Sun et al. [51]. Previously, Sun et al. [52] reported the successful use of air injection to mitigate inter-blade vortices. They determined that an air volume fraction of 0.7 provided the best balance between reducing the vortex and minimizing energy consumption. By injecting air into water, formation of inter-blade vortices was significantly reduced. This was due to the presence of air cavities in low-pressure flow regions, which disrupted the flow and altered the distribution of streamlines in the runner.

To investigate the influence of air on the unsteady vortex rope behavior, they chose an operating mode with parameters Q_{11} = 92.49% and n_{11} = 117.78% that produced 70% rated output power within the partial-load zone. The calculation involved two stages: the first stage dealt with a single-phase problem and the second stage introduced an additional dispersed air volume with a mean diameter of 0.0001 m into the homogeneous multiphase model from the first stage. This allowed the researchers to examine the impact of air admission on the vortex structure at different air volume fractions, ranging from 0 to 3%.

Injecting 1.0% air into the runner cone maintained the visibility and strength of the helical vortex rope, similar to conditions without air. Increasing the air injection to 2.0% caused some disordered and distinct vortex structures in the elbow section, but the helical vortex rope in the cone section remained intact. At 3.0% air injection, the vortex rope disappeared in the draft tube, leaving an umbrella-shaped vortex structure near the inlet of the cone section and a free vortex in the elbow section. As a result, the researchers observed significant drops in pressure amplitude at air volume fractions of 1.0% and 2.0%, with amplitudes decreasing by 41.1% and 49.3%, respectively. No significant pulsations were detected at an air volume fraction of 3.0%. One can refer to Figure 15 for details. The authors noted that introducing air caused pressure redistribution in the horizontal section, resulting in a larger lower-pressure area but a smaller pressure drop between the conditional vortex core and the periphery. The study also examined the draft tube loss factor and turbine efficiency and found that when the gas content was increased from 2% to 3%, the total loss factor rose, while turbine efficiency decreased by approximately 2%. They also observed reduction in the swirl parameter from S = 0.64 to S = 0.47 at an air volume fraction of 3%, which was unexpected given the low density of air.

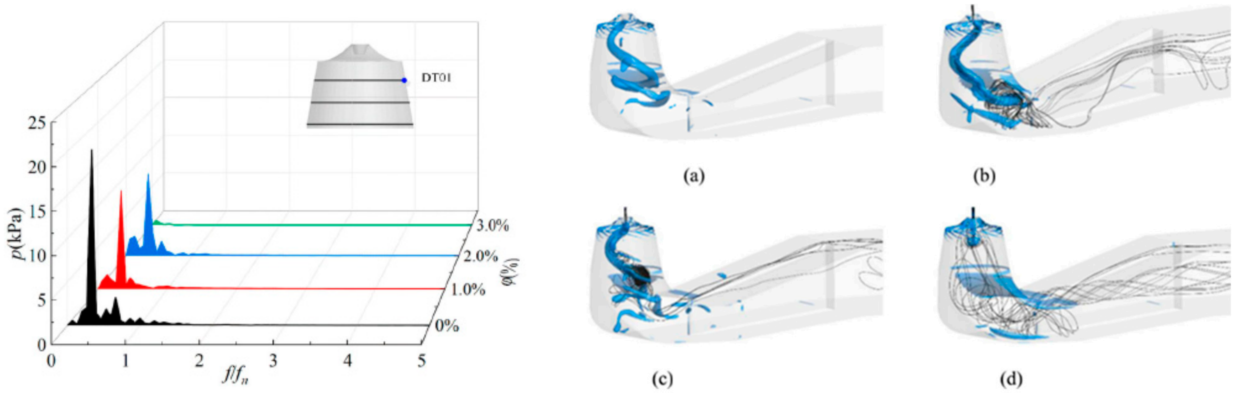

Figure 15. (**Left**)—The frequency domain of pressure fluctuation in dependence of air volume fraction φ (%). (**Right**)—The visualization of vortex structure by the Q = 8000 criteria surface and air streamlines with respect to air volume fraction: (**a**) air free; (**b**) 1.0% air injection; (**c**) 2.0% air injection; and (**d**) 3.0% air injection [51].

Overall, the authors concluded that further research into pressure redistribution mechanisms would be needed to improve air supply methods for turbines. They only varied the airflow rate, while keeping injection site and operating conditions unchanged. Nonetheless, this work brings us closer to understanding the complex mechanisms of interaction between unsteady vortices and the multiphase swirling flow.

In contrast to numerical works, analytical approaches for describing two-phase swirling flows in the presence of large-scale vortex structures are extremely rare. This is primarily due to the complexity of constructing models that must account for the interaction between air bubbles of different scales and the vortex core. Furthermore, the lack of quantitative experimental data containing reliable information on the instantaneous velocity and pressure fields for both phases has hindered the development of analytical approaches that could shed light on the complex vortex phenomena. Simple analytical models [53–55], such as one-dimensional models, typically describe the pulsations associated with changes in the volume of the cavity per se, which is more typical of full-load turbine conditions. These models allow one to consider how filling the cavity with air changes the natural frequency and cavitation compliance, but they do not account for the precession frequency of the vortex rope. Among the few three-dimensional analytical models worth mentioning is the one presented in [56]. Kuibin et al. [56] utilized the single-phase vortex model [57] as a foundation for their two-phase model, which has demonstrated adequate accuracy in describing single-phase flows [58]. The frequency of a vortex is a complex parameter that is influenced by various factors. These factors include the vortex curvature, the vortex torsion, the impact of the tube wall, translational motion, and the uneven vorticity distribution within the vortex core. When the air vortex core is filled, changes occur that affect the curvature and vorticity distribution within the core. This shift from a circular to an annular structure has a significant impact on the precession frequency of the vortex.

Geometrical relationships are considered to analyze the impact of the gas phase on the precession frequency of the vortex. It is suggested that the observed decrease in precession frequency during the transition from a pure liquid to a two-phase condition can only be explained by a non-monotonic dependence of the helical vortex pitch on the gas cavity size. This decrease is followed by an increase in frequency as the gas flow rate increases.

Without delving into the mathematical calculations presented by Kuibin et al. [56], one can turn to the final Figure 16, which predicts the behavior of the precession frequency as a function of the volume flow rate. Despite several simplifications and assumptions, the gas–liquid vortex model adequately describes the frequency response according to the experimental data reported by Shtork et al. [59].

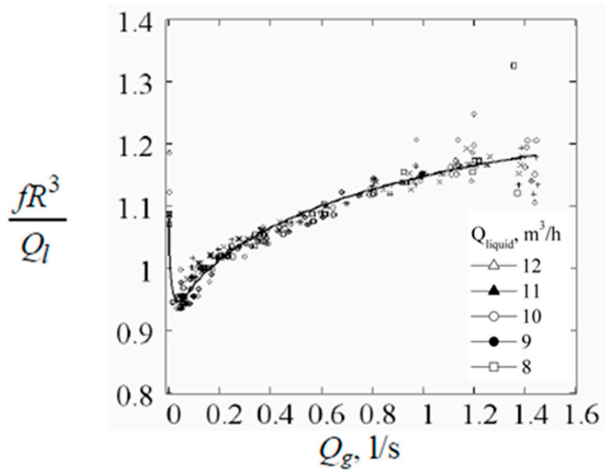

Figure 16. Dimensionless vortex precession frequency vs. gas flow rate; the maximum gas flow rate corresponded to 40% gas content [56].

Further development of the model requires extensive experimental data on the vortex structure, such as the vortex core size, precession radius velocity at the vortex axis, and pitch of the helical structure in different engineering applications and flow configurations. However, for the vortex control purpose, precession frequency is rarely studied due to its small variation in experimental works falling within the range of 0–3% gas content, beyond which pressure pulsations associated with the vortex rope are typically suppressed.

3. Auxiliary Fluid Jets

In the multitude of methods aiming at reducing pressure pulsations caused by vortex rope, the most promising method seems to be based on injection of auxiliary fluid. Thus, injection of auxiliary fluid aims to eliminate the stagnation zone that leads to rope formation [60,61]. This is carried out by transmitting a pulse from the liquid injected at an appropriate place and at an appropriate velocity. There are two methods of jet delivery: tangential and axial injections.

3.1. Tangential Injection

Seibert's master's thesis [62] is one of the first experimental attempts to suppress PVC using tangentially oriented jets. The work was carried out for a modified model vortex chamber from the study by Cassidi [63]. Air was used as the working medium. It was shown that formation of PVC can be eliminated by using optimal configuration of tangential jets. The main effect is achieved by reducing the swirl number S of the flow below the supercritical value for the PVC formation ($S < 0.6$) according to [64]. However, this method cannot be considered energy-efficient because it requires energy losses due to the use of tangential jets in the opposite direction to the primary swirl.

H. Francke significantly improved and developed the tangential water injection technique to extend the operating range of real hydroturbines [65]. In the detailed and comprehensive study, the effect of the angle of the jets and their number (one to five) on the induced pressure pulsations and velocity distribution was investigated. The effect of suppressing PVC pulsations was studied on model rigs, which also included a full hydraulic turbine prototype (the Tokke model turbine at NTNU Waterpower Laboratory, Trondheim, Norway). Figure 17 shows the design sketch and photo of a real device with tangential nozzles mounted on the draft tube cone of the Tokke model turbine. Moreover, tangential jet devices have been tested on the draft tube cone at Skibotn Power Station and Skarsfjord Power Station.

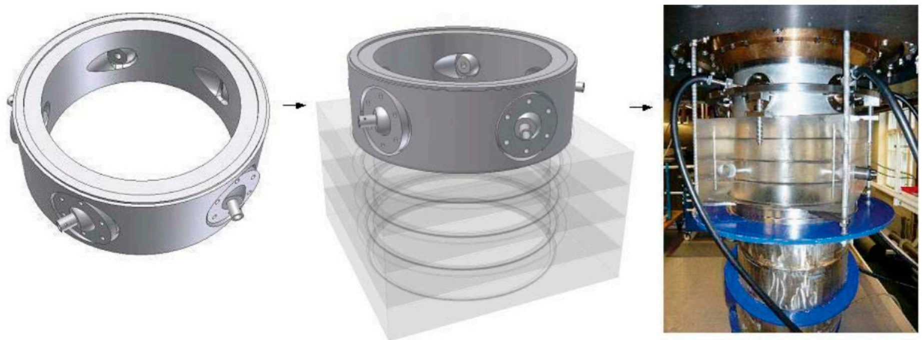

Figure 17. Arrangement of movable nozzles mounted on the draft tube cone in the Tokke model turbine [65].

To decrease the amplitude of pressure fluctuations, water was injected tangentially in the opposite direction to the vortex motion. Nozzles with adjustable injection angles were mounted on the draft tube wall. Significant vortex rope suppression was achieved when one or two nozzles were activated. Contrariwise, when four or five nozzles were activated, the pressure pulsations increased. This could be caused by the fact that increased flow induced noise from the nozzles. This method reduced the amplitude of pressure pulsations but did not eliminate them. The vortex rope was still rotating inside the draft tube. The fact that the nozzles reduced the amplitude of the RVR could be due to either a decrease in the pressure spread or reduction in the RVR per se. Furthermore, H. Francke also compared changes in hydraulic efficiency depending on the vertical and horizontal nozzle angles. The results attested to better hydraulic efficiency with the water injection pointing downwards. The total efficiency loss was noticeably high (3.43–3.95%) for the case with low mechanical power (30% with respect to BEP). However, in the case of 40% with respect to BEP, the efficiency loss was already lower. The total efficiency loss including nozzle bypass was between 0.42 and 0.92%. The results of the hydraulic efficiency test indicated little or no connection between the horizontal angle and changes in hydraulic efficiency. Therefore, the results suggested that the concept of tangential water injection worked well but could be upgraded by optimizing the nozzle duct.

3.2. Axial Injection

The method for controlling vortex structures based on supplying an axial jet is presented more extensively in the literature. A group led by Prof. Susan-Resiga significantly contributed to the development of methods for controlling vortex structures in Francis turbines.

Susan-Resiga et al. [14] stated that vortex breakdown at part loads was directly related to flow deceleration downstream of the runner. They have made an assumption that the axial velocity and specific energy deficit at the draft tube center was responsible for the development of vortex rope; hence, they proposed a method for injecting water axially through the turbine shaft (see Figure 18). The main concept was to enhance the flow momentum that is stagnant in the centerline of the draft tube and eliminate the high-velocity gradients, which cause the formation of the shear layer and helical vortex rope. The axial momentum around the centerline was increased, while shearing effects along the interface between the backflow zone and the main flow were decreased [66]. This decrease in pressure pulsation amplitudes was attributed to the downward movement of the quasi-stagnant region associated with RVR [10]. The system does not require any modifications to the runner and can be adjusted to suit the operating point. According to reports, jet injection is more efficient than geometrical modifications [44]. The authors proposed a jet control technique that directly addresses the development of vortex rope, thereby reducing the main source of pressure fluctuations or at least modifying the precession frequency. Additionally, jet injection improves kinetic-to-static head conversion in the discharge cone [67].

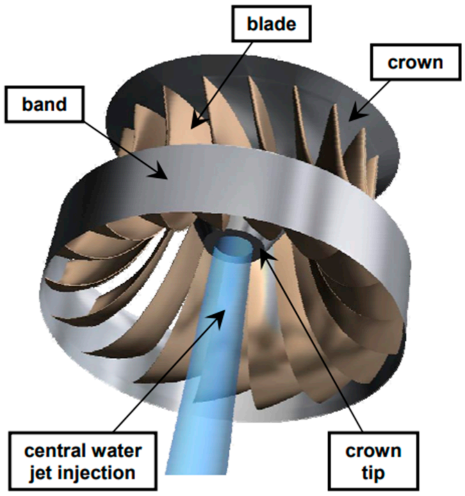

Figure 18. Jet control technique for swirling flow in the discharge cone of Francis turbines [66].

A swirl apparatus has been developed to simplify modeling of the hydraulic turbine (Figure 19, left). The convergent–divergent test section is characterized by 100 mm throat diameter and a 200 mm long conical diffuser with 8.5° half angle. Upstream of the throat, there is a swirl generator that uses two blade rows. This swirl apparatus creates a swirling flow configuration at the inlet to the divergent part of the test section, similar to that of a Francis turbine [68]. It was found experimentally that the amplitude of pressure pulsation behaves differently for different distances from the runner. As the flow rate of the jet increases, the quasi-stagnant area associated with the vortex rope moves downstream. This causes pressure pulsations at levels MG0–MG2 to decrease and, at level MG3, to increase. However, when the flow rate of the jet reaches ~11.5% of the total flow rate, the pressure pulsations at all the levels are significantly reduced. At level MG0, the amplitude is reduced by 50%, at level MG1 the amplitude is decreased by 60%; at level MG2 the amplitude is reduced by 67%; and for level MG3, the amplitude is mitigated by 25%. In addition, the Strouhal number of the PVR is mitigated by 35%, from 0.393 to 0.252. In this way, it was possible to determine the required flow rate of the axial jet and describe the effects that are observed in the flow when this jet is injected.

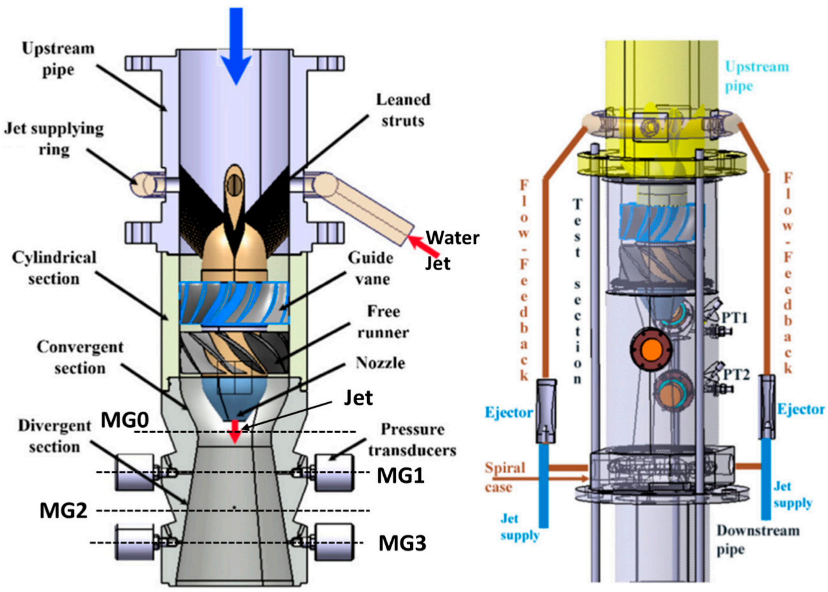

Figure 19. (**left**): the experimental setup without the flow-feedback method [69]; (**right**): the experimental setup with the flow-feedback method [70].

Bosioc et al. [67] found that introducing a water jet along the axis of the draft tube increases the wall pressure recovery coefficient by 30% compared to the case without a jet, which is significant for hydraulic power generation with short discharge cones. The paper discusses a technique to improve flow momentum and eliminate high-velocity gradients in the centerline of the draft tube using axial jet injection, which can align the hillchart of Francis hydraulic turbines in the off-design regimes while maintaining high efficiency. Numerical calculations given in the paper agree quite well with the measured values of the wall pressure recovery coefficient. The efficiency of this technique was investigated using proper orthogonal decomposition (POD) [71] to analyze the flow field and identify ways to improve it. The method was developed based on previous work by Susan-Resiga's group [72] and was compared with the experimental data studied by Muntean et al. [73].

Previous works by Susan-Resiga's group [72,74] determined that the flow rate of the control jet should be of the order of 11%. Based on this, six jet flow rates were selected for POD analysis: 2%, 5%, 8%, 11%, 12%, and 14% of the total swirl generator output. The spatial and temporal behavior of the POD modes with axial water injection was analyzed and compared with the behavior obtained from the experimental data.

At 2% jet discharge, the first and second modes maintained their positions below the swirl generator hub, whereas at 5% jet discharge, they were shifted downstream in the diffuser. That is, the beam was so powerful that it affected the modes in the upstream section at 5% flow. A clear decrease in vortex dynamics was observed at 8% jet discharge; only the first and second modes were visible, while the spectra of higher modes were suppressed. The frequency of the first and second modes decreased continuously as the jet discharge increased from 2 to 14%. Therefore, the POD method showed similar results to those obtained earlier by Susan-Resiga's group.

Direct feeding of the axial jet is a fairly simple method for controlling vortex structures. Although the method does remove asynchronous pressure pulsations (rotating), dangerous synchronous pressure pulsations with small amplitude still remain in the flow path. Moreover, to suppress the vortex structures, the axial jet flow rate must exceed 11% of the total fluid flow rate, thus resulting in a significant loss of hydroturbine efficiency [74]. This reduces the turbine efficiency. In this regard, the axial jet control has been modernized by Susan-Resiga's group in [75]. If the jet discharge is obtained from upstream of the turbine, thus bypassing the runner, the overall efficiency of the turbine will be considerably decreased. Susan-Resiga et al. [75] demonstrated that reducing vortex breakdown can be accomplished with a moderate jet velocity and proposed the concept of using water from downstream of the diffuser cone, where the pressure is sufficient compared to the nozzle outlet pressure, to generate a control jet.

The idea of a flow feedback system came about after numerical simulations [76] of the flow pressure in the Francis hydraulic turbine model. In the part-load regime of a hydraulic turbine, the flow behind the runner is highly swirled [77]. The swirling flow causes excess pressure at the discharge cone wall. Meanwhile, there is a pressure deficit at the runner crown tip. The numerical calculation showed that the pressure difference between the two parts of the water turbine can drive the control jet to fully mitigate the quasi-stagnant region.

Another advantage of this method is that the flow-feedback method is a self-regulating system. As the hydraulic turbine approaches optimum operation, the pressure differential decreases. Consequently, the flow rate of the control jet decreases, up to its absence. However, asynchronous pressure pulsations are inherent only in part-load regimes [78]. Thus, there is no need for a control jet when the turbine is operating near the best efficiency point. It means the jet "turns itself off".

Pressure recovery in the cone is greatly improved with respect to the initial condition. The overall turbine efficiency is also increased as a result of increased suction at the runner outlet. The flow feedback method allows the size of the discharge cone to be reduced without impairing pressure recovery, since this method can level out the dependence of wall performance on jet discharge by treatment of the boundary layer [66]. This approach to flow control is successful in eliminating the vortex breakdown and significantly reduces the total hydraulic losses in the conical diffuser with swirl.

It is worth noting that the magnitude of pressure differential created between the cone wall and the nozzle outlet pressure does not produce the jet flow required. It has been mentioned many times before that for noticeable suppression of asynchronous pressure pulsations, the control jet flow rate should be ~11–12% of the main flow rate. To achieve the required threshold of jet discharge and reduce hydraulic losses on the return circuit, ejector pumps are used to partially overcome the hydraulic losses in the return pipes (Figure 19, right). The magnitude of pressure difference between the cone wall and the outlet pressure of the jet nozzle ensures the flow rate of the jet is ~10%, the remaining 2% being additionally provided by the ejector pumps [79].

Researchers have developed a setup where the driving jets in the ejector are supplied with an auxiliary pump. However, in real turbines, high-pressure water could be used to supply these driving jets from upstream. By using water injection, the amplitude reduction can be as high as 65%, and the Strouhal number decreases from 0.39 to 0.23, resulting in lower precession frequency (Figure 20). The advantage of the flow-feedback method is that it requires only a 2% discharge for the ejector pump motor jets compared to the 12% discharge for plain water jet injection. However, this method results in residual plunging fluctuations, which have lower amplitude and frequency than PVR fluctuations.

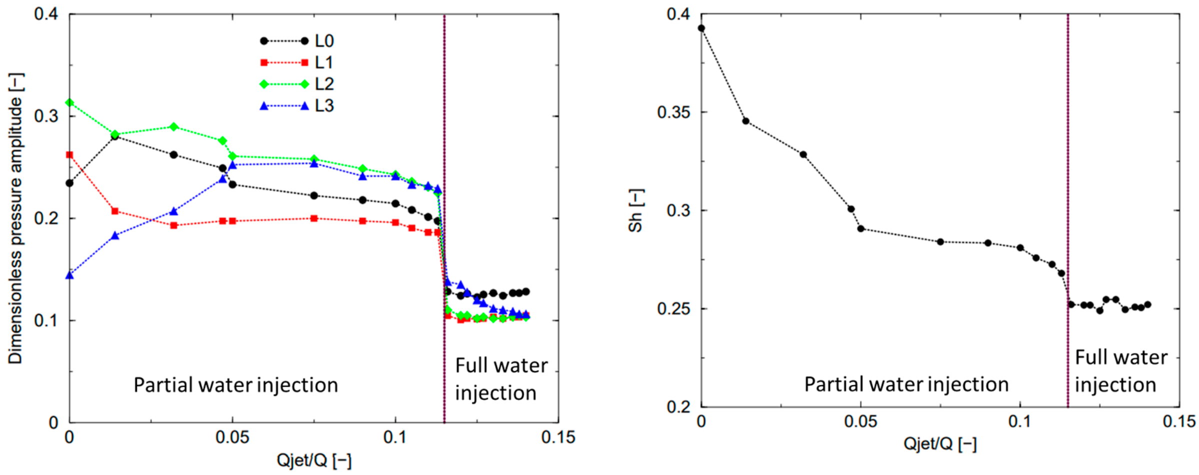

Figure 20. Equivalent amplitudes corresponding to levels from the test section (**left**) and Strouhal number (**right**) vs. Q_{jet}/Q ratio [69].

In order to thoroughly analyze the flow, researchers used a laser Doppler anemometer to examine the velocity fields in various sections behind the hydroturbine model's runner [80]. They studied the velocity profiles with and without water jet injection, both qualitatively and by measuring the averaged profiles. The results showed that introducing a water jet from the main discharge, ranging from 5 to 13%, mitigated or even eliminated the quasi-stagnant region associated with the vortex rope. The mean meridian velocity profiles demonstrated that this effect was noticeable starting from 7–10% water jet injection.

In addition to calculating the required axial jet flow rate, it is also important to determine the optimal jet radius (the radius of the nozzle from which the jet is delivered). Several jet radii were numerically investigated and evaluated by Foroutan and Yavuzkurt [81]. They carried out numerical calculations for the simplified Francis turbine draft tube, which was investigated in the FLINDT project [82]. A water jet can be supplied from the high-pressure flow upstream of the turbine spiral case by a bypass line, without needing an extra pump. This method was found to increase the axial flow momentum in the center and eliminate the stagnation region, thereby changing the precession frequency of the vortex rope in both cases. The loss ratio was reduced by 50% for the 0.9 BEP flow case and by 14% for the 0.7 BEP flow case. The optimal jet radius for the 0.9 BEP flow case was found to be 6.5 mm, which corresponds to a jet radius to runner radius of about 0.05, and reduces the total loss by 13% compared to the no-jet condition. The amount of water used for the optimized jet is less than 0.3% of the turbine flow. Monitoring the transient wall pressure for the 0.7 BEP flow case shows that using a water jet that eliminates the vortex rope and stabilizes the flow reduces the amplitude of pressure fluctuations in the draft tube by about one-third.

In continuation of Foroutan and Yavuzkurt's study, Mohammadi et al. [44] conducted numerical simulations to determine the appropriate nozzle size. In this work, a more accurate result regarding the choice of nozzle diameter was given. It was found that only the smallest nozzle diameter (0.1 times the runner tip diameter) reduced the losses in the draft tube.

A study conducted by Kirschner's group on vortex control using a combination of air and water is of particular interest. The study [83] involved investigating two operating points with different fluctuation characteristics, namely high part-load operating $Q = 0.72\ Q_{BEP}$ (PVR is present) and low part-load operating $Q = 0.43\ Q_{BEP}$ (PVR is absent). The researchers used an axial jet in a draft tube of a model pump-turbine to mitigate pressure fluctuations and compared the suppression capabilities of two nozzle diameters, 30 mm and 38 mm.

First, the high part-load operating $Q = 0.72\ Q_{BEP}$ was considered. At a water flow rate of 8% of the main flow rate through the 38 mm diameter nozzle, the oscillation amplitude was reduced by ~20% compared to the case when there was no jet in the flow; the PVR frequency was also slightly reduced. In the case of a 30 mm diameter nozzle and injected water flow rate of 7.4% of the turbine flow rate, the pressure pulsations were reduced by 60% compared to the case with no jet in the flow. As in the case of the nozzle with a larger diameter, there is also a shift toward smaller frequencies of the amplitude peak in the pressure fluctuation spectrum. The most interesting case is a combination of air and water. In this case, the water flow was 2.8% of the main flow through the 38 mm diameter nozzle, and the mass flow of the injected air was 0.023% of the mass flow of water through the turbine runner. A ~55% reduction of oscillation amplitude was obtained compared to the no-flow case; the PVR frequency was also slightly reduced. It turns out that in order to reduce the amplitude of pressure pulsations caused by the vortex runner, it does not make sense to combine a water supply with an air supply. The difference in results is rather insignificant.

At the low part-load regime of $Q = 0.43\ Q_{BEP}$, the use of only a water jet through a 38 mm diameter nozzle with a flow rate of 13.5% of the main flow does not efficiently reduce pressure pulsations, which appear to be caused by vortex movement modulated by the impeller speed. However, the use of a 30 mm diameter nozzle does slightly improve the situation by reducing pressure pulsation suppression by 50%. The situation changes significantly when a mixture of air and water is injected through a 38 mm diameter nozzle. The injected stabilizing water discharge is 4.8% of the discharge through the turbine runner, and the mass flow of injected air is 0.040% of the mass flow of water through the turbine runner. This method reduces pressure fluctuation amplitude by over 80% in the time domain, but only if the pressure fluctuation is not caused by a rotating vortex rope. Therefore, injecting water alone is not as efficient as injecting both water and air in reducing pressure fluctuations at this operating point.

Research conducted by Susan-Resiga's group [66] revealed that using a lower velocity but higher discharge jet is more efficient for reducing pressure pulsations than using a low discharge and high-velocity control jet. The jet velocity should be of the same order of magnitude as the average axial velocity at the turbine throat [9], and the jet can be supplied from a low-pressure water source downstream of the impeller without reducing the impeller output. This approach is the basis of the flow-feedback control method.

The findings obtained by Susan-Resiga's group [66] somewhat contradict those reported by Kirschner's group [83], who found that reducing the nozzle area or increasing the jet velocity is more efficient in suppressing pressure pulsations. In our opinion, using a jet with a lower velocity is preferable, and increasing the nozzle area (jet radius) can help reduce the jet velocity while maintaining a low loss factor. For example, jet radii equivalent to 10% and 50% of the runner crown radius can reduce the loss coefficient by 14% and 50%, respectively [11].

Jafarzadeh Juposhti et al. [84] have also drawn a similar conclusion through numerical simulations of vortex rope suppression using an axial water jet. They recommended implementing the maximum injection radius based on geometrical limitations and calculating the injection velocity according to the required axial momentum and jet radius. The choice of injection mode should consider volumetric loss competing against flow separation, and the flow-feedback methods can offset this problem. The present study was conducted for the model Francis turbine, specifically the Francis-99 turbine, which is a 1:5.1 scale model of a prototype turbine [85].

In another study [86], Khullar et al. investigated the optimum nozzle shape for water jet injection in partial-load operation and fully developed RVR. They compared the jet supply from the original cone to two modified cones with different nozzle positions. In this study, the nozzle diameter was 9% of the runner outlet diameter. A comparison was made between the jet supply from the original cone and the two modified cones (Figure 21). In Case 1, the nozzle was at the bottom of the cone, while in Case 2, the nozzle was 1.5D (where D is runner outlet diameter) and located upstream of the bottom to provide a stabilizing length for the jet. The length of the modified cones was identical to the original one. The authors used a two-equation k-ω-based shear stress transport model and the commercial code ANSYS CFX to obtain their results. They recommended using a stabilizing length for the jet by placing the nozzle upstream of the cone bottom.

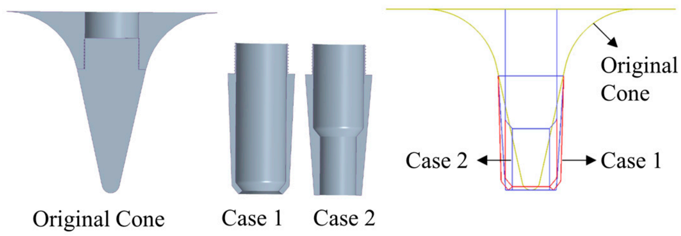

Figure 21. Schematic of runner cone profiles. Reused with permission from [86]. Copyright © 2022 Elsevier Ltd.

Preliminary measurements of turbine efficiency and power with different cone shapes, but without the control jet in the flow, were made. This comparison showed that there was a slight reduction in efficiency when the modified cones were installed in the flow in the partial-load regime, in which a PVR is observed. However, in the near-optimum regime, the modified cones had almost no effect on the energy performance of the turbine. Adding an axial jet to the flow increased the turbine power output and the flow rate. Thus, if the jet flow rate was 10% of the main flow rate, the gain in turbine flow rate was 4.24% for the first modified cone and 4.61% for the second modified cone. A jet with a flow rate of 10% increased the output power by 13.2%. Therefore, the water jet injection may shift the prototype turbine unit's hill curve. The authors believed that the gain in flow rate could be attributed to this increase in pressure difference across the runner. The turbine efficiency at the draft tube outlet varied non-monotonically with increasing jet flow rate. In general, the jet supply reduced the efficiency by ~2–5% compared to the efficiency when there was no jet in the flow.

More interesting results are that it is sufficient to feed an axial jet with a flow rate of 5% of the main flow to mitigate the vortex rope from the draft cone. Since the second modified cone (the nozzle being 1.5D) has a passage at the nozzle outlet to stabilize the water jet, the jet for this cone does not deviate from the central axis for almost the entire distance from the impeller. This means that it is more efficient to use the cone with stabilizing length than the cone with the nozzle at the bottom to deliver an axial jet.

An important practical conclusion can be drawn from analyzing the pressure recovery coefficient. When selecting the flow rate of the axial jet, it is important to consider two aspects. First, increasing the flow rate of the jet leads to better suppression of pressure pulsations caused by the vortex rope. Additionally, increasing the axial jet flow rate increases the pressure recovery coefficient and consequently the efficiency of the draft tube. Second, increasing the jet flow rate to 8–10% of the main flow rate results in a very low average pressure drop due to very high jet velocities. Low average pressures in the draft tube cone can make the turbine operation more susceptible to cavitation if it is already operating near the critical Thoma's number. Furthermore, at high jet flow rates, pressure pulsations increase, relative to the regime with a jet flow rate of 2–5% of the main flow rate. This contradicts the findings reported by Susan-Resiga's group [72] suggesting that the axial jet may be more efficient at higher discharge rates. An explanation for this effect has also been provided by Khullar et al. [86]. The increase in pressure pulsation at high discharge of the jet was attributed to the impact of the jet on the draft tube wall. High velocity of the jet allows it to reach the bend without significant dispersion. Due to the impact on the bend wall, this jet can cause synchronous pressure pulsations that can propagate upstream. This can be the cause of higher-pressure pulsations. Therefore, it is important to strike a balance when selecting the flow rate of the axial jet.

A comprehensive numerical simulation of the effect of a water jet on a vortex rope was carried out by Altimemy et al. [87]. The modeling was carried out using the large eddy simulation method. In the paper, the PVC control using a central axial jet as well as jets at the periphery of the draft tube cone at an angle of 25° from the axial direction was investigated. Therefore, efficiencies of the two methods of PVC suppression for flow rates of 2, 4, and 6% were compared. In order to control flow-induced pressure fluctuations, central and peripheral water injections at different flow rates were considered. Central injection at 4% and 6% flow reduced high-amplitude pressure fluctuations by 40% and 75% at part load. Peripheral water injections were inefficient in stabilizing system operation at partial loads. Moreover, the amplitude of pressure fluctuations at the blade exit increased significantly when using peripheral water injection. This could be due to the fact that the areas of peripheral influence were selected without reliance on theoretical calculation, without identifying areas of greatest susceptibility of the flow to perturbations. The obtained result is opposite to those reported in the aforementioned study by Francke [65], where the author managed to achieve suppression of pressure pulsations by using tangential jets under certain conditions. The influence of water injection on the turbine power generation was negligible in both operating regimes.

In 2006, Susan-Resiga et al. [14] proposed the axial jet method for PVC control, which was later improved by Javadi and Nilsson [88]. They conducted a numerical study of PVC control using annular jets injected from the runner crown, and compared seven jet types with different momentum fluxes, injection angles, and positions at the runner crown. The goal was to find a small flow rate that could manipulate the boundary layer at the crown to prevent the initiation of a vortex rope. The authors found that the upstream jet controls the flow more efficiently than the conventional injection point at the bottom part of the runner crown in terms of massive separation from the crown. They inferred that the angle of injection and position of the slot are important factors for flow control efficiency. Figure 22 demonstrates the PVC control effect using a 3% flow rate of the swirl generator through an annular slot jet.

A numerical study focusing on the impact of jet injection for mitigation of vortex rope pulsations was carried out [89]. Seven design modifications of runner crown were tested (Figure 23). The study was performed for the same experimental conditions as those used in [14]. The annular jet with different gap size and orientation, as well as the pulsating jet, was considered. The authors attempted to perturb the region with the highest strain rate. The results indicated that the vortex rope behavior is especially influenced by flow along the diffuser axis in the momentum deficit region. More pronounced suppression of pressure pulsation has not been achieved compared to that reported in [14].

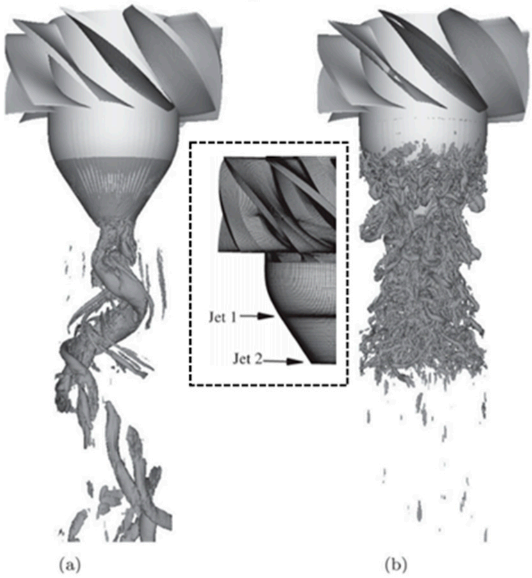

Figure 22. The iso-surface of Q-criterion (from [88]) at a part-load condition with formation of the PVC. Comparison between the baseline case (**a**) and the C1 control case (**b**). C1 means the slot located at "Jet 1"; the control flow rate is Q_{jet}/Q = 0.027; orientation of velocity component is ctan (U_θ $/U_a$), where U_θ and U_a are tangential and axial components of velocity, respectively.

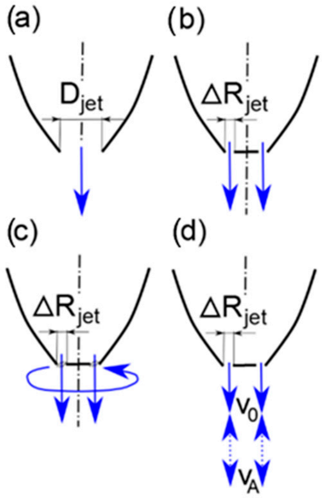

Figure 23. Different types of water injection (from [89]): (**a**) full circular injection [14]; (**b**) annular injection; (**c**) annular injection with an opposite swirl; and (**d**) annular injection with pulsating jet.

The method of controlling a vortex rope by means of axial jet was investigated by Tanasa et al. (2017) [90]. The authors suggested feeding a pulsating axial jet instead of a constant flow jet. This paper presented three-dimensional numerical simulations of several cases with and without injection of pulsating water jet. The calculation was performed for a model Francis turbine. By injecting the pulsating water jet, the quasi-stagnant region associated with the vortex rope was mitigated. The pulsating jet was specified as a constant-velocity modulation by a sinusoidal signal with an amplitude between 2.5% and 20% of the mean velocity. It was shown, although without detailed explanations, that a pulsating jet with low amplitude can deal more efficiently with vortex flow than a constant-velocity jet. Furthermore, the pulsating water jet method enhances pressure recovery (12%) and reduces losses along the discharge cone.

3.3. Periodic Perturbation

In the literature, there are studies where vortex suppression is achieved by imposing azimuthal disturbances near the vortex formation region. The control actually deals with interaction between disturbances and the vortex per se rather than with reducing the overall swirl of the flow. By imposing disturbances, it is possible to reduce wall pressure fluctuations and transfer the vortex breakdown point downstream, thus stabilizing the vortex core closer to the centerline of the draft tube.

The novel method based on the idea of azimuthal perturbations was proposed in [91]. Control over the PVC is investigated numerically using ANSYS CFX (Figure 24a). It was shown that the azimuthal injection of pulsating momentum from four nozzles on the draft tube wall (Figure 24b) could significantly mitigate the rotating component and the overall amplitude of the PVC pressure pulsations for a jet flow ratio of approximately 5%.

(**a**)

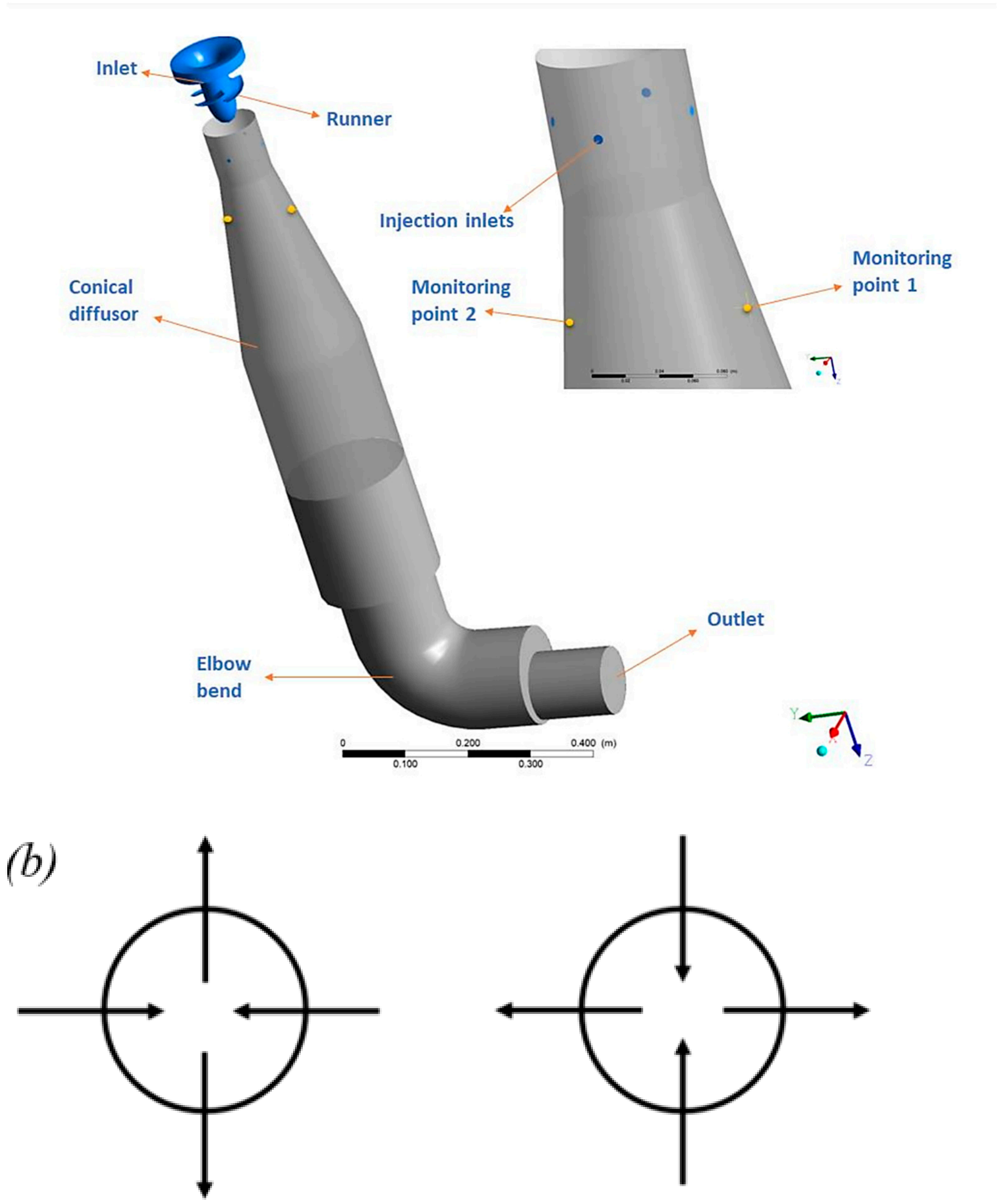

Figure 24. A numerical setup consisting of a runner, a conical diffuser, an elbow bend, and point of injections (**a**) and the injection pattern (**b**). Two 180-degree phase shifted injections occur simultaneously with two 180-degree phase shifted ejections [91].

An alternative approach in this case is to use four solid rods instead of water jets. Experimental and numerical results for this method were presented in papers [92] and [93], respectively. The method is based on periodic perturbation of the PVC by pushing/pulling solid metal rods into the flow (Figure 25). The authors analyzed the impact of these protrusions on the swirl flow and pressure pulsations in terms of rotating and plunging components. The idea was to manipulate the shear layer at the interface between the stagnant region and outer swirl flow. It was shown that by pushing/pulling the rods consecutively in the direction of the runner's rotation, the rotating component of the RVR can be suppressed. However, the protrusions frequently cause an increase in the plunging mode level.

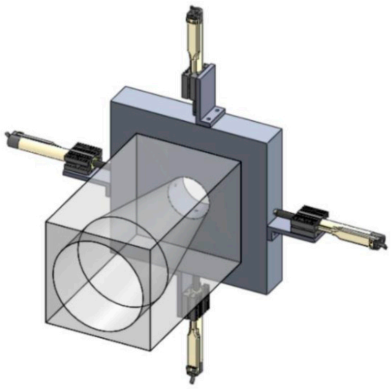

Figure 25. Schematic view of the device to control the PVC [94].

An original approach based on "noise cancellation" of the PVC was described in [95]. Blomaert et al. presented an approach to reduce pressure pulsation by using a pulsating jet injected only in one point on the draft tube wall. A small water flow (1–2% of turbine output), modulated by a rotary valve, was injected into the draft tube cone as a forced excitation to eliminate the self-induced pressure fluctuations generated by the vortex rope during partial discharge. The method targets the effects of pressure fluctuations within the hydroacoustics of the system rather than the main source of excitation. The obtained overall decrease in the amplitude was only 25% of pressure pulsations without control. The power consumption of the system was found to be relatively low compared to that of the turbine (~0.43%). Water consumption through the system was estimated to be 0.12% of the nominal water flow in the turbine. The authors inferred that pressure pulsations at a specific frequency could be reduced with this system. However, there was an increase in the higher harmonics in the pressure pulsation spectrum. This is indicative of non-linear interaction between the PVR and the control system. The reason for this increase could be the non-optimal location of the jet that was chosen to control the flow. Most likely, it was not the location of the highest sensitivity of the PVR to control, so the control system interacted with the PVR trail downstream. Unfortunately, the authors of this review are not aware of any further studies other than the one mentioned.

3.4. Control Based on the Results of Theoretical Framework of LSA

In vortex burner systems, the occurrence of PVC allows for intricate coupling between the acoustics, combustion, and swirl [5]. Owing to these implications control over PVC is an important issue in such applications. The mechanism of PVC formation in combustion units is similar to that observed in a conical diffuser of hydroturbine. Therefore, papers focusing on the PVC control in vortex combustors are of great interest to this review.

The promising theoretical framework for analyzing and controlling PVC is based on global linear stability analysis (LSA). Gallaire et al. [96] proposed that the helical instability mode originates from the region of absolute instability in the wake of the recirculation zone. This was later demonstrated in [97–99], showing that the resulting eigenmodes accurately predict the PVC generated by global mode (azimuthal wave number m = 1). Even more importantly, the linear framework allows one to calculate adjoints of the global modes, which reveal the receptivity of the modes to mean field modifications [100] or periodic forcing (e.g., [101]).

According to the theoretical framework, the control strategy is aimed at forcing the flow by several (at least two) independently controllable and either radially or axially directed periodic jets in the high-sensitivity flow regions [102]. Later, Müller et al. [103] showed that this theoretical framework of LSA can be adopted from a swirling jet with the PVC to flow in a hydroturbine model. Müller et al. [103] conducted a mean flow sensitivity analysis to gain insights into the impact of changes in the mean flow on the vortex rope instability. The sensitivity of the eigenvalue to mean flow modifications is represented as a magnitude plot of the real part, with the most sensitive region coinciding with the region of reverse flow on the runner crown and the maximum value attained at the runner crown edge. Consequently, a recent publication [104] described automated experiments to determine the most efficient orientations of the control jets for reducing pressure fluctuations and measure the optimal control flow rate. The experiments showed that the best result can be achieved using radial control jets.

The particularly interesting approach from the viewpoint of energy cost is the closed-loop approach with zero-net mass flux (ZNMF), i.e., without significant energy consumption. Lückoff et al. [105,106] improved the closed-loop approach with ZNMF previously described by Kuhn et al. [107]. The active control approach presents a four-loudspeaker-based zero-net mass flux (ZNMF) actuator integrated into a swirl-stabilized combustor. Lückoff et al. [108] studied the lock-in behavior of PVC for actuation when using different designs of actuator. As a result, the final best actuator design was determined. Further, the closed-loop control was realized in [106]. This closed-loop scheme for phase-opposition flow control employed a set of circumferentially arranged pressure sensors to acquire the current phase and amplitude of the PVC. After that, an actuation signal in phase-opposition to the measured PVC was generated. This signal was transmitted to the actuation unit with four loudspeakers and actuation channels, providing corresponding (phase-shifted) actuation jets that suppressed the PVC by actuating a phase-opposed coherent structure. In this experimental work, helical ($m = 1$) ZNMF actuation was applied at the source of the global mode, with an actuation amplitude of only 0.03% of the main flow. This location was determined from the adjoint of the global mode as it is the most receptive flow region. This makes the control approach very efficient because it exploits the natural amplification of flow perturbations given by the inherent global hydrodynamic instability.

4. Summary and Perspective

Based on a review of the open-access literature focusing on the feasibility of controlling the vortex rope by adding air or using auxiliary jets/excitation methods, several conclusions can be drawn.

The initial research into air supply focused on increasing the dissolved oxygen levels below hydroelectric dams. In addition to this, researchers also studied the impact of air supply on suction pipe losses and turbine efficiency. Later, it was discovered that air could also reduce pressure pulsations under the sub-optimal operating conditions. Despite numerous experimental and numerical studies since Nakanishi's work in 1964 [27], there have been no fundamentally new findings. However, some understanding of the mechanism behind pressure pulsation reduction has been achieved through numerical studies, in particular in terms of the amount and location of air injection.

In some cases, the available research into gas phase injection presents conflicting results. Despite varying injection methods and gas volumes, both a decrease and increase in turbine efficiency at the same gas content values have been observed, as well as changes in pressure pulsations. There are limited data on the effect of gas injection on pulsation frequency, although frequency shift in the case of resonance conditions may also be required. Furthermore, the influence of air bubble size on the unsteady flow characteristics has hardly been investigated and, although in some papers the air bubble size has been a parameter, no information on the resulting dispersion has been provided. Moreover, the bubble size may be a parameter which could explain the difference in results between the numerical and experimental works.

By adjusting air flow rates, pressure fluctuations can be cushioned by increasing vortex core pressure and weakening axial pressure gradients. The stabilization mechanism involves changing the vortex rope shape based on the amounts of injected air, with small amounts maintaining a corkscrew shape and high rates creating a cylindrical shape. Sufficient air supply eliminates the vortex rope, while inadequate supply may lead to resonance due to decreasing natural frequency with increasing cavity volume.

Overall, injecting ~2% of air from the impeller fairing cone appears optimal for suppressing pressure pulsations without significant efficiency loss. The cost of air injection is rarely estimated, but the use of an automatic venting system can minimize overheads and potentially improve efficiencies at low gas contents.

Experimental studies have shown that application of optimal configurations of tangential jets can eliminate the formation of PVC. However, this method is not energy efficient as it requires energy losses due to the use of tangential jets in the opposite direction to the primary swirl. The results suggest that the concept of tangential water injection works well but could be upgraded through nozzle duct optimization.

The axial central jet is the most well-developed method for active control over PVC. The use of axial injection through the turbine shaft can efficiently control vortex structures and mitigate pressure pulsations. This technique increases the momentum of the stagnant flow in the centerline of the draft tube, thus reducing shearing effects and decreasing amplitudes of pressure pulsations. A group led by Prof. Susan-Resiga has made a significant contribution to controlling PVC by axial jet in Francis turbines. Their research demonstrated remarkable suppression of pressure pulsations, equivalent to 11–12% of the main flow rate, through the use of an axial jet. Follow-up publications have shown that the control efficiency can be significantly improved by optimizing the injection point and jet configuration. Different values of the control jet flow rate are provided in the literature for achieving efficient suppression of pressure pulsations, ranging from 3 to 12% of the main flow rate. The only limitation to the use of axial water jets is their high energy requirements.

In this respect, methods based on azimuthal flow excitations appear more promising. The focus of controlling pressure pulsations in Francis turbines is not to decrease the overall swirl of the flow but rather to interact with disturbances and stabilize the vortex core. This is achieved by actuating perturbations that can reduce wall pressure fluctuations and shift the vortex breakdown point downstream. Global linear stability analysis (LSA) is a promising theoretical framework for finding the best control strategy in hydroturbines.

However, practical implementation of these strategies is still challenging as it requires accurate knowledge of system dynamics and the ability of real-time flow manipulation.

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References

1. Kishore, T.S.; Patro, E.R.; Harish, V.S.K.V.; Haghighi, A.T. A Comprehensive Study on the Recent Progress and Trends in Development of Small Hydropower Projects. *Energies* **2021**, *14*, 2882. [CrossRef]
2. Nishi, M.; Liu, S. An Outlook on the Draft-Tube-Surge Study. *Int. J. Fluid Mach. Syst.* **2013**, *6*, 33–48. [CrossRef]
3. Jonsson, P.P.; Mulu, B.G.; Cervantes, M.J. Experimental Investigation of a Kaplan Draft Tube–Part II: Off-Design Conditions. *Appl. Energy* **2012**, *94*, 71–83. [CrossRef]
4. Liang, H.; Maxworthy, T. An Experimental Investigation of Swirling Jets. *J. Fluid Mech.* **2005**, *525*, 115–159. [CrossRef]
5. Syred, N. A Review of Oscillation Mechanisms and the Role of the Precessing Vortex Core (PVC) in Swirl Combustion Systems. *Prog. Energy Combust. Sci.* **2006**, *32*, 93–161. [CrossRef]
6. Żywica, G.; Bagiński, P.; Breńkacz, Ł. Dynamic State Assessment of the Water Turbine with the Power of 600 KW. *Diagnostyka* **2013**, *14*, 65–70.
7. March, P. *Hydraulic and Environmental Performance of Aerating Turbine Technologies*; Electric Power Research Institute: Palo Alto, CA, USA, 2011; pp. 19–21.
8. Rheingans, W.J. Power Swings in Hydroelectric Power Plants. *J. Fluids Eng.* **1940**, *62*, 171–177. [CrossRef]
9. Masoodi, F.A.; Goyal, R. Efficacy of Ancillary Fluid Injection Technique for Mitigation of Vortex Rope in Hydraulic Turbines: A Review. *Mater. Today Proc.* **2021**, *47*, 3043–3053. [CrossRef]
10. Kumar, S.; Cervantes, M.J.; Gandhi, B.K. Rotating Vortex Rope Formation and Mitigation in Draft Tube of Hydro Turbines—A Review from Experimental Perspective. *Renew. Sustain. Energy Rev.* **2021**, *136*, 110354. [CrossRef]
11. Muhirwa, A.; Cai, W.-H.; Su, W.-T.; Liu, Q.; Binama, M.; Li, B.; Wu, J. A Review on Remedial Attempts to Counteract the Power Generation Compromise from Draft Tubes of Hydropower Plants. *Renew. Energy* **2020**, *150*, 743–764. [CrossRef]
12. Wang, L.; Cui, J.; Shu, L.; Jiang, D.; Xiang, C.; Li, L.; Zhou, P. Research on the Vortex Rope Control Techniques in Draft Tube of Francis Turbines. *Energies* **2022**, *15*, 9280. [CrossRef]
13. Tanasa, C.; Bosioc, A.; Stuparu, A.; Muntean, S.; Susan-Resiga, R. A Perspective Review of Passive Techniques Applied to Control the Swirling Flow Instabilities from The Conical Diffuser of Hydraulic Turbines. *Appl. Mech. Rev.* **2023**, 1–89. [CrossRef]
14. Susan-Resiga, R.; Vu, T.C.; Muntean, S.; Ciocan, G.D.; Nennemann, B. Jet Control of the Draft Tube Vortex Rope in Francis Turbines at Partial Discharge. In Proceedings of the 23rd IAHR Symposium on Hydraulic Machinery and Systems, Yokohama, Japan, 17–21 October 2006; ResearchGate: Berlin, Germany, 2006; pp. 67–80.
15. Tănasă, C.; Bosioc, A.; Muntean, S.; Susan-Resiga, R. A Novel Passive Method to Control the Swirling Flow with Vortex Rope from the Conical Diffuser of Hydraulic Turbines with Fixed Blades. *Appl. Sci.* **2019**, *9*, 4910. [CrossRef]
16. Urban, O.; Kurková, M.; Pochylý, F. Control of Swirling Flow in a Diffuser Using Various Installations. *AIP Conf. Proceeding* **2023**, *2672*, 020020.
17. Imamura, H.; Kurokawa, J.; Matsui, J.; Kikuchi, M. Others Suppression of Cavitating Flow in Inducer by J-Groove. In Proceedings of the Fifth Intemational Symposium on Cavitation (CAV2003), Osaka, Japan, 1–4 November 2003.
18. Kurokawa, J.; Imamura, H.; Choi, Y.-D. Effect of J-Groove on the Suppression of Swirl Flow in a Conical Diffuser. *J. Fluids Eng.* **2010**, *132*, 071101. [CrossRef]
19. Biela, V.; Beltran, H. Draft Tube Fins. Procedings of the 19th IAHR symposium on Hydraulic Machinery and Cavitation, Singapore, 9–11 September 1998; pp. 454–461.
20. Sentyabov, A.; Minakov, A.; Platonov, D.; Dekterev, D.; Zakharov, A.; Semenov, G. Numerical Investigation of the Influence of Special Structures On Suppression of Pressure Pulsations in The Draft Tube of a High-Head Hydraulic Turbine. *J. Eng. Phys. Thermophys.* **2019**, *92*, 1489–1500. [CrossRef]
21. Dörfler, P.; Sick, M.; Coutu, A. *Flow-Induced Pulsation and Vibration in Hydroelectric Machinery: Engineer's Guidebook for Planning, Design and Troubleshooting*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2012.
22. Lückoff, F.; Naster, M.; Müller, J.; Sieber, M.; Litvinov, I.; Oberleithner, K. Impact of Runner Crown Shape Modifications on the Onset of the Precessing Vortex Core. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Chennai, India, 23–24 July 2022; IOP Publishing: Chiyoda City, Tokyo, 2022; Volume 1079, p. 012051.
23. Qian, Z.; Li, W.; Huai, W.; Wu, Y. The Effect of Runner Cone Design on Pressure Oscillation Characteristics in a Francis Hydraulic Turbine. *Proc. Inst. Mech. Eng. Part J. Power Energy* **2012**, *226*, 137–150. [CrossRef]
24. Li, Y.; Liu, H.; Lin, Y.; Li, W.; Gu, Y. Design and Test of a 600-KW Horizontal-Axis Tidal Current Turbine. *Energy* **2019**, *182*, 177–186. [CrossRef]
25. Joy, J.; Raisee, M.; Cervantes, M.J. A Novel Guide Vane System Design to Mitigate Rotating Vortex Rope in High Head Francis Model Turbine. *Int. J. Fluid Mach. Syst.* **2022**, *15*, 188–209. [CrossRef]
26. Murakami, M. Vibration of Water Turbine When Air Is Admitted to Its Draft Tube: Experimental Study. *Bull. JSME* **1958**, *1*, 298–304. [CrossRef]
27. Nakanishi, K.; Ueda, T. Air Supply into Draft Tube of Francis Turbine. *Fuji Electr. Rev.* **1964**, *10*, 81–91.
28. Casanova García, F.; Mantilla Viveros, C.A. Experimental Analysis of the Vibration on the Draft Tube of a Francis Hydraulic Turbine during Operation at Different Power Levels. *Rev. Fac. Ing. Univ. Antioq.* **2010**, *55*, 90–98.
29. Papillon, B.; Sabourin, M.; Couston, M.; Deschenes, C. Methods for Air Admission in Hydroturbines. In Proceedings of the XXIst IAHR Symposium on Hydraulic Machinery and Systems, Lausanne, Switzerland, 9–12 September 2002; pp. 6–11.

30. Papillon, B.; Sabourin, M.; Segoufin, C.; Gaudin, E. The Technical Challenges of Dissolved Oxygen Enhancement EPRI. In *EPRI-DOE Conference on Environmentally-Enhanced Hydropower Turbines: Technical Papers*; U.S. Department of Energy Office of Scientific and Technical Information: Oak Ridge, TN, USA, 2011; Volume 49, p. 072008. [CrossRef]
31. Türkmenoğlu, V. The Vortex Effect of Francis Turbine in Electric Power Generation. *Turk. J. Electr. Eng. Comput. Sci.* **2013**, *21*, 26–37. [CrossRef]
32. Muntean, S.; Susan-Resiga, R.F.; Campian, V.C.; Dumbrava, C.; Cuzmos, A. In Situ Unsteady Pressure Measurements on the Draft Tube Cone of the Francis Turbine with Air Injection over an Extended Operating Range. *UPB Sci. Bull. Ser. D* **2014**, *76*, 173–180.
33. Nakashima, T.; Matsuzaka, R.; Miyagawa, K.; Yonezawa, K.; Tsujimoto, Y. Study on Flow Instability and Countermeasure in a Draft Tube with Swirling Flow. *IOP Conf. Ser. Earth Environ. Sci.* **2014**, *22*, 032007. [CrossRef]
34. Nakashima, T.; Matsuzaka, R.; Miyagawa, K.; Yonezawa, K.; Tsujimoto, Y. Study on Flow Instability and Countermeasure in a Draft Tube with Swirling Flow. *Int. J. Fluid Mach. Syst.* **2015**, *8*, 230–239. [CrossRef]
35. Skripkin, S.G.; Kuibin, P.A.; Shtork, S.I. The Effect of Air Injection on the Parameters of Swirling Flow in a Turbine-99 Draft Tube Model. *Tech. Phys. Lett.* **2015**, *41*, 638–640. [CrossRef]
36. Tănasă, C.; Muntean, S.; Bosioc, A.I.; Susan-Resiga, R.; Ciocan, T. Influence of the Air Admission on the Unsteady Pressure Field in a Decelerated Swirling Flow. *UPB Sci. Bull. Ser. D* **2016**, *78*, 161–170.
37. Unterluggauer, J.; Maly, A.; Doujak, E. Investigation on the Impact of Air Admission in a Prototype Francis Turbine at Low-Load Operation. *Energies* **2019**, *12*, 2893. [CrossRef]
38. Platonov, D.; Minakov, A.; Dekterev, D.; Maslennikova, A. An Experimental Investigation of the Air Injection Effect on the Vortex Structure and Pulsation Characteristics in the Francis Turbine. *Int. J. Fluid Mach. Syst.* **2020**, *13*, 103–113. [CrossRef]
39. Bucur, D.M.; Dunca, G.; Bunea, F.; Calinoiu, C. Aeration Process Influence over the Operation of a Small Hydro Turbine—Generator Unit. In Proceedings of the 2017 10th International Symposium on Advanced Topics in Electrical Engineering (ATEE), Bucharest, Romania, 23–25 March 2017; IEEE: Bucharest, Romania, 2017; pp. 746–751.
40. Bunea, F.; Ciocan, G.D.; Bucur, D.M.; Dunca, G.; Nedelcu, A. Hydraulic Turbine Performance Assessment with Implementation of an Innovative Aeration System. *Water* **2021**, *13*, 2459. [CrossRef]
41. Qian, Z.; Yang, J.; Huai, W. Numerical Simulation and Analysis of Pressure Pulsation in Francis Hydraulic Turbine with Air Admission. *J. Hydrodyn.* **2007**, *19*, 467–472. [CrossRef]
42. Chirkov, D.V.; Shcherbakov, P.K.; Cherny, S.G.; Skorospelov, V.A.; Turuk, P.A. Numerical Investigation of the Air Injection Effect on the Cavitating Flow in Francis Hydro Turbine. *Thermophys. Aeromechanics* **2017**, *24*, 691–703. [CrossRef]
43. Chirkov, D.; Scherbakov, P.; Skorospelov, V.; Cherny, S.; Zakharov, A. Numerical Simulation of Air Injection in Francis Turbine. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *240*, 022043. [CrossRef]
44. Mohammadi, M.; Hajidavalloo, E.; Behbahani-Nejad, M. Investigation on Combined Air and Water Injection in Francis Turbine Draft Tube to Reduce Vortex Rope Effects. *J. Fluids Eng.* **2019**, *141*, 051301. [CrossRef]
45. Luo, X.; Yu, A.; Ji, B.; Wu, Y.; Tsujimoto, Y. Unsteady Vortical Flow Simulation in a Francis Turbine with Special Emphasis on Vortex Rope Behavior and Pressure Fluctuation Alleviation. *Proc. Inst. Mech. Eng. Part J. Power Energy* **2017**, *231*, 215–226. [CrossRef]
46. Zhu, L.; Zhang, R.; Yu, A.; Lu, L.; Luo, X. Suppression of Vortex Rope Oscillation and Pressure Vibrations in Francis Turbine Draft Tube Using Various Strategies. *J. Hydrodyn.* **2021**, *33*, 534–545. [CrossRef]
47. Luo, X.; Yu, A.; Yu, W.; Wang, L.; Xu, H. Pressure Oscillation Suppression by Air Admission in a Francis Turbine Draft Tube. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *240*, 022008. [CrossRef]
48. Zhang, R.; Yu, A.; Nishi, M.; Luo, X. Numerical Investigation of Pressure Fluctuation and Cavitation inside a Francis Turbine Draft Tube with Air Admission through a Fin. *J. Phys. Conf. Ser.* **2021**, *1909*, 012017. [CrossRef]
49. Kim, S.-J.; Cho, Y.; Kim, J.-H. Effect of Air Injection on the Internal Flow Characteristics in the Draft Tube of a Francis Turbine Model. *Processes* **2021**, *9*, 1182. [CrossRef]
50. Shahzer, M.A.; Kim, S.-J.; Cho, Y.; Kim, J.-H. Effect of Air Injection Holes Intrusiveness on Internal Flow Phenomena of a Draft Tube Inside a Francis Turbine Model. *KSFM J. Fluid Mach.* **2022**, *25*, 5–12. [CrossRef]
51. Sun, L.; Li, Y.; Guo, P.; Xu, Z. Numerical Investigation of Air Admission Influence on the Precessing Vortex Rope in a Francis Turbine. *Eng. Appl. Comput. Fluid Mech.* **2023**, *17*, 2164619. [CrossRef]
52. Sun, L.; Guo, P.; Wu, L. Numerical Investigation of Alleviation of Undesirable Effect of Inter-Blade Vortex with Air Admission for a Low-Head Francis Turbine. *J. Hydrodyn.* **2020**, *32*, 1151–1164. [CrossRef]
53. Pejovi, S. Air Influence on Stability of Real and Theoretical Hydraulic System. *Sci. Rev. Serbian Sci. Soc. Belgrade* **1996**, *16*, 23–38.
54. Dörfler, P.K. Dissolved-Gas Influence on the Francis Part-Load Oscillation. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *405*, 012015. [CrossRef]
55. Skripkin, S.; Zuo, Z.; Tsoy, M.; Kuibin, P.; Liu, S. Oscillation of Cavitating Vortices in Draft Tubes of a Simplified Model Turbine and a Model Pump–Turbine. *Energies* **2022**, *15*, 2965. [CrossRef]
56. Kuibin, P.A.; Pylev, I.M.; Zakharov, A.V. Two-Phase Models Development for Description of Vortex-Induced Pulsation in Francis Turbine. *IOP Conf. Ser. Earth Environ. Sci.* **2012**, *15*, 022001. [CrossRef]
57. Alekseenko, S.V.; Kuibin, P.A.; Okulov, V.L.; Shtork, S.I. Helical Vortices in Swirl Flow. *J. Fluid Mech.* **1999**, *382*, 195–243. [CrossRef]
58. Litvinov, I.V.; Shtork, S.I.; Kuibin, P.A.; Alekseenko, S.V.; Hanjalic, K. Experimental Study and Analytical Reconstruction of Precessing Vortex in a Tangential Swirler. *Int. J. Heat Fluid Flow* **2013**, *42*, 251–264. [CrossRef]

59. Shtork, S.I.; Alekseenko, S.; Okulov, V.L.; Kuibin, P.A. Vortex Precession in a Gas-Liquid Flow. *Heat Transf. Res.* **2010**, *41*, 465–478. [CrossRef]
60. Zhang, R.-K.; Mao, F.; Wu, J.-Z.; Chen, S.-Y.; Wu, Y.-L.; Liu, S.-H. Analysis and Control of Part-Load Unsteady Flow in Francis Turbine's Draft Tube. In Proceedings of the Volume 6: Turbo Expo 2007, Parts A and B; ASMEDC, Montreal, QC, Canada, 1 January 2007; Volume 47950, pp. 1647–1658.
61. Nishi, M.; Yoshida, K.; Yano, M.; Okamoto, M.; Miyagawa, K.; Liu, S. *A Preliminary Study on the Swirling Flow in a Conical Diffuser with Jet Issued at the Center of the Inlet*; ResearchGate: Berlin, Germany, 2007; pp. 24–26.
62. Seybert, T. Injection Nozzle Geometries Pursuant to the Reduction of Draft Tube Surge in Hydroelectric Pump-Turbines. Master's Thesis, Pennsylvania State University, University Park, State College, PA, USA, Applied Research Lab, Setagaya City, Tokyo, Japan, 1978.
63. Cassidy, J.J. Experimental Study and Analysis of Draft-Tube Surging. In *BUR Reclam REP HYD-591 May 1969*; Bureau of Reclamation: Washington, DC, USA, 1969; p. 31.
64. Gupta, K.; Lilley, D.G.; Syred, N. *Swirl Flows*; Abacus Press: Kent, UK, 1984.
65. Francke, H.H. Increasing Hydro Turbine Operation Range and Efficiencies Using Water Injection in Draft Tubes. Ph.D. Thesis, Norwegian University of Science and Technology, Norvay, Trondheim, 2010.
66. Susan-Resiga, R.; Muntean, S.; Bosioc, A.; Stuparu, A.; Milos, T.; Baya, A.; Bernad, S.; Anton, L.E. *Swirling Flow Apparatus and Test Rig for Flow Control in Hydraulic Turbines Discharge Cone*; ResearchGate: Berlin, Germany, 2007; Volume 52, pp. 203–216.
67. Bosioc, A.I.; Tanasa, C.; Muntean, S.; Susan-Resiga, R. Pressure Recovery Improvement in a Conical Diffuser with Swirling Flow Using Water Jet Injection. In *Romanian Academy, Series A: Mathematics, Physics, Technical Sciences, Information Science*; ResearchGate: Berlin, Germany, 2010; ISSN 14549069.
68. Ciocan, G.D.; Iliescu, M.S.; Vu, T.C.; Nennemann, B.; Avellan, F. Experimental Study and Numerical Simulation of the FLINDT Draft Tube Rotating Vortex. *J. Fluids Eng.* **2007**, *129*, 146–158. [CrossRef]
69. Bosioc, A.I.; Tanasa, C.; Muntean, S.; Susan-Resiga, R.F. Unsteady Pressure Measurements and Numerical Investigation of the Jet Control Method in a Conical Diffuser with Swirling Flow. *IOP Conf. Ser. Earth Environ. Sci.* **2010**, *12*, 012017. [CrossRef]
70. Tănasă, C.; Bosioc, A.I.; Susan-Resiga, R.F.; Muntean, S. Experimental Investigations of the Swirling Flow in the Conical Diffuser Using Flow-Feedback Control Technique with Additional Energy Source. *IOP Conf. Ser. Earth Environ. Sci.* **2012**, *15*, 062043. [CrossRef]
71. Štefan, D.; Rudolf, P.; Muntean, S.; Susan-Resiga, R. Proper Orthogonal Decomposition of Self-Induced Instabilities in Decelerated Swirling Flows and Their Mitigation Through Axial Water Injection. *J. Fluids Eng.* **2017**, *139*, 081101. [CrossRef]
72. Bosioc, A.I.; Susan-Resiga, R.; Muntean, S.; Tanasa, C. Unsteady Pressure Analysis of a Swirling Flow With Vortex Rope and Axial Water Injection in a Discharge Cone. *J. Fluids Eng.* **2012**, *134*, 081104. [CrossRef]
73. Muntean, S.; Susan-Resiga, R.; Bosioc, A.I. *Numerical Investigation of the Jet Control Method for Swirling Flow with Precessing Vortex Rope*; ResearchGate: Berlin, Germany, 2009; Volume 1, pp. 65–74.
74. Muntean, S.; Susan-Resiga, R.; Bosioc, A.; Stuparu, A.; Baya, A.; Anton, L.E. *Mitigation of Pressure Fluctuation in a Conical Diffuser with Precessing Vortex Rope Using Axial Jet Control Method*; ResearchGate: Berlin, Germany, 2008.
75. Susan-Resiga, R.; Muntean, S.; Hasmatuchi, V.; Ruprecht, A.; Sandor, B. *Development of a Swirling Flow Control Technique for Francis Turbines Operated at Partial Discharge*; ResearchGate: Berlin, Germany, 2007; Volume 200, pp. 625–637.
76. Susan-Resiga, R.; Muntean, S. Decelerated Swirling Flow Control in the Discharge Cone of Francis Turbines. In *Fluid Machinery and Fluid Mechanics*; Xu, J., Wu, Y., Zhang, Y., Zhang, J., Eds.; Springer: Berlin/Heidelberg, Germany, 2009; pp. 89–96. ISBN 978-3-540-89748-4.
77. Litvinov, I.V.; Suslov, D.R.; Gorelikov, I.V.; Sadbakov, O.U.; Shtork, S.I. Swirl Number Analysis in the Air Hydro-Turbine Model. *AIP Conf. Proc.* **2018**, *2027*, 040057. [CrossRef]
78. Litvinov, I.; Sharaborin, D.; Gorelikov, E.; Dulin, V.; Shtork, S.; Alekseenko, S.; Oberleithner, K. Modal Decomposition of the Precessing Vortex Core in a Hydro Turbine Model. *Appl. Sci.* **2022**, *12*, 5127. [CrossRef]
79. Tănasă, C.; Susan-Resiga, R.; Muntean, S.; Bosioc, A.I. Flow-Feedback Method for Mitigating the Vortex Rope in Decelerated Swirling Flows. *J. Fluids Eng.* **2013**, *135*, 061304. [CrossRef]
80. Bosioc, A.I.; Tănasă, C. Experimental Study of Swirling Flow from Conical Diffusers Using the Water Jet Control Method. *Renew. Energy* **2020**, *152*, 385–398. [CrossRef]
81. Foroutan, H.; Yavuzkurt, S. Flow in the Simplified Draft Tube of a Francis Turbine Operating at Partial Load—Part II: Control of the Vortex Rope. *J. Appl. Mech.* **2014**, *81*, 061011. [CrossRef]
82. Avellan, F. *Flow Investigation in a Francis Draft Tube : The Flindt Project*; ResearchGate: Berlin, Germany, 2000.
83. Kirschner, O.; Schmidt, H.; Ruprecht, A.; Mader, R.; Meusburger, P. Experimental Investigation of Vortex Control with an Axial Jet in the Draft Tube of a Model Pump-Turbine. *IOP Conf. Ser. Earth Environ. Sci.* **2010**, *12*, 012092. [CrossRef]
84. Jafarzadeh Juposhti, H.; Maddahian, R.; Cervantes, M.J. Optimization of Axial Water Injection to Mitigate the Rotating Vortex Rope in a Francis Turbine. *Renew. Energy* **2021**, *175*, 214–231. [CrossRef]
85. Cervantes, M.; Trivedi, C.; Dahlhaug, O.G.; Nielsen, T. Francis-99 Workshop 2: Transient Operation of Francis Turbines. *J. Phys. Conf. Ser.* **2017**, *782*, 011001. [CrossRef]
86. Khullar, S.; Singh, K.M.; Cervantes, M.J.; Gandhi, B.K. Influence of Runner Cone Profile and Axial Water Jet Injection in a Low Head Francis Turbine at Part Load. *Sustain. Energy Technol. Assess.* **2022**, *50*, 101810. [CrossRef]

87. Altimemy, M.; Attiya, B.; Daskiran, C.; Liu, I.-H.; Oztekin, A. Mitigation of Flow-Induced Pressure Fluctuations in a Francis Turbine Operating at the Design and Partial Load Regimes—LES Simulations. *Int. J. Heat Fluid Flow* **2019**, *79*, 108444. [CrossRef]
88. Javadi, A.; Nilsson, H. Active Flow Control of the Vortex Rope and Pressure Pulsations in a Swirl Generator. *Eng. Appl. Comput. Fluid Mech.* **2017**, *11*, 30–41. [CrossRef]
89. Rudolf, P.; Litera, J.; Alejandro Ibarra Bolanos, G.; Štefan, D. Manipulation of the Swirling Flow Instability in Hydraulic Turbine Diffuser by Different Methods of Water Injection. *EPJ Web Conf.* **2018**, *180*, 02090. [CrossRef]
90. Tanasa, C.; Ciocan, T.; Muntean, S. Numerical Assessment of Pulsating Water Jet in the Conical Diffusers. *AIP Conf. Proc.* **2017**, *1906*, 050002. [CrossRef]
91. Holmström, H.; Sundström, J.; Cervantes, M.J. Vortex Rope Mitigation with Azimuthal Perturbations: A Numerical Study. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *774*, 012144. [CrossRef]
92. Holmström, H.; Sundström, J.; Cervantes, M.J. Vortex Rope Interaction with Radially Protruded Solid Bodies in an Axial Turbine: A Numerical Study. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1079*, 012055. [CrossRef]
93. Shiraghaee, S.; Sundström, J.; Raisee, M.; Cervantes, M.J. An Experimental Investigation on the Effects of Cylindrical Rods in a Draft Tube at Part Load Operation in Down-Scale Turbine. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1079*, 012007. [CrossRef]
94. Shiraghaee, S.; Sundström, J.; Raisee, M.; Cervantes, M.J. Mitigation of Draft Tube Pressure Pulsations by Radial Protrusion of Solid Bodies into the Flow Field: An Experimental Investigation. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *774*, 012004. [CrossRef]
95. Blommaert, G.; Avellan, F.; Prenat, J.E.; Boyer, A. Active Control of Francis Turbine Operation Stability. In Proceedings of the 3rd ASME/JSME Joint Fluids Engineering Conference, San Francisco, CA, USA, 18–23 July 1999.
96. Gallaire, F.; Ruith, M.; Meiburg, E.; Chomaz, J.-M.; Huerre, P. Spiral Vortex Breakdown as a Global Mode. *J. Fluid Mech.* **2006**, *549*, 71. [CrossRef]
97. Oberleithner, K.; Sieber, M.; Nayeri, C.N.; Paschereit, C.O.; Petz, C.; Hege, H.-C.; Noack, B.R.; Wygnanski, I. Three-Dimensional Coherent Structures in a Swirling Jet Undergoing Vortex Breakdown: Stability Analysis and Empirical Mode Construction. *J. Fluid Mech.* **2011**, *679*, 383–414. [CrossRef]
98. Oberleithner, K. On Turbulent Swirling Jets: Vortex Breakdown, Coherent Structures, and Their Control. Ph.D. Thesis, Technical University of Berlin, Berlin, Germany, 2012.
99. Pasche, S.; Avellan, F.; Gallaire, F. Part Load Vortex Rope as a Global Unstable Mode. *J. Fluids Eng.* **2017**, *139*, 051102. [CrossRef]
100. Pasche, S.; Avellan, F.; Gallaire, F. Optimal Control of Part Load Vortex Rope in Francis Turbines. *J. Fluids Eng.* **2019**, *141*, 081203. [CrossRef]
101. Müller, J.S.; Lückoff, F.; Oberleithner, K. Guiding Actuator Designs for Active Flow Control of the Precessing Vortex Core by Adjoint Linear Stability Analysis. *J. Eng. Gas Turbines Power* **2019**, *141*, 041028. [CrossRef]
102. Müller, J.S.; Lückoff, F.; Paredes, P.; Theofilis, V.; Oberleithner, K. Receptivity of the Turbulent Precessing Vortex Core: Synchronization Experiments and Global Adjoint Linear Stability Analysis. *J. Fluid Mech.* **2020**, *888*, A3. [CrossRef]
103. Müller, J.; Lückoff, F.; Kaiser, T.; Oberleithner, K. On the Relevance of the Runner Crown for Flow Instabilities in a Francis Turbine. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Bristol, UK, 24 November 2022; IOP Publishing: Bristol, UK, 2022; Volume 1079, p. 012053.
104. Litvinov, I.; Suslov, D.; Tsoy, M.; Gorelikov, E.; Alekseenko, S.; Oberleithner, K. Active Control of the Vortex Induced Pressure Fluctuations in a Hydro Turbine Model via Axial and Radial Jets at the Crown Tip. *Int. J. Fluid Mach. Syst.* **2023**, *in press*.
105. Lückoff, F.; Sieber, M.; Paschereit, C.O.; Oberleithner, K. Characterization of Different Actuator Designs for the Control of the Precessing Vortex Core in a Swirl-Stabilized Combustor. *J. Eng. Gas Turbines Power* **2018**, *140*, 041503. [CrossRef]
106. Lückoff, F.; Sieber, M.; Paschereit, C.O.; Oberleithner, K. Phase-Opposition Control of the Precessing Vortex Core in Turbulent Swirl Flames for Investigation of Mixing and Flame Stability. *J. Eng. Gas Turbines Power* **2019**, *141*, 111008. [CrossRef]
107. Kuhn, P.; Moeck, J.P.; Paschereit, C.O.; Oberleithner, K. Control of the Precessing Vortex Core by Open and Closed-Loop Forcing in the Jet Core. In *Volume 4B: Combustion, Fuels and Emissions*; American Society of Mechanical Engineers: Seoul, Republic of Korea, 2016; p. V04BT04A036.
108. Lückoff, F.; Sieber, M.; Paschereit, C.O.; Oberleithner, K. Characterization of Different Actuator Designs for the Control of the Precessing Vortex Core in a Swirl-Stabilized Combustor. In *Volume 4A: Combustion, Fuels and Emissions*; American Society of Mechanical Engineers: Charlotte, NC, USA, 2017; p. V04AT04A040.