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Pressure pulsations and fatigue loads in high head Francis turbines

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Abstract. The Norwegian power system today includes a relatively large percentage of Francis turbines with a head of above 300m, in the world. This leads to a need to maintain and develop the national competence regarding the challenges connected to this type of turbine. The importance of this competence is increased by the fact that these turbines have a high installed capacity and are therefore crucial to the production stability. In the later years the old runners in Norwegian high head power plants have begun to show signs of fatigue. Taking the average age of these runners, which is approaching 45 years, into account, this may not be surprising. The surprising fact is that the same signs of fatigue, and in some cases total breakdown due to cracks, also occur in new and modern Francis runners. This leads to a hypothesis that the problem stems from sources other than the turbine runners themselves. The suspected cause of this reduction in the expected lifetime is the change the pattern of turbine operation to accommodate new intermittent energy in the power system and progress in the manufacturing technology enabling thinner blades. As an example the Horizon2020 project HydroFLEX initialised by the European Union aim to produce technology that allows for 30 start-stops per day for Francis runner. A research project funded by the Norwegian Research Council and the Norwegian Hydro Power Industry, aim to increase the available knowledge regarding these high head Francis turbines. The research is done both on a basic and applied level where the focus is to increase the knowledge of the phenomena and to produce validation data for numerical simulations of said phenomena. The fundamental research focus on the hydrodynamic dampening applied on a hydrofoil within a high velocity water flow. The applied research is focused on the Francis-99 runner, a model runner of a High Head Francis turbine, which has been instrumented in order to study the Rotor-Stator-Interaction(RSI) and the structural response of the runner. The research areas both consist experimental and numerical studies, where the experimental results are used to validate the numerical. This paper presents the background of the project, the different activities and some preliminary results from selected activities. The aim of the paper is to introduce the project, participants and the participants view on the future of High Head Francis runners that do not crack due to RSI.

Keywords: Francis, Resonance, Fatigue, RSI

1. Introduction

As the effects of climate change become more visible, the need for a shift towards renewable electricity production becomes evident. The possibility for new hydro power in the western world has, to some degree, been maximised[1]. Hence, new renewable technology is needed in order to meet the increasing energy demand. The new intermittent renewable technologies consist of both solar and wind power, and is produced when the conditions are within the operating envelope of the machinery and said conditions cannot be controlled. Their introduction therefore require balancing power from the other power production technology in the grid to regulate the frequency and voltage[2]. Hydraulic turbines are well suited to provide the needed balancing power as they can quickly respond to a change in the electricity demand in the grid[3, 4]. Francis runners are one of the most common hydraulic turbines in use today, and they have the ability to adjust the power production in order to tackle changes in demand with a response time in the order of seconds or less[4, 5].

In the resent years, old Francis runners have shown cracks caused by fatigue loading, which have been seen as a symptom of their age. New runners have also shown the same types of fatigue problems and some have even reached failure after a short time of operation[6, 7]. The cause of such failures are believed to be linked to the RSI and the subsequent pressure pulsations affecting the runner.

The Norwegian hydro power system has an annual power production in the order 136GWh[1] and includes a large amount of the worlds high head Francis runners. This is a driving force behind the need to maintain and improve the national and international knowledge regarding high head Francis runners. From this need, a research project called HiFrancis, focusing on the fatigue problems in high head Francis runners was started in 2016. The research is conducted by the Waterpower Laboratory (Norwegian University of Science and Technology) and EDR&Medeso. The experimental research is done by the Waterpower Laboratory and most of the numerical research is done by EDR&Medeso. This paper will focus on the research connected to the HiFrancis project and will present the aim of the project, the different research areas and some preliminary results.

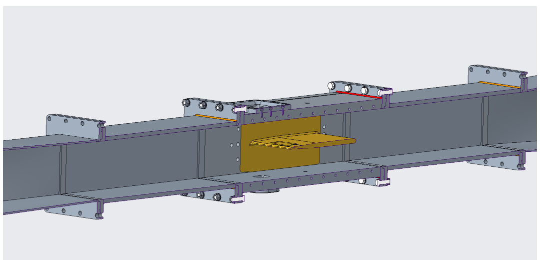
2. Research focus

The research conducted in connection to the HiFrancis project can be seen as a combination of basic and applied research, utilising both experimental and numerical techniques. The two research areas and the motivation for including them in the project, and some preliminary results will be presented here.

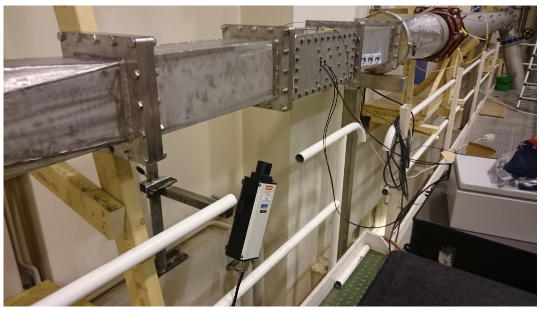
2.1. Basic research

As the use of numerical simulations, both fluid and structure focused, have become increasingly important in the study and design of hydraulic turbines, the mechanisms of interest have become increasingly complicated to both measure and quantify experimentally. One of these important mechanisms is the hydrodynamic dampening, caused by the water flowing through the runner, which contribution is of importance when evaluating the structural response of the runner during operation. Previous research within this field has focused on hydrofoils, both semi-constrained[8, 9, 10, 11] and fully constrained[7, 12, 13, 14].

2.1.1. Test rig The research concerning hydrodynamic dampening utilises a new test rig, denoted the Cascade Rig, at the Waterpower Laboratory built especially for testing hydrofoils in high velocity flow. Figure 1a shows a 3D rendering of the Cascade Rig, while Figure 1b shows the rig during the measurements. The experimental setup includes piezoelectric patches (known as MFCs) mounted on the hydrofoil for excitation [15], the response of the hydrofoil is measured by both external Laser-Doppler Velocimeter and semiconductor based strain gauges mounted on the hydrofoil. The experimental setup is similar to that of previous experiments on fully constrained hydrofoils[12]. An important phenomenon regarding vibrating structures within a fluid flow is lock-in, where the vortex shedding is controlled by the vibrational frequency of the structure instead of the Strouhal law[16]. This phenomenon will synchronise the vortex shedding frequency and the vibrational frequency of the structure for a range of flow velocities. It is impossible to state unambiguously where high-head Francis turbines are, with respect to lock-in, in their operating range. This is due to the large range of operational conditions, and thereby velocities, the runner blades are exposed. In addition, the flow velocity is not constant across the blade at the trailing edge, which leads to an ambiguous value of the flow velocity. As the relationship between dampening and the free stream velocity is the main focus of the project, the main focus of the experimental work was chosen to be velocities above the lock-in condition, i.e. velocities where the vortex shedding is above the natural frequency of the structure.



(a) 3D Rendering with cross section inside water volume, hydrofoil seen in gold.



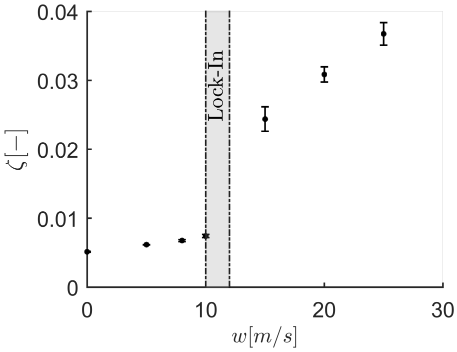
(b) Closed, instrumented cascade rig with Laser-Doppler Velocimeter below.

Figure 1: Cascade Rig at the Waterpower Laboratory.

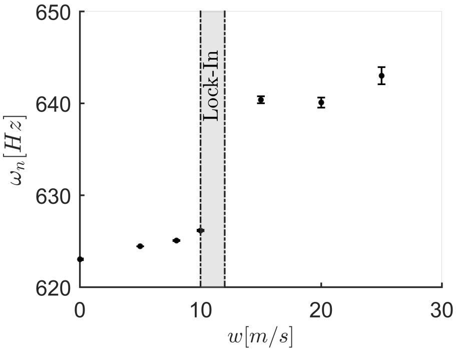
At this point in time two of three iteration of the research conducted on the Cascade Rig have been completed. The first iteration revealed problems with the hydrofoil design causing the inception of cavitation on the leading edge, at a free stream velocity of 25 m/s. In addition, the trailing edge design resulted in lock-in occurring at approx. 11.5 m/s, which reduces the possibility of investigating the behaviour of the hydrofoil at a wide range of high above lock-in conditions. For the second iteration a revision of the hydrofoil geometry was conducted and lock-in was moved to approx. 6.5 m/s, and no cavitation problems were caused by the hydrofoil. Figure 2 show the changes implemented on the hydrofoil through the revision. The maximum velocity for the second iteration was found to be 28 m/s, limited by the surrounding piping system which caused problems with cavitation at higher velocities.

Figure 2: Changes to the hydrofoil of iteration 1(blue) and iteration 2(orange).

2.1.2. Results The results from the basic research follow previously published results well with regard to the linear trend in hydrodynamic dampening at above lock-in conditions[12, 13, 14]. However, a change in the slope across the lock in region was found, as seen in Figure 3a, which is previously not seen in the literature regarding fully constrained hydrofoils. This discrepancy may be caused by the relatively high natural frequency of the hydrofoil studied in this project ($f_n \approx 630Hz$) compared to the other cases [12, 13, 14]($f_n \approx 75Hz$). Which in turn will lead to the lock-in condition of the latter being achieved at a extremely low velocity compared to the hydrofoil study presented here. The difference in the trend of hydrodynamic dampening have previously been found for the first torsion mode of semi-constrained hydrofoils[10]. This mode of vibration can be viewed as most similar to the first mode of vibration for a fully constrained hydrofoil.



(a) Damping ratio.



(b) Natural freqency.

Figure 3: Damping and natural frequency[17].

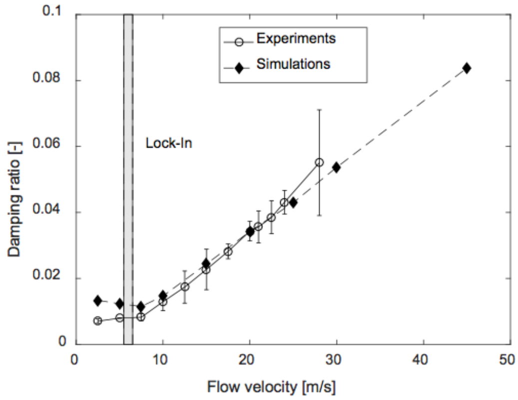


Figure 4: Dampening ratio found experimentally and numerically for the second iteration hydrofoil [18]

The natural frequency found during the first iteration of the Cascade Rig study also contains a discontinuity across the lock-in region. This discontinuity is previously not reported for fully constrained hydrofoils, but have been found, but not studied further, for the first torsion mode for semi-constrained hydrofoils[10].

During the study of the second iteration the change in slope when passing through lock-in was again found. As the lock-in condition was moved to a lower flow velocity due to the the design revision, the size of the above lock-in condition region was enlarged, which can be seen in Figure 4

The numerical work conducted as part of the Cascade Rig study correspond well with the results found from the experiments, as shown in Figure 4. Simulations are conducted on the structure and fluid volume separately, but the deflection of the hydrofoil is enforced on the mesh of the fluid volume. This requires a very fine mesh, especially close to the hydrofoil surface in order to capture the minute movement of the hydrofoil as it vibrates.

2.2. Applied research

The applied research is focused on industry adapted solution of high head Francis turbines. The aim is to investigate the consequences of RSI (i.e. amplitudes of RSI frequencies at critical locations in the turbine), resonance and the corresponding mode-shapes under both steady state and transient operating conditions. In addition to the experimental studies, extensive numerical analysis is conducted including the accurate verification and validation of the industry standard numerical model[19], optimization of numerical effort with regard to cost and time and fluid-structure interaction (FSI) of complete runner. Furthermore, exclusive sets of measurements are conducted for the second and third workshops of Francis-99 [20, 21]. The measurement data and CAD models are available to all interested researchers and academic students for numerical simulations and validations.

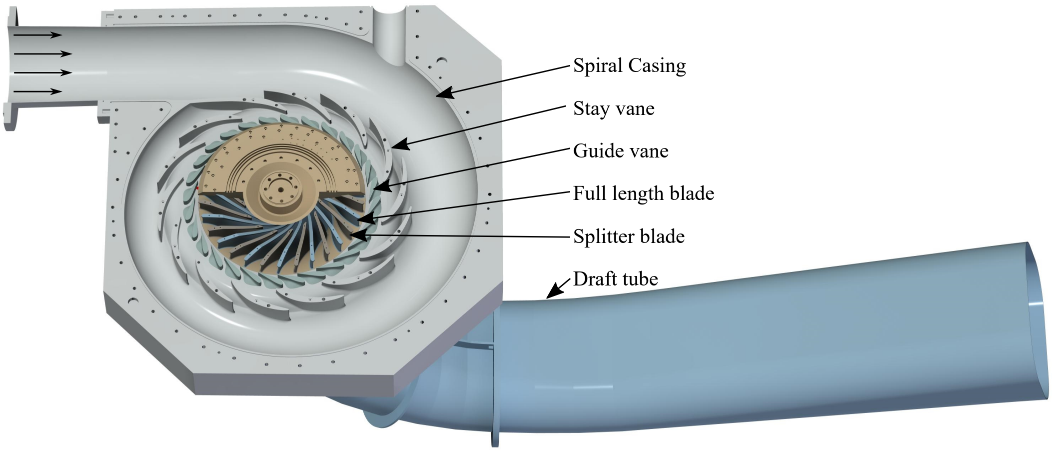


Figure 5: Model Francis turbine installed in test rig.

2.2.1. Test rig The state-of-the-art facility available at the Waterpower Laboratory, NTNU, is used to conduct experiments and supercomputers available at EDR&Medeso AS and NTNU are used for numerical analysis. A model Francis turbine (Francis-99) available in the laboratory, shown installed in the test rig in Figure 5, is a reduced scale model of a high head prototype Francis turbines. The hydraulic system is capable of producing a head up to 16 m in open loop and up to 100 m in closed loop. In the open loop, overhead tank acts as a large upper reservoir and downstream tank acts as tailrace. Hence, for this project open loop is more appropriate due to requirement of transient operations identical to the prototypes. The turbine includes 14 stay vanes, 28 guide vanes, a runner with 15 blades and 15 splitters, and an elbow-type draft tube. The runner includes an alternating arrangement of a splitter and a blade. The runner inlet and outlet diameters are 0.63 m and 0.347 m, respectively. The runner is directly coupled to a DC generator, which also operates as a motor in pumping mode. The test rig may also be used for industrial model testing in accordance with IEC 60193[22] in a closed loop (30 m head, $Re = 4 \cdot 10^6$), and it is equipped with standard instruments used to measure the head, discharge, torque, power, water temperature and rotational speed. Additional pressure sensors are flush mounted to acquire pressure data from different locations, and a slip-ring mechanism is used to transmit data from the runner. To investigate the resonance and associated mode-shapes of the runner, an excitation system is integrated in the runner crown that allows frequency sweep up to 10th harmonic of RSI frequency. This novel mechanism enables the study of the structural behaviour of the runner during operation and the corresponding mode-shapes under resonance condition. The measurements aimed for three distinct conditions of the runner − determine added mass in air, still water and during operation in the test rig. Furthermore, strain gauges are integrated at distinct locations on the blade trailing edge to determine deflection and strain amplitudes under the resonance condition.

The best efficiency point (BEP) of the model turbine was obtained at a guide vane opening $\alpha = 9.9°$, with a flow rate $Q = 0.199\,\mathrm{m^3/s}$ ($Q_{ED} = 0.15$) and a rotational speed $n = 333\,\mathrm{rpm}$ ($n_{ED} = 0.18$), with a hydraulic efficiency $\eta_h = 93.1 \pm 0.2\%$.

The runner was rotating at the synchronous speed, i.e., 333 rpm, under all operating conditions. The total uncertainty ($\hat{e}_t$) of $\pm 0.2\%$ includes both systematic ($\hat{e}_s$) and random ($\hat{e}_r$) uncertainties.

$$\hat{e}_t = \sqrt{\hat{e}_s^2 + \hat{e}_r^2} \tag{1}$$

The systematic uncertainty ($\hat{e}_s$) is the root-sum square of the uncertainties in the volume flow rate ($\hat{e}_Q$), head ($\hat{e}_H$), torque ($\hat{e}_T$), runner rotational speed ($\hat{e}_n$) and water density ($\hat{e}_\rho$) measurements. More details about the pressure sensors, calibrations, repeatability and uncertainty quantifications is available in the literature [23].

2.2.2. Results The results are divided into three categories: (1) pressure measurements at distinct locations in the turbine and the subsequent determination of the amplitudes of RSI frequencies, (2) resonance and modal analysis and (3) development of viscous wake in the vaneless space. Unlike other turbines, high head Francis turbines include quite a large number of blades and guide vanes. The resulting amplitudes of RSI frequencies are so high that they may take a toll on the operating life of the machine. The blade and guide vane interaction frequency is high, often near the runner natural frequencies, and a new pressure wave is developed before the former wave is dampened in the turbine. Consequently, amplitudes of RSI at far upstream and downstream of point of interaction are high as compared to the other turbines. Time for the consecutive RSI can be estimated using Equation 2,

$$t_{RSI} = \frac{|z_b - z_{gv}|}{n \cdot z_b \cdot z_{gv}} \tag{2}$$

where z_b is the number of blades, z_{gv} is the number of guide vanes and n is the rotational speed in revolutions per second. Distinction between the static and dynamic, as well as between the deterministic and stochastic, loading is important to determine fatigue loading on the blades under different operating conditions, including load variation, start-stop and speed-no-load. The HiFrancis project aims to study the pressure amplitudes and development of pressure waves in the turbine. Four pressure sensors are integrated in one of the blade channels at equal intervals from runner inlet to the outlet. The linear arrangement of the sensors enable the study of how pressure amplitudes vary along the blade channel and, more importantly, with respect to the angular position relative to the guide vanes. In fact, such analysis revealed quite interesting flow physics in the blade channel − how the average and the fluctuating component of pressure changes with time (angular rotation of runner). Furthermore, the linear arrangement of the sensors enable the investigation of the amplitudes of deterministic and stochastic frequencies along the blade length. Figure 6 show the factors of pressure fluctuations ($\tilde{p}_E$) pertained to guide vane passing frequency (f_{gv}) in

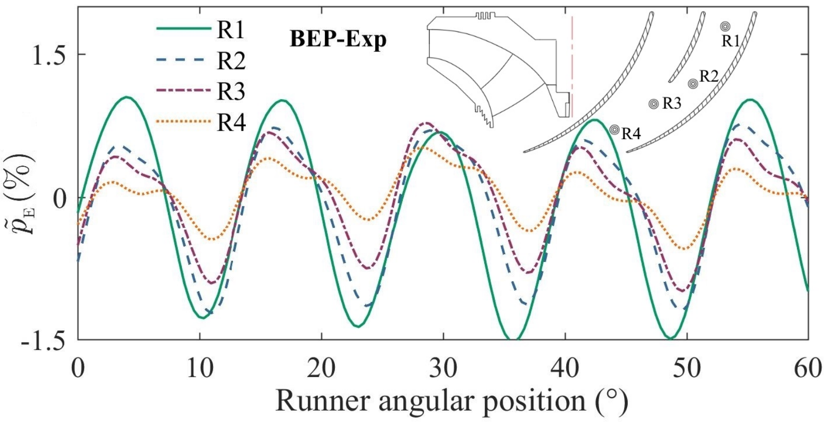


Figure 6: Factor of pressure fluctuations pertained to guide vane passing frequency in the blade channel at BEP.

the blade channel at BEP. Surprisingly, amplitudes from R1 to R4 are not consistent and not exactly periodic with runner rotation, which is contrary to the assumption of periodic flow for majority of numerical simulations. For example, at 30° angular position of runner, the amplitudes in the entire channel are almost same. The small distortion at R3 to R4 locations may be attributed to the modulation around the RSI with the stochastic fluctuations.

$$f_{gv} = n \cdot z_{gv} \qquad \text{[Hz]} \tag{3}$$

$$\tilde{p}_E = \frac{p - \bar{p}}{(\rho \cdot E)_{BEP}} \tag{4}$$

where p is the acquired pressure in Pa, $\bar{p}$ is the average pressure at the corresponding location in Pa, ρ is the water density in kg/m^3, and E is the specific hydraulic energy in J/kg.

Under the HiFrancis project, extensive numerical studies have been conducted to optimize the numerical modeling of high head Francis turbines and to reduce the time and effort [24, 25, 26]. The optimization includes model reduction, automatic meshing, influence of boundary conditions and the effect of flow compressibility. The aim is to prepare a recommended practice for the turbine simulations and provide a check list that may be used to assess the credibility of numerical model in the absence of rigorous validation. The computational domain consists of entire turbine and the investigations showed that the global errors are smaller than the local errors in the turbine. The error in hydraulic efficiency was less than 5% at BEP. Figure 7 shows uncertainty in mesh discretization at BEP, the average error in pressure prediction in the runner and the validation error ($\hat{e}_v$) that was found to be 14%, i.e. almost three time the global error. Hence, verification and validation with local parameters, such as pressure and velocity at critical locations in the turbine, is essential in addition to the global parameters. The numerical studies provided quite interesting results. For example, comparisons of

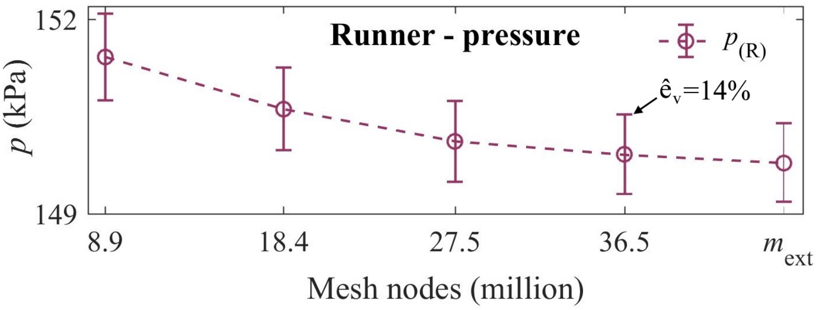


Figure 7: Quantification of discretization error in local parameter, an average pressure at R1 location in the blade channel at BEP, $\hat{e}_v$ is the validation error in the corresponding mesh density, m_{ext} is the extrapolated mesh computed using procedure described in the literature[27].

results with tetrahedral and hexahedral meshes in the turbine, showed similar results of average flow parameters. Compressible flow analysis provided more accurate prediction of RSI compared to that of the incompressible flow, especially in the runner and draft tube, but also result in approx. twice the CPU time requirement. Such studies, with the complete turbine, may not be a suitable option for the industrial computations. Furthermore, mass flow inlet and static pressure outlet type boundaries give minimum error as compared to the other combinations. Blade and guide vane passage modelling using advanced numerical techniques, such as the Fourier transform, harmonic transform and the time transform proved to be very good alternative of complete turbine modelling. However, user should be aware of the consequences of Fourier coefficients; inappropriate selection of the coefficients may produce incorrect frequencies and amplitudes of RSI. Alternative approach of passage modelling may be useful however, the passage modelling approach is subject to strict pitch requirement between the rotor and the stator.

Another set of measurements were focused on the runner natural frequencies and the mode-shape. Unlike the measurements reported in the literature [28, 29, 30, 31], the present measurements are conducted inside the Francis turbine that accounted all possible effects and response from the adjacent structure. Some of the measurements are available under the third workshop of Francis-99. The added-mass effect is studied when the runner was in the air, in still water and during operation in the test rig. Several rotational speed values are investigated, which allowed measurements identical to the prototype conditions. The runner was excited using integrated excitation system in the crown and the response was measured through integrated pressure sensors and strain gauges. The mode-shapes and corresponding deformations were compared with the numerical results of FSI analysis. Quite good agreement between the experimental and numerical results was obtained. The natural frequency was found near to the RSI frequencies of the runner, hence measurements are believed to be of a high importance, especially with regard to the investigation of the resonance condition. Numerical studies also focused on reduction of computational time for structural analysis under this project. A toolkit integrated with ANSYS structural analysis will be developed that enables minimum human effort for setting up the model and faster solution times. Thereby simplifying industrial structural analysis, especially for hydraulic turbines.

3. Conclusion

The HiFrancis project is aimed to study and investigate the challenges experienced by high head Francis turbines in the context of resonance and fatigue loading. The project is divided into two main tasks; basic research and applied research. Basic research focused on understanding of flow physics and find the solution from the fluid mechanics point. Applied research focused on understanding the complex flow condition on fluids engineering point and provide industry implementable solution. From the previous studies and the literature, it is clear that the hydrodynamic damping may play a critical role on reducing the amplitudes of structure vibrations during the resonance. Fully constrained hydrofoils with two different profiles were studied and the maximum attained velocity was 28 m/s. The present measurements confirmed that the flow velocity has linear relation (although, this was known from the literature but it was unclear due to high uncertainty) with the hydrodynamic damping up to certain extent, especially after the lock-in condition. Hence, for an actual turbine, the location of lock-in for the guide vanes and blades may be a point of interest with regard to hydrodynamic damping when the entire structure is considered, i.e., blades, hub, shroud and labyrinth seals. Under the category of applied research, amplitudes of RSI, resonance and the corresponding mode-shapes of the high head Francis runner were studied. In addition, exclusive measurements were proposed for the third workshop of Francis-99, which is scheduled during 28th-29th of May 2019. The measurements revealed the non-linear dampening of RSI amplitudes from the point of interaction. The dampening is dependent on the geometrical shape and the reflection of pressure waves, for example, in the runner, the amplitude decreased almost linearly along the blade channel, but in the guide vane passage, it is completely different. To meet another objective of the project, extensive numerical studies have been conducted considering different modelling approaches of the model Francis turbine. A recommended practice is being prepared for the industrial simulations, which includes different modelling approaches of the turbine, accurate verification (global and local), and a guide for the passage modelling of hydraulic turbines. The measurements for added-mass effect and resonance were conducted inside the Francis turbine that accounted all possible effects and response from the adjacent structure. Good agreement between the experimental and numerical results were obtained. Experimental results are being evaluated and the focus is consequences of resonance and increase of amplitudes under different mode-shapes of the runner. More importantly, reduction of amplitudes due to added-mass during operation is also a focus. This will allow us to determine the change of natural frequencies when (1) the runner is isolated and (2) integrated in the test rig.

Acknowledgments

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