Expected load spectra of prototype Francis turbines in low-load operation using numerical simulations and site measurements

M Eichhorn\textsuperscript{1}, A Taruffi\textsuperscript{2} and C Bauer\textsuperscript{1}
\textsuperscript{1} TU Wien, Institute for Energy Systems and Thermodynamics, Getreidemarkt 9/302, 1060 Vienna, Austria
\textsuperscript{2} Andritz Hydro, Rue des Deux Gares 6, 1800 Vevey, Switzerland
E-mail: markus.eichhorn@tuwien.ac.at

Abstract.

The operators of hydropower plants are forced to extend the existing operating ranges of their hydraulic machines to remain competitive on the energy market due to the rising amount of wind and solar power. Faster response times and a higher flexibility towards part- and low-load conditions enable a better electric grid control and assure therefore an economic operation of the power plant. The occurring disadvantage is a higher dynamic excitation of affected machine components, especially Francis turbine runners, due to pressure pulsations induced by unsteady flow phenomena (e.g. draft tube vortex ropes). Therefore, fatigue analysis becomes more important even in the design phase of the hydraulic machines to evaluate the static and dynamic load in different operating conditions and to reduce maintenance costs. An approach including a one-way coupled fluid-structure interaction has been already developed using unsteady CFD simulations and transient FEM computations. This is now applied on two Francis turbines with different specific speeds and power ranges, to obtain the load spectra of both machines. The results are compared to strain gauge measurements on the according Francis turbines to validate the overall procedure.

1. Introduction

As solar and wind power generation is growing steadily, their volatility rises the necessity of large and also flexible energy storage. Even other systems like compressed-air or battery solutions will become more advanced in the future [1], pumped hydro energy storage will remain the most competitive technology in the next years [2]. The pending challenge for manufacturer and operators of pumped storage power plants (PSP) will be an increase of operating flexibility towards off-design operation with a simultaneously prevention of lifetime reduction. Due to unsteady flow phenomena in part-load, low-load and overload conditions of especially Francis and pump turbines, higher pressure fluctuations may appear inducing an increasing dynamic excitation of affected structures like the runner [3]. Therefore, the prediction of critical operating conditions and the fatigue analysis in the design phase of Francis and pump turbines is becoming more significant. The increasing capabilities of numerical computations enable their application for such investigations. To evaluate their accuracy as well, unsteady CFD and transient FEM simulations are performed on two prototype Francis turbines in low-load operating conditions: a high head runner with a specific speed of $n_q \approx 24 \text{ min}^{-1}$ (PSP-HH) and a medium head
runner with a specific speed of $n_q \approx 52 \text{ min}^{-1}$ (PSP-MH). The results are used to compute the expected load spectra with the rainflow counting algorithm. Prototype site measurements should help to validate the whole approach, which has been partially published already (see [4] and [5]). Therefore, several single strain gauges (SG) have been applied on one runner blade at the pressure side (PS) and suction side (SS) close to the trailing edge (see figure 1). The position and orientation of the sensors have been recorded for the comparison with the numerical results.

Figure 1: Schematic contour of the meridional section including the positions of the strain gauges on the runner blades and the pressure measurements in the draft tube for PSP-HH (left) and PSP-MH (right).

Further, pressure measurements have been done in the draft tube cone ($p_{DT}$) of both machines to validate the appearing pressure oscillations in the CFD simulations. One main difference between the two investigated Francis turbines, beside the specific speed, is the shaft going through the draft tube cone at PSP-HH, which has also a major impact on the flow behavior. The measured stress amplitudes $\sigma_a$, normalized by the yield strength of the runner material $\sigma_y$, are displayed in figure 2.

Figure 2: Measured dynamic stress amplitudes at different strain gauge positions and operating points for PSP-HH (left) and PSP-MH (right).

At PSP-HH a relative high stress amplitude level can be observed in all operating points due to the influence of the rotor-stator interaction (RSI). At low-load operation, with a normalized power of $P/P_{opt} \approx 0.34$, the stress amplitudes are obviously increasing with the highest values appearing close to the hub of the runner (SG PS4 and SS4). A similar behavior can be observed for the medium head Francis runner. Due to the higher gap size between the wicket gate and the runner and therefore a lower impact of the RSI, the dynamic stresses are lower in high-
and full-load operation. In part- and low-load operation, the stress amplitudes are dramatically increasing, especially at the runner hub region (SG PS4 and SS4), with the highest values appearing also at $P/P_{opt} \approx 0.37$. Hence, these two low-load operating points are of special interest and will be therefore used for the numerical simulations described in the following sections.

2. Unsteady CFD simulations

As the dynamic excitation of the Francis runners is mainly depending on the pressure oscillation inside the machine, unsteady CFD simulations are performed with OpenFOAM, to investigate the flow phenomena in the critical operating points. Therefore, the relevant components of the two hydraulic machines are considered, including the spiral casing, the stay vanes, the guide vanes, the runner and the draft tube. The different domains are discretized separately with hexahedral meshes using ANSYS ICEM CFD and ANSYS Turbogrid (see figure 3). The mesh of PSP-HH consists of about 6 million cells and the one for PSP-MH of about 9 million cells. To accurately predict the pressure fluctuations inside the runner, the discretization is refined in this domain with about 2.6 million cells for PSP-HH and about 3.3 million cells for PSP-MH. The guide vane opening position is adjusted according to the measurements. The unsteady CFD simulations are performed for several runner rotations using a transient rotor-stator analysis. A frozen-rotor simulation is used as initial solution to improve and speed-up the convergence. The discharge is defined as boundary condition at the spiral inlet according to the measurements. At the draft tube outlet the static pressure is set to an averaged value. The time step size is fixed to an according runner rotation of $0.36^\circ$ for PSP-HH and $0.6^\circ$ for PSP-MH resulting in a maximum Courant number of $C_{max} = 25$. The CFD simulations are performed using the two-equation turbulence model $k-\omega$ SST as well as the Scale Adaptive Simulation (SAS) approach, to evaluate the influence of the turbulence modeling.

![Figure 3: Discretization of the hydraulic components for the CFD simulations of PSP-HH (left) and PSP-MH (right).](image_url)

In figure 4 the spectral power density of the measured and computed pressure signals in the draft tube cone $p_{DT}$ at low-load operation for PSP-HH ($P/P_{opt} \approx 0.34$) and PSP-MH ($P/P_{opt} \approx 0.37$) are displayed. The pressure fluctuations $\Delta p$ are normalized by the energy corresponding to the rotational speed $p_E = \rho u_2^2/2$ with the circumferential velocity at the runner outlet $u_2 = D_2 f_0 \pi$ and the rotational frequency of the runner $f_0$, as proposed in [6]. For a more convincing comparison between the long measurement duration (120 s) and the short CFD simulations, the measured pressure signal is split into several windows according to the computations. Afterward, the mean values (EXP mean) and the standard deviations (EXP range) are evaluated to express the range of the measurements. The measured results of PSP-HH reveal higher dynamic pressure fluctuations in the normalized frequency range of $0 \leq f/f_0 \leq 5$. 
Figure 4: Comparison of the spectral power density between the measured and computed pressure fluctuations in the draft tube cone $p_{DT}$ at low-load conditions for PSP-HH (left) and PSP-MH (right).

The CFD simulations of both turbulence models show also higher values in this range with a slightly underestimation of the SST model. At PSP-MH a more distinct peak is appearing at $f/f_0 \approx 0.8$. The $k$-$\omega$ SST model reveals only a small peak at the rotational frequency $f/f_0 = 1$. The SAS model on the other hand shows more accurate results even the amplitude is underestimated. In figure 5 the numerically computed pressure amplitudes with the SAS model at the runner surfaces of both machines are shown together with appearing draft tube vortices, which are displayed by iso-pressure surfaces.

Figure 5: Pressure amplitudes on the Francis runner surfaces computed with the SAS turbulence model and appearing draft tube vortices at PSP-HH (left) and PSP-MH (right).

At PSP-HH high pressure fluctuations are appearing at the runner inlet due to the RSI. At the outlet the rotating draft tube vortices are inducing pressure oscillations as well, especially in the hub region of the runner. One characteristic of PSP-HH is the shaft going through the draft tube. Hence, multiple smaller and bigger vortices are appearing and collapsing again along the time, inducing a broadband excitation as visible in figure 4. At PSP-MH one bigger draft tube vortex rope is appearing and rotating more stable in the runner direction. Therefore, the highest pressure amplitudes are appearing at the runner outlet. Only small excitations are visible at the leading edges due to a less impact of the RSI at PSP-MH.

3. Transient FEM simulations
The results of the unsteady CFD simulations are used to evaluate the structural behavior and the dynamic stresses of the Francis runners by transient FEM simulations with the open-source tool Code_Aster. The model and the discretization of the investigated turbines are displayed
in figure 6. The tetrahedral mesh of each runner geometry consists of about 0.5 million nodes. This relative small size is achieved by refining only one runner blade in the critical zones, which is also used for the stress evaluation. A grid convergence study has been performed as well to assure reliable results.

![Figure 6: Discretization and boundary conditions for the transient FEM simulations for PSP-HH (left) and PSP-MH (right).](image)

The time-dependent pressure distributions from the CFD computations are applied to the surfaces of the blade channels for each time step. The pressure distributions in the runner side chambers are assumed to be static and are computed by an analytical model as described in [7]. The Francis turbines are fixed at the bolt circles and the circumferential and gravitational forces are considered as well. The transient FEM simulations are performed for several runner rotations with an according time step size of 3.6° for PSP-HH and 3.0° for PSP-MH. The damping of the structure is considered by an equivalent Rayleigh damping as described in [5]. Monitoring points at the refined runner blade are used to compare the stresses with the measured data at the strain gauge positions. The overall dynamic stress amplitudes of the FEM simulations and the measurements at the strain gauge positions for PSP-HH and PSP-MH at the investigated low-load operation points are displayed in figure 7.

![Figure 7: Comparison of the dynamic stress amplitudes calculated by the RMS values between the measured data and the transient FEM simulations at low-load operation for PSP-HH (left) and PSP-MH (right).](image)

The measured stress signal, with a length of 120 s, is separated in smaller windows according to the FEM simulations to calculate the mean values (EXP mean) and the measurement range. To determine the influence of the turbulence model on the structural response, the pressure distributions of the SST and the SAS model are used. The results show an accurate agreement with the measurement tendencies, even the computed values underestimate the measured peaks.
Due to the higher accuracy of the SAS model regarding the pressure fluctuations in the draft tube, the overall stress amplitudes are predicted more precise as well, with the highest values appearing close to the hub of the runner. According to the numerical flow simulations, the results for PSP-MH reveal much bigger differences between the turbulence models, with a total underestimation of the stress amplitudes by the SST model. The SAS model shows the highest amplitudes also close to the hub at SG PS4 and SS4. The spectral power densities of the measured and simulated stress signals at the strain gauge PS4 for PSP-HH reveal higher stress amplitudes in the low frequency range due to the pressure fluctuations in the draft tube (see figure 8). At the first and second harmonic of the blade passing frequency \( f/f_0 = 20 \) and \( f/f_0 = 40 \) higher stress amplitudes are visible, even the SAS turbulence model overestimates the measured values. For PSP-MH a high peak is visible at the normalized frequency \( f/f_0 \approx 0.8 \) induced by the appearing vortex rope according to figure 4. In contrast to the SST model, the curve of the SAS model is in a good agreement with the measurements.

![Figure 8](image)

**Figure 8:** Comparison of the spectral power density between the measurements and the computed stresses at low-load operation for PSP-HH (left) and PSP-MH (right).

4. Expected load spectra
The results of the transient FEM simulations performed with the SAS turbulence model are used for a rainflow counting analysis at the strain gauge positions and at the critical locations of both Francis runners. In figure 9 the dynamic stress amplitudes, calculated by the standard deviation of the time signals, in low-load operation at the refined runner blades are displayed.

![Figure 9](image)

**Figure 9:** Stress amplitudes at the Francis runner blades at low-load operation for PSP-HH (left) and PSP-MH (right) computed with the SAS turbulence model.

At PSP-HH the highest values are appearing in the notch at the leading edge (LE) of the runner due to the rotor-stator interaction but also at the trailing edge (TE) due to the pressure...
fluctuations in the draft tube. For PSP-MH the dynamic stresses at the leading edge are lower due to the less impact of the RSI. The critical location with the maximum excitation, induced by the draft tube vortex rope, is appearing at the trailing edge close to the hub of the runner. To determine the impact of the dynamic excitation of the high and medium head runner in low-load operation a rainflow counting analysis is performed. Therefore, the measured and computed uni-axial stress signals at the strain gauge positions and the multi-axial stresses at the critical runner locations, obtained by the FEM simulations, are used. To evaluate the measurement range the signals are again divided into several windows according to the computations. To gain a more convincing comparison between the measurements and the simulations a stress extrapolation, based on the extreme value theory described in [8], is performed. This approach has been already applied for a fatigue analysis of a Francis runner at speed-no-load operation (see [9]). For the evaluation of the damage by the three-dimensional stress state in the notches, the algorithm of Brown and Miller [10] is used, considering the influence of the shear and normal strains. The obtained load spectra of both Francis turbines are displayed in figure 10 including the corresponding stress-cycle (S-N) curve of the runner material for a 99 % survival probability. The measured and computed stress signals are extrapolated up to a time length of 1000 s. The rainflow counting analysis reveals an accurate agreement between the results of the measurements and the FEM simulations at the strain gauge positions for both turbines. The evaluation of the multi-axial stresses at the critical locations shows slightly higher amplitudes compared to the strain gauges as expected. The rainflow curves of both Francis turbines are below the fatigue limit of the runner material, even considering the measurement range.

![Figure 10: Load spectra of the measured and computed stresses with the SAS turbulence model at low-load operation for PSP-HH (left) and PSP-MH (right).](image)

5. Conclusion
The strain gauge measurements on a high head and a medium head prototype Francis runner revealed increased dynamic excitations in low-load operating conditions at about one third of the rated output power. Additional pressure measurements in the draft tube cone showed higher amplitudes in the lower frequency range for both machines at the same operation points. To investigate the reason for the high stress peaks and to obtain the load spectra of the turbines, numerical computations consisting of unsteady CFD and FEM simulations were performed. Therefore, two different turbulence models - the k-ω SST and the Scale Adaptive Simulation (SAS) model - were used. The flow simulations revealed increased pressure fluctuations at the leading edge of the high head runner due to the major impact of the rotor-stator interaction. At the turbine outlet higher pressure amplitudes occurred as well for both
hydraulic machines due to the influence of appearing draft tube vortex ropes. Compared to the pressure measurements, the SAS turbulence model seems to better predict the impact of the vortices on the pressure oscillations. The transient FEM simulations in the low-load operating points revealed an accurate determination of the overall stress amplitudes. The application of the time dependent pressure distributions computed by the SAS turbulence model lead to more precise results, especially for the medium head turbine. The transient FEM simulations exposed different locations with higher dynamic excitations for both turbines: At the leading edge for the high head runner induced by the rotor-stator interaction and at the trailing edge due to the draft tube vortex ropes for both machines. The measured and computed stresses at the strain gauge positions and at the critical notches were further used for a rainfall counting analysis together with a stress extrapolation approach. The results revealed an appropriate agreement between the simulations and the site measurements with stress-cycle curves below the fatigue limit of the runner material. For a valuable lifetime prediction of the Francis runners, additional investigations should be performed considering geometrical deviations, numerical simplifications and further uncertainties.

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