Simulation of the structural behavior of a Francis runner in Deep Part Load Operation

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Abstract. With the need for flexible operation, Francis runners are exposed to various operating conditions beyond the traditional operating range. These machines have to be designed for long time Part Load Operation in order to meet hydraulic and structural requirements. Deep Part Load Operation (DPL) mainly consists of stochastic loads on the blades. Whereas calculation methods for the dynamic stress at full load operation are well established, calculation of the dynamics during low load operation are in the focus of current research to increase the prediction accuracy. An unsteady flow simulation has been performed for a deep part load operating condition with the goal to derive the time-dependent pressure distribution in the runner. Based on the results, a FEA simulation with a 360° model is performed for multiple time steps to calculate the structural behavior. For a subsequent comparison to a strain gauge measurement, relevant characteristics with regard to material fatigue are identified. In addition, the calculation time in relation to the accuracy of the main characteristics of the flow induced stresses will be discussed.

1. Introduction

In the past decade hydro power has been subjected to reviews as solar and wind power developments have been spreading substantially and stepping into competition. Nowadays, grid stability is a major demand on hydro power since sufficient controllability and storage capacity is required [1].

Due to the volatile power received from solar and wind power plants, the energy market requires highly variable hydro power machines and fast changes of operating regimes. High numbers of start-ups, shut-downs and operation beyond traditional guaranteed operating ranges can have significant influence on the fatigue life of hydro components. Stress is a result of both geometry and load induced by flow. Especially the peak stresses are dependent on the local geometry (e.g. notches). A robust design is defined through a runner that withstands the complex load spectrum for a given lifetime.

In order to realize 0-100% operation, the mean stresses and the dynamic stresses for multiple conditions need to be considered during the design. Different operating conditions such as operation cycles, dynamics due to rotor-stator-interaction (RSI) and especially long time part load operation can reduce the fatigue life of the runner.

One approach to predict the stochastic behavior of part load operation during the design phase is the use of suitable simulation methods. Since pressure fluctuations as a function of time are required, unsteady Computational Fluid Dynamics (CFD) simulations have to be conducted and afterwards a structural assessment using the Finite Element Method (FEM) has to be performed. The complex
calculations are very time consuming and yet the results have to be discussed in terms of accuracy which is done through comparison to measurement results. A model test with multiple sensors in the stationary and rotating frame of a model Francis runner has been performed for a recent design. This includes both pressure sensors and strain gauges on the runner blades. The advantage of model testing is that various boundary conditions can be tested and visual observations can be made.

This publication is based on the research project Francis PLUS which investigates the part load behavior of Francis turbines to ensure a safe, reliable and cost efficient operation. A detailed description of the model test can be found in [2] and about the CFD simulation in [3].

2. Operating Conditions

The flow phenomena in a Francis turbine can be distinguished by operating zones. These phenomena have impact on the pressure fluctuations and therefore have impact on the runner structure. Stable flow conditions around the Best Efficiency Point (BEP) result in low dynamic loads. They are referred to as Normal Operation (NO). The vortex ropes can be distinguished between an axial symmetric rope at full load and a cork screw shaped vortex rope at Part Load (PL). Both are mainly visible in the draft tube cone. Interblade vortices appear for low discharges in Deep Part Load (DPL). Figure 1 shows an example of the interblade vortices of the model test. These are vortices that originate in the crown region of each channel and extend past the discharge edge of the blade into the draft tube cone (channel vortex). The visibility is dependent on cavitating volume and therefore the tail water pressure. The phenomena that appeared in the measurement are explained more detailed in [2]. The investigations presented within this document concentrate on the DPL operating condition.

![Figure 1. Channel vortex at Deep Part Load condition (view into the runner channel from the vaneless space).](image)

3. Model Test Setup

The proof of hydraulic parameters through a model test is well accepted as most of the parameters are transposable by hydraulic similarity laws [4]. Therefore, with similar flow conditions the load on the blades is comparable to the prototype. The major challenge is the transfer of the structural behavior of a model runner, as eigenfrequencies and stiffness do not scale accordingly.

Since the joints of a sectored model runner would lead to an undefined stiffness, a “monoblock” runner is mandatory for a sensor equipped model test to grant a defined stiffness and a geometry that can be investigated through simulation models (Figure 2). The runner material is congruent to the prototype runner material (CA6NM). The model runner has been manufactured according to the standards used for hydraulic model testing with very high accuracy. Due to the sensor application, the
crown and band sections of the model runner show deviations in comparison to the prototype, however, these deviations have been accounted for in the simulation models. The hydraulic faces are not influenced by the sensor application.

Multiple blades of the mid-range specific speed runner ($n_q = 40-60$) are equipped with strain gauges close to the transition of the blade towards crown and band. In this paper, the strain gauge at the crown is referred to as SG1 and the one at the band as SG2, see Figure 3. Strain gauges with very high sensitivity have been used to measure the full spectrum of loads. Six Pressure sensors were installed at the Draft Tube Cone (DTC) below the runner. A sketch indicating the locations of all installed sensors in detail can be found in [2].

Due to an increased stiffness, the eigenfrequencies of a model runner shift to higher frequencies. The increase of the model’s nominal speed, as relation to the exciting frequencies, is only linked to the hydraulic similarity laws. With mainly stochastic loading in part load operation, eigenfrequencies have minor impact on the overall structural results. In order to get more insight on the eigenfrequencies including all applied sensors and electronics, an Experimental Modal Analysis (EMA) has been performed. The setup for the test included a water basin where the model runner was submerged. Since not all of the blades are equipped with sensors, different impact positions and multiple acceleration sensors were used for the EMA. Figure 4 shows the Fast Fourier Transformation (FFT) for multiple impacts. The eigenfrequencies can be clearly identified. A deviation between the eigenfrequencies of each impact can be explained with different positions of impact and the differences in the blade stiffness due to the applied sensors. For a comparison to the strain gauge measurement, a global estimation of eigenfrequencies has been established.
Figure 4. FFT of the experimental modal analysis and identified eigenfrequencies normalized to the nominal speed of the runner (eigenfrequencies above 110 not included).

4. Simulation

For the FEM simulations, the pressure field on the runner blades has to be prescribed for the DPL operating condition ($Q/Q_{\text{BEP}} = 33\%$). This pressure distribution is derived from an unsteady single-phase CFD simulation. One exemplary result for the pressure on the runner blade and the shape of the channel vortices is presented in Figure 5. The visualized interblade vortices show a good correlation to the observations during the test, compare to Figure 1. Within the CFD simulations, the stress-blended eddy simulation (SBES) turbulence model has been applied and the time step is approximately $0.4^\circ$ of one runner revolution. This results in an averaged Courant number of 0.8. The simulation domain for the CFD ranges from the spiral case inlet to the outlet of the tail water tank. The complete computational grid comprises about 25 million cells, with the highest share of cells in the runner domain to ensure a sufficient resolution of the inter-blade vortices. A more detailed description of the CFD simulation setup can be found in [3].

Figure 5. CFD result of the pressure on the suction side (left) and pressure side (right) of one runner blade including visualized vortex structures.

The FEM model includes a $360^\circ$ geometry of the runner. The simulation model was generated as a circular pattern of one blade. The strain gauge positions and cable routing is incorporated in the model which enables the evaluation of stresses for each blade. In the regions of high interest, a very fine mesh is generated to receive converged results. The dynamic part of the pressure distribution from CFD is applied to all surfaces of the runner in the Finite Element Analysis (FEA). The FEA is performed as multiple static linear calculation for each of the $0.4^\circ$ time steps gained from the CFD simulation. Time integration has been turned off. Hence, calculation time is reduced, however, on the other side dynamic
effects due to eigenfrequencies and effects due to surroundings are neglected. In the post processing step, each strain gauge position is evaluated. An artificial time signal is then generated by joining the values at the same strain gauge position of each blade. To generate a longer data set, the values for all blades are joined to one total signal that can finally be compared to the measurement results.

5. Discussion of characteristic values

It is common practice to evaluate measured pressure pulsations through the characteristic peak-peak value (char. p-p) according to IEC standard [4], however, with regard to a robust runner design and fatigue life evaluation the distribution of cycles is of higher importance. Therefore, both approaches will be discussed. Since the calculation time is limited compared to the measurement results, a certain time frame has to be chosen and a possible error has to be evaluated.

First, the impact of the signal length on the char. p-p is investigated for both strain and pressure transducers. Figure 6 shows the development of the char. p-p values (based on 100 classes, 97% confidence level) normalized to the value after 600 revolutions. As the class width is dependent on the minimum and maximum value of the time frame, global values were calculated and used for all time frame lengths. Due to the stochastic behavior, a certain signal length is required before the error can be reduced for the strain gauges. In the data set under evaluation, the error is already < +/- 5% after 20 revolutions and slowly decreasing further. For the pressure transducers an error of < +/- 5% is reached after 80 revolutions. The height and direction of the error below 10 revolutions mainly depends on the starting position in the time signal. It is feasible to look at a shorter time frame than measured due to the limitation of calculation time and compare this to a deviation band based on floating char. p-p values of the measurement. The floating values are calculated based on a time frame that is moved through the total time signal. Both the average and the deviation band can be calculated for a statistical evaluation.

![Figure 6](image)

**Figure 6.** Char. p-p for strain (top) and pressure (bottom) for different length of time frames expressed through number of revolutions.

The so-called Rainflow counting method has been established in the fatigue life calculation of components to consider complex load spectra [5]. It is well known that stochastic loads cannot be described by only one single value, such as e.g. char. p-p. There are different amplitudes in combination with material-specific SN-curves that have to be considered and that will result in the total fatigue damage for an individual load case. Therefore it is important to understand the specific Rainflow
characteristics for each load case. Due to different dominating flow phenomena (e.g. RSI, Part Load Vortex, stochastic pressure pulsation), the Rainflow characteristics are subject to change. Figure 7 shows the normalized Rainflow amplitudes for different loadings with 100 Rainflow classes. It is feasible to normalize the Rainflow matrix to the char. p-p value as it represents the dynamic base load. Figure 7 is normalized to the char. p-p of deep part load (left) and to the individual value (right). The x-axis shows the accumulated cycles of all amplitudes. The intersection of the curve with the x-axis represents the total number of counted cycles for a given signal length. The relative maximum amplitude of the different operating conditions in the left diagram, corresponding to the intersection with the y-axis, shows a good correlation to the char. p-p over power diagram that is shown in [2]. The highest dynamics are present in speed no load (SNL) due to stochastic fluctuations and close to the BEP where the dynamics significantly decrease since RSI is dominant. A 100% random signal mathematically results in a linear regression (for the log x-axis) with the slope depending on the signal length. A signal dominated by one sinusoidal amplitude (as it is the case for RSI) results in a horizontal line. If every load case is normalized to the individual char. p-p value, the Rainflow matrices are almost congruent. For this project the amplitudes due to RSI in NO are very small compared to the stochastic part of the signal. Therefore, the project shows a stochastic behavior. This will be different for projects with higher RSI load, such as low specific speed runners.

![Figure 7. Rainflow matrices for different operating conditions normalized to the char. p-p of DPL (left) and to the individual char. p-p (right) of the strain signal.](image)

The methodology described above was applied for several prototype measurements with different specific speeds (nq = 23-80) to identify general characteristics. It is important to mention that the individual measurement conditions are similar and that the signal length represents the same number of revolutions for all projects. In Figure 8, the results for deep part load operation for 5 different projects are compared. The strain gauges were placed at the crown and at the band trailing edge positions. A good correlation can be observed for the region with high accumulated cycles. However, some differences can be determined at the individual maximum amplitudes, where only single or a very little number of events are contained in the time signal length. A trend arising from different specific speeds of the considered projects cannot be identified. One influence factor could be the specific section of the operation analyzed which will be discussed next. Through comparing different projects it can be stated that a clear trend can be established independent of the specific speed. Any simulation of a stochastic operating condition should therefore result in similar Rainflow characteristics compared to the measurement, in order to safely predict the stress amplitudes for the fatigue assessment.

Due to limitations in the computational resources, the simulation time represents only a small fraction of the recorded time signal at the test rig. For a comparison, both data sets need to have the same length, therefore different time frames of the measurement have been Rainflow counted (Figure 9). Similar to the results of different prototype measurements, a good correlation is achieved especially for a higher cumulative number of cycles. In this diagram the impact of different starting positions of the time frame can be identified through the different amplitudes for single events. A linear trend (like for a random signal) can be established as a maximum possible distribution.
Figure 8. Normalized Rainflow matrices for different prototype strain gauge measurements in DPL.

Figure 9. Normalized rainflow matrices with identical time frame length at different start positions of the measurement strain signal.

6. Comparison Simulation to Model Test

For a comparison between simulation and model test results, parameters such as sampling rate and signal length have to be taken into account to generate comparable results. The available pressure data at the pressure transducer location covers four times the time span of the stresses at the strain gauge locations. To evaluate the impact of eigenfrequencies, the measurement results are compared to the eigenfrequencies determined in the simulations. A comparison between calculated eigenfrequencies and FFT processed strain gauge signals from the measurement are shown in Figure 10. In addition, the vertical lines represent the eigenfrequencies identified in the EMA (compare Figure 4). For SG 2 increased values between $f/f_{Ru} = 50-60$ are present and therefore match an accumulation of eigenfrequencies. Higher orders of eigenfrequencies can be observed with lower amplitudes. This leads to the hypothesis that the eigenfrequency can have an impact on the measurement results. Since the simulation was performed without time integration, no dynamic effects are considered. However, overall a good correlation between experimental and numerical results could be observed especially for SG 2. For SG 1 the absolute strain values in the measurement are lower. This deviation may result from neglecting of the vapor phase in the single phase numerical CFD simulation. Observations at the test rig show cavitation shields especially in the transition region between the blade trailing edge and the runner hub. This explanation needs to be confirmed by a two-phase simulation.

The peak amplitude around $f/f_{Ru} = 95$ in the simulation results cannot be explained yet, but it is likely related to numerical effects. The pressure results do not show any increase, which corroborates the influence of eigenfrequencies on strain results.

The results of SG 2 are more profound due to the significantly higher amplitude. Since dynamic effects are not included in the simulation (giving a benefit in calculation time), a band-stop filter was applied on both the strain gauge measurement signals and the simulation results (compare Figure 10).
The char. p-p of SG 2 changes by 8\% for DPL due to the band-stop filter. Since the resulting protrusion is even less, the eigenfrequencies are regarded as a minor impact. In the connected publication a comparison between prototype and model measurement is shown [2]. Although the eigenfrequencies of the model and prototype are different, both evaluations the char. p-p over power and the Rainflow matrix show good agreement. This proves the minor impact of the eigenfrequencies on the chosen evaluation methods.

![Figure 10](image-url) **Figure 10.** FFT results of both strain from the measurement and the simulation for SG 1 (top) and SG 2 (bottom) in comparison to the eigenfrequencies.

A comparison of the char. p-p values for both strain and pressure in the draft tube cone has been made based on a floating char. p-p value from the measurement. The frame length corresponds to the simulation results. With this attempt a range and average value is calculated and can afterwards be compared to the simulation results. In Figure 11 the floating results are presented. SG 2 shows the highest impact on the chosen time frame, whereas SG 1 and the pressure sensors only show a minor impact. In Figure 12 the results are summarized by showing average values and deviation bands for the measurement. The DTC positions for the pressure sensors show a constant offset to higher dynamics in the simulation. SG 1 shows an over prediction as already discussed in the FFT results.

The simulation results of SG 2 are predicting lower amplitudes than the measurement, however, close to the lower band depending on the time frame. Overall it can be noticed that the simulation does have an averaged offset of approximately +5\% for pressure pulsations and -3\% for SG 2 towards the deviation band.

After performing a Rainflow counting of the simulation data, the characteristic shape is compared to the measurement in Figure 13. For SG 2 (solid lines in Figure 13 left), a good agreement is observed within the chosen time frame. As discussed in Figure 9, the Rainflow matrix is sensitive to the chosen time frame for single counts, therefore the time trend is additionally implemented in the diagram. For SG 1 a larger deviation is noticed, possible reasons for this behavior in the simulation have already been discussed above. It seems feasible that the DTC pressure can be Rainflow counted in addition. This is presented on the right hand side of Figure 13. In general, a similar behavior can be noted. Since it is expected that the turbulent flow in the runner channels due to vortices will balance or change its distribution below the runner, no comparison between strain gauges and pressure is made.
Figure 11. Floating char. p-p for strain with 20 revolutions (left) and for pressure with 80 revolutions (right).

Figure 12. Char. p-p of simulation vs. measurement with equal data length.

Figure 13. Normalized rainfall matrices for strain gauges (left) and pressure (right) for simulation and measurement with equal numbers of revolutions.
7. Summary

A model test with multiple sensors on the Francis runner has been performed as a basis for the verification of the simulation methods for deep part load. For this operating condition, a single phase CFD simulation and a structural analysis have been conducted. A major impact on the simulation is its complexity and therefore the time to realize reliable results that can be used for a fatigue evaluation.

At part load operation the stochastic pressure load on a blade resulting from the channel vortex is dominant. Both char. p-p and Rainflow counting were discussed with the goal to describe the characteristics of the stochastic signals that are relevant for the fatigue calculation. The investigated parameters are sensitive to the analyzed time frame and starting position. Therefore, fundamental care concerning e.g. sampling rate, number of revolutions, normalization and positioning of the time frame has to be taken when different sets of data are compared. Independent of the operating condition and design (different projects), the distribution of the Rainflow matrix for a stochastic load shows a similar characteristic.

The strain gauge results at the runner band show a good correlation between measurement and simulation, although the char. p-p value is lower in the simulation. At the runner crown position large deviations occur, likely due to the missing impact of vapor pressure in the single phase CFD simulation. All pressure transducers at the draft tube cone show a good correlation with the simulation results.

Next, a two phase simulation will be carried out in order to evaluate further improvements with increasing simulation effort. Afterwards, an evaluation of simulation effort, accuracy and time can be performed as basis for a process optimization in the design of variable load machines.

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