Dynamic loads in Francis runners and their impact on fatigue life

U Seidel, C Mende, B Hübner, W Weber, A Otto
Voith Hydro Holding GmbH & Co. KG
Alexanderstr. 11, 89522 Heidenheim, Germany
E-mail: ulrich.seidel@voith.com

Abstract. Reliable fatigue life assessment of Francis runners combines two parts: At first, the load universe describing how the plant will be operated. And secondly, for all essential operating conditions, component stresses due to static and dynamic loading have to be predicted and considered in the design process by the manufacturer. Therefore, dynamic loading conditions and the resulting impact on the fatigue life of hydroelectric components are an integral part of research activities. Especially off-design conditions and transient operations have been addressed in the last years. Based on strain gauge measurements in prototype runners, model test experiences, and advanced numerical simulations, the understanding of dynamic loads has been highly improved. From correlations of measurement and simulation, standard procedures have been developed to enhance the fatigue life. The present paper summarizes findings of recent investigations enabling Francis runners which combine high efficiency and a robust mechanical design.

1. Introduction

In the past, hydro power plants equipped with Francis turbines were mainly used for base load operation while pumped-storage plants or gas turbines provided regulatory power, especially around noon when the electricity demand reaches its daily maximum. Hence, Francis turbines were operated continuously around the best efficiency point (BEP) with only one or two start-stop cycles per day. Beside transients and speed-no-load (SNL) operation, the main fatigue contributor for higher head Francis turbines was the rotor-stator interaction (RSI) which nowadays can be predicted quite accurately by numerical simulations, see Seidel et al. [1]. However, especially in Europe, today’s operating conditions of hydro power units are characterized by an increasing energy volatility due to the massive expansion of renewable energies, such as wind and solar energy. The infeed from these sources of energy is not reliably foreseeable and does not take into account the actual demand. As a result, the requirements for electrical grid stabilization (frequency control), energy storage, and peak load supply increase dramatically while hydroelectric installations are the most efficient way to supply this additional regulatory power. In consequence, hydraulic machines are operated more and more at low part load. Also the number of start-stop cycles is increasing. The contribution of transient conditions and operation far below optimum condition on material fatigue is significant, especially in low to medium high head Francis runners.

In order to exemplify the impact of plant operation on the fatigue life, the damage contributions of two different load universes are compared for a medium high head Francis runner. The runner is subjected to a typical base load scenario on the one hand and to a demanding plant operation for grid stabilization on the other hand. Respective load universes are given in Table 1. The relative partial damage contributions, shown in Figure 1, are derived from strain gauge measurements at a prototype runner during operation.
In the grid stabilization scenario, the expected life time decreases by one order of magnitude. Low part load becomes the main fatigue contributor followed by start-ups, although fatigue optimized start procedures (see Section 4.1) are applied in both scenarios. For lower head Francis runners, the impact of the load universe on the fatigue life may even be stronger.

| operational mode       | start up [cycles/day] | speed no load [%] | low part load [%] | part load [%] | around BEP [%] | high load [%] |
|------------------------|-----------------------|-------------------|-------------------|---------------|----------------|---------------|
| base load              | 1                     | 1                 | 0                 | 25            | 49             | 25            |
| grid stabilization     | 10                    | 4                 | 24                | 24            | 24             | 24            |

**Table 1**: Assumed load universes for different operational modes of a medium high head Francis turbine

The demonstrated impact of actual plant operation on the fatigue life of Francis-turbine runners and components may have serious consequences for availability, reliability and safety of power plants. Therefore, Voith Hydro and others [2] continuously investigates all kinds of dynamic loading and the resulting impact on the fatigue life of hydroelectric components. Especially off-design conditions (e.g. speed no load, low part load) and transient operations (e.g. start up, load rejection) of Francis runners have been addressed by recent research activities. Based on numerous strain gauge measurements at prototype runners [3], model test experiences [4], and advanced computational fluid dynamics (CFD) or fluid-structure interaction (FSI) analyses [5-6], the understanding of dynamic loads has been highly improved. From correlations of measurement and simulation, standard design procedures have been developed to optimize the fatigue life of Francis runners. These procedures do not only consider the runner type (specific speed) but also operating requirements of individual projects (e.g. start-up time). After recapitulating unsteady flow phenomena at different operating conditions in the next section, subsequent sections summarize recent findings related to runner dynamics and fatigue. On this basis, high efficiency and a robust mechanical design are combined in Francis runner developments.

### 2. Theoretical background

The first part of this section summarizes the flow physics at different operating conditions of a Francis turbine. The second part discusses the impact of different excitation phenomena with regard to fatigue life.

#### 2.1. Flow characteristics depending on operating conditions

A characteristic feature of Francis turbines is that runner blades are fixed and cannot be adjusted to the operating condition. The flow pattern in a certain operating point is formed by the inflow towards the runner blades and the outflow from the runner into the draft tube. In a limited part of the operating range, the flow characteristics can be called ideal, with a high efficiency and low fluctuations of
pressure and output. In other, so-called off-design operating conditions, the inflow angle to the runner blades may deviate from the ideal flow angle, and the flow pattern in the draft tube is characterized by swirl, flow separation, and backflow. For the basic operating conditions of a Francis turbine, typical flow patterns from model testing are shown in Figure 2. The respective flow behavior is shortly characterized below. A more comprehensive description of the operational behavior with focus on cavitation phenomena is given e.g. by Aschenbrenner et al. [7].

Figure 2: Typical flow patterns of a Francis turbine observed in model tests at plant sigma:

a) high load,  b) around BEP,  c) part load,  d) low part load,  e) speed no load,  f) runaway

a) At high load, the fluid in the runner tends to flow towards the machine axis causing a swirl against the runner rotation when entering the draft tube. The static pressure in the swirl center is very low, and at vapour pressure, cavitation is generated in the vortex core, see Figure 2a. Usually, this condition is stable with small pressure fluctuations in the draft tube. However, under certain circumstances, the vortex core volume may fluctuate and interact with the hydraulic plant system such that unstable pressure oscillations follow, see Flemming et al. [8] for more details. In the vaneless space of higher head Francis turbines, periodic pressure fluctuations due to rotor-stator interaction may be dominant at high load and around best efficiency point, see [1].
b) In the range around best efficiency, the inflow to the runner blades is consistent to the blade angle, and the streamlines follow the geometric design of hydraulic runner contours to a large extend. The draft tube flow is widely smooth and stable with a low swirl intensity, see Figure 2b.

c) At part load, the fluid in the runner tends to flow towards the outer region of the machine, and the flow leaves the runner with a swirl rotating in direction of the runner. This outflow condition leads to a backflow in the center of the draft tube cone and a vortex rope of helical shape, see Figure 2c. Since the pressure inside of the vortex is quite low, the vortex forms a cavitation bubble in the draft tube. Due to its movement, this vortex rope creates periodic pressure fluctuations in the turbine at a low frequency which is below the rotational speed of the runner.

d) At loads below the load where periodic pressure fluctuations occur, the flow in the runner still tends to larger radii. In addition, the inflow to the runner blades is not consistent to the blade angle, and secondary flow effects between the runner blades cause channel vortices with low pressure regions in the vortex core which generate cavitation, see Figure 2d. In this operating range, the flow induces high amplitude pressure fluctuations of stochastic nature with a broad banded frequency distribution which decreases from very low to medium frequencies.

e) At rated speed without load (SNL), the flow pattern of low part load is even more emphasized. The large backflow region in the draft tube extends into the runner. The unorganized flow in the runner causes cavitating channel vortices and results in high amplitude pressure fluctuations of stochastic nature, see Figure 2e.

f) At runaway, the flow is characterized by significant deviations between inflow and blade angle leading to strong secondary flow effects and cavitation in runner and draft tube, see Figure 2f.

Beside the above described stationary operating conditions, also transients may induce strong pressure fluctuations with high impact on the fatigue life of Francis runners. During start up and shutdown, the turbine is operated temporarily at off-design regions of extreme part load causing a pressure loading which strongly deviates from design conditions. Even more demanding for the integrity of the runner may be a load rejection where the loading of the turbine changes from the actual load to no load with varying rotational speed.

In summary, if Francis turbines run beyond the operating range of ideal flow, static pressure loads deviate from design conditions and pressure fluctuations increase. This becomes more significant with growing deviation from ideal flow behavior.

2.2. Fatigue assessment and optimization

During the various operating conditions of a Francis turbine, different types of dynamic loading are acting on the runner and have to be distinguished when assessing the fatigue life:

- A precise cyclic (periodic) loading pattern occurs with specific frequencies and amplitudes, e.g. due to rotor-stator interaction or rotating vortex rope at part load.

- Dynamic loading occurs with stochastic characteristics which can be described by a broadband frequency spectrum with varying amplitudes, e.g. at speed no load or low part load.

- A change in the static loading is superimposed by a cyclic loading with stochastic characteristics. This behavior occurs during transient operating conditions like start up or load rejection. The static load change causes an additional high amplitude load cycle while the characteristics of the frequency spectrum may change over time.

For a better understanding of dynamic loading conditions and their impact on the fatigue life, strain gauge measurements were carried out at various Francis runner prototypes during operation, see [3]. Based on measured time histories of strains, the partial damage contributions of single operating conditions as well as the total damage contribution of an assumed load universe can be determined. At
first, load cycles have to be identified using Rainflow counting. The damage of each identified load cycle follows by evaluating the S-N curve which includes effects of mean stress, water environment, and surface quality. The entire damage caused by the regarded operation results from linear damage accumulation according to Miner’s rule. This yields to integrated damage contributions of transient operations and damage rates for steady-state operating conditions, see Weber et al. [9].

Based on detailed analyses of strain gauge results, transient operating procedures as well as runner designs may be optimized with regard to the runner fatigue life. Exemplarily, for two different lower head Francis runner designs with equal specific speed, relative damage rates normalized to BEP are compared in Figure 3. Although both designs feature same specific speed, they differ hydraulically and mechanically due to individual project requirements. While design A works fine for base load scenarios, design B exhibits significantly smaller damage rates at off-design conditions. Design B is more suitable for being operated highly flexible in a grid stabilization scenario. Nevertheless, compared to BEP, off-design damage rates are generally much higher in Francis turbines. More examples of measurement based fatigue optimizations are given in Section 4 and by Mende et al. [10].

Combining advanced numerical analysis procedures and knowledge derived from strain gauge results, static and dynamic stresses can be well predicted by calibrated computer methods. This is a proven technology for all kinds of static loads as well as for periodic loading conditions like part load vortex excitation and rotor-stator interaction, see [1]. For mainly stochastic excitation phenomena like SNL, numerical load predictions are described in Section 3.2.

![Figure 3: Comparison of two different lower head Francis runner designs with regard to the relative damage rates of various operating conditions](image)

### 3. Assessment of speed-no-load operation

For the mechanical design of Francis runners, the speed-no-load operation considered by CFD analysis is taken into account for several years. While the static stress calculation is state of the art, the prediction of dynamic stresses is still a subject of research. The challenge of the dynamic loading is the stochastic nature of the flow field which gets more pronounced when reducing turbine output from part load to no load. Stationary mean values describing the time averaged flow field can be predicted quite well by steady-state CFD, and subsequent finite element analyses provide accurate static stress distributions. The following subsections present the CFD procedure for analyzing the averaged flow field as well as current research work using scale-resolved unsteady CFD analyses to capture the stochastic nature of the flow.
3.1. Steady state CFD analysis

Steady-state flow simulations of SNL based on Reynolds-averaged Navier-Stokes (RANS) equations can be performed using sector models of distributor and runner in order to reduce significantly the computational effort. This requires equal flow patterns in all runner passages, what can be checked by regarding the steady-state solution of a complete runner model, as shown in Figure 5a for a medium high head runner at SNL. The simulation usually features a standard two-equation turbulence model (e.g. shear-stress-transport model). At the distributor inlet, mass flow and flow direction are imposed, while static pressure is prescribed at the outlet of the fluid domain. The fluid itself is considered to consist only of a single water phase, neglecting cavitation bubbles.

Typical results of SNL simulations reveal distinct recirculation zones in the flow field, as shown in Figure 4 by means of surface streamlines on pressure and suction side of a runner blade. Starting at the trailing edge close to the band, the flow initially leaves the runner before it turns towards the runner axis and then re-enters the runner close to the crown. By hitting the blade suction side, a stagnation zone develops close to the trailing edge. Following the flow into the runner channel, a sudden change into a low pressure zone appears, which is accelerating the flow, see pressure contours in Figure 5a. Subsequently, the flow turns towards the band and then towards the trailing edge before leaving the runner again. Overall, only a small flow rate is passing through the runner while most of the flow is recirculating, especially at the suction side.

Due to the above described flow behavior, which strongly differs from design conditions around BEP, the time averaged pressure distribution with its steep gradients causes a very distinctive stress loading. Hence, steady-state CFD analyses of SNL and subsequent static stress calculations by finite elements are an integral part of mechanical design optimizations of Francis runners. The procedure is validated and calibrated by comparing simulation results with strain gauge measurements at several prototype runners which all agree quite well.

![Figure 4: Steady-state CFD results for SNL operation: Surface streamlines on pressure side (a) and suction side (b) of a Francis runner blade](image)

3.2. Scale-resolved unsteady CFD analysis

In order to resolve the stochastic fluctuations at SNL, which are observed in measurements, different kinds of unsteady simulation approaches were investigated. The presented results refer to a large eddy simulation (LES) of a medium high head turbine. The model consists of complete runner and draft tube, since the turbulent structures to be resolved are not cyclic-symmetric. For this kind of simulation, it is necessary to discretize the entire domain with a preferably uniform mesh which resolves all coherent turbulent structures and larger eddys. Only the small-scale turbulence with a homogeneous and isotropic distribution is modeled by a subgrid-scale model, e.g. [11]. Also boundary layers should
be resolved up to the viscous sublayer. Together, this results in a grid of about 100 million elements. In addition, a very small time step is required such that the larger turbulent scales are fully resolved. In connection with the large number of elements, an extraordinary computational effort follows.

Looking at a snapshot of the resulting pressure field (Figure 5b), the cyclic-symmetric flow pattern of the steady-state solution (Figure 5a) is basically present, but it is superimposed by stochastic variations in space and time which are responsible for the pressure fluctuations typically measured at SNL.

![Figure 5: CFD pressure on runner suction side for SNL: Steady-state solution (a) and LES snapshot (b)](image)

In order to compare the LES pressure with model test data and unsteady RANS results (also received for a model consisting of complete runner with draft tube), a monitor point at the draft tube wall shortly below the runner is regarded. A good agreement is found between LES and measurement with respect to frequency content and characteristic amplitude which is 1.4% of head in the LES compared to 1.8% of head in the model test. And the broadbanded frequency characteristics of LES pressure fluctuations, shown in Figure 6, is comparable to the measured data. In contrast, the unsteady RANS analysis does not resolve any turbulent fluctuations. Only the blade passing frequency is visible in the pressure amplitude spectrum. Hence, URANS simulations cannot at all predict the dynamic loading with stochastic characteristics at SNL or low part load. But LES analyses are a promising way to improve the understanding of such loading conditions in order to derive simplified models and procedures suitable for dynamic characterization of Francis runners.

![Figure 6: Amplitude spectra of draft tube pressure for SNL: Comparison of LES and unsteady RANS](image)
4. Fatigue life optimization based on prototype experience

Besides numerical simulations and analytical approaches, fatigue assessments based on or supported by prototype experience are an important part of fatigue life optimizations for Francis runners. Transient procedures of existing turbines can be optimized by strain gauge measurements. However, for optimizing the runner in the design phase, or if strain gauge measurements are not possible due to time or economic constraints, a comprehensive database of reliable measurement results is a basic prerequisite. The database includes static and dynamic results of strains, pressures, vibrations, acoustics, governor signals, and other quantities, and it covers a variety of different prototypes. The knowledge derived from such extensive prototype experience offers the ability to optimize not only start-up procedures but also mechanical design and robustness of runners, as shown in the following subsection.

4.1. Optimization of start-up procedures

The start procedure determines the guide vane opening sequence which governs rotor acceleration and turbine flow variations. Hence, the opening sequence is responsible for the amplification of dynamic stresses during start up. By minimizing this stress amplification, the fatigue impact of a start-up procedure can be optimized, see Gummer and Etter [12].

In order to optimize start procedures systematically, the conditions (interaction of flow rate, speed, opening, and so on) being responsible for the highest damage contributions have to be identified. This task is accomplished by transient fatigue analyses, see [9], based on strain gauge data from prototype runners. By evaluating the time resolved damage accumulation together with synchronized governor data, improved settings for different start phases can be derived. If a strain gauge measurement campaign is carried out for a given project, different start sequences can be investigated and afterwards, the optimized version can be determined, implemented, and directly checked. An example of such an approach is given in Figure 7 where the optimized start procedure is compared to a normal start which was the starting point of the process. Maximum strain amplitudes are significantly reduced leading to minimized damage contributions.

By analyzing measurement results of different start sequences from several projects, generalized findings can be deduced how to define a fatigue optimized start sequence depending on the specific speed of the turbine. On this basis, start-up optimizations are feasible without the need of strain gauge measurements, even though quantitative assessments of damage reduction are not possible. However, indirect quantities e.g. from pressure or vibration measurements are used as “damage indicators” allowing a relative comparison of different start sequences. Hence, the checking if an optimized start procedure will clearly improve the fatigue life is possible with little effort, see [10] for more details.

Figure 7: Measured runner strains during normal and optimized start sequence (a) and corresponding curves of speed and damage accumulation (b)
5. Conclusion

Hydropower schemes with storage capacity, which are often equipped by Francis turbines, are more and more operated in the entire power range. However, by increasing the operating range, also pressure fluctuations and dynamic loadings increase in Francis turbines. Hence, assessing the fatigue life especially of the runner is of high importance and has to consider the load universe, including off-design conditions and transient operations.

As shown in this contribution, advanced CFD simulations by LES (large eddy simulation) help to get an improved understanding of the complex flow physics in the runner. Dynamic measurements in model and prototype scale lead to improved understanding of dynamic exciting phenomena and dynamic response of the runner. Appropriate methods to evaluate the fatigue contribution of start-up and individual operating conditions are explained and applied for optimization of operation sequences.

References

[1] Seidel U, Hübner B, Löfflad J, Faigle P, 2012, Evaluation of RSI-induced stresses in Francis runners, 26th IAHR Symposium on Hydraulic Machinery and Systems, Beijing.
[2] Bjørndal H, Reynaud AP, Holo AL, 2011, Mechanical robustness of Francis runners, requirements to reduce the risk of cracks in blades, HYDRO 2011, Prague.
[3] Löfflad J, Eissner M, Graf B, 2012, Strain gauge measurements of rotating parts with telemetry, 9th International Conference on Hydraulic Efficiency Measurements, Trondheim.
[4] Avellan F, Etter S, Gummer JH, Seidel U, 2000, Dynamic pressure measurements on a model turbine runner and their use in preventing runner fatigue failure, 20th IAHR Symposium on Hydraulic Machinery and Systems, Charlotte.
[5] Flemming F, Fisher RK, 2009, Application of unsteady CFD to assess dynamic loads on a Francis runner, Waterpower 16, Spokane.
[6] Hübner B, Seidel U, Koutnik J, 2012, Assessing the dynamics of turbine components using advanced fluid-structure interaction, HYDRO 2012, Bilbao.
[7] Aschenbrenner T, Otto A, Moser W, 2006, Classification of vortex and cavitation phenomena and assessment of CFD prediction capabilities, 23rd IAHR Symposium on Hydraulic Machinery and Systems, Yokohama.
[8] Flemming F, Foust J, Koutnik J, Fisher RK, 2008, Overload surge investigation using CFD data, 24th IAHR Symposium on Hydraulic Machinery and Systems, Foz do Iguaçu.
[9] Weber W, Mende C, Koutnik J, 2013, Advanced fatigue analysis for transient operating conditions of Francis turbines, 5th IAHR International Workshop on Cavitation and Dynamic Problems in Hydraulic Machinery, Lausanne.
[10] Mende C, Weber W, Seidel U, Koutnik J, D’Agostini Neto A, 2013, Potential of start optimization for Francis turbines, 5th IAHR International Workshop on Cavitation and Dynamic Problems in Hydraulic Machinery, Lausanne.
[11] Ferziger JH, Perić M, 2002, Computational Methods for Fluid Dynamics, 3rd edition, Springer, Berlin.
[12] Gummer JH, Etter S, 2008, Cracking of Francis runners during transient operation, Hydropower & Dams, Issue 4.