Operation Cycle Concept for the fatigue life prediction of Francis runners

Florian von Locquenghien¹, Benjamin Leibing¹, Andreas Greck¹
¹Voith Hydro Holding GmbH & Co. KG, Alexanderstraße 11, 89522 Heidenheim, Germany

E-Mail: Florian.Locquenghien@voith.com

Abstract. A Francis runner is exposed to various loading conditions of steady and transient nature that need to be considered in a fatigue life assessment. Steady state conditions (e.g. Speed No Load, Full Load) have a constant stress amplitude pattern and therefore it is best practice to calculate a fatigue damage rate that can be multiplied by the operation time to determine fatigue damage values. Transient conditions (e.g. Start, Stop, Load Rejection) are characterized by time dependent mean stress and stress amplitudes. Traditionally, strain gauge signals are Rainflow counted and the results are evaluated using SN-curves for each separate event. With this approach, major fatigue damage driving events across operating conditions might be missed. With the introduction of the Operation Cycle Concept, the strain gauge signal is regarded from Standstill to Load to Standstill as one cycle. The influence of this approach compared to the traditional one is presented based on strain gauge measurements of Francis runners. Operating conditions with potential for optimization are identified. This knowledge is especially important for machines that are faced to flexible operation, including numerous Start-ups and Shut-downs.

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. Grid stability by sufficient control and reserve of power is a major demand on hydro power [1].

Due to the fluctuating 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 guaranteed operating range can have significant influence on the fatigue life of hydro power unit components.

The most accurate prediction of the fatigue life of a Francis turbine can be made with a strain gauge measurement in combination with a reliable load universe and reliable material data. Additionally during a measurement campaign transient operating conditions can be interactively optimized to minimize the fatigue damage contribution and the partial fatigue damages for each operating condition can be determined. This contributes to the definition of inspection intervals, maintenance or assessment of refurbishment.

In the past decade measurement techniques have been advanced and more reliable data is generated. Through the strain gauge application technique the risk of strain gauge loss during the measurement, especially in turbulent operating conditions such as Part Load, Start, Stop and Load Rejection is minimized. 3D scans of the actual strain gauge positions are a major improvement for the correlation to simulated strains and extrapolation to fatigue hot spots. The knowledge gained over
many projects significantly improves the knowledge of critical loading conditions, the fatigue calculation and the prediction during the design phase [2].

2. Loading Conditions
For a fatigue calculation loading conditions can be classified in two majors: Steady state conditions and Transient conditions. Steady state conditions are characterized by constant gate opening over time. Examples for steady operating conditions are Speed No Load (SNL), Deep Part Load (DPL), Normal Operation (NO). A stress signal is Rainflow counted and the resulting amplitudes are compared to a SN-curve. Using linear damage accumulation according to Palmgren and Miner and normalizing the calculated damage to the length of the considered time signal, a damage rate per second can be determined for each steady operating condition under consideration.

With a load universe it is now easy to multiply the damage rate with the time span of operation within the steady state operating conditions. Through Rainflow counting e.g. stochastic loading (including all frequencies) is part of the fatigue calculation. Examples for steady operating conditions are shown in Figure 1. For Normal Operation the loading is dominated by Rotor-Stator-Interaction (RSI), whereas for Part Load Operation a broad band of frequencies is generated due to stochastic flow phenomena. The example data is from a strain gauge measurement of a mid-range specific speed \( n_{q} = 40-60 \) project. The strain is scaled to stress via the Young’s modulus.

Transient conditions are characterized through a change in gate opening over time. Examples for transient operating conditions are Start, Loadchange, Stop, Load Rejection (LR) and the transition into and out of Synchronous Condenser Operation. These time signals are Rainflow counted, however, afterwards a partial damage sum per event is calculated. This signal includes the stochastic amplitudes as well as a change in mean stress. Most events are characterized by very few large spikes that build the envelope cycle, which is a major damage contributor. The distributed stochastic load has comparable low influence to the damage of the whole event. Figure 1 shows example plots for transient conditions. The time signal is normalized to the maximum stress at full load.

![Figure 1. Time Signal for SNL, DPL, NO, Start, Stop and LR](image-url)
3. Operation Cycle Concept

A damage calculation can be performed for each transient operation condition separately. With this calculation each individual envelope cycle will be the major contributor, however, envelope cycles that arise across transient conditions are neglected. To avoid a misreading of the strain gauge signals any maxima/minima in the Rainflow counting, i.e. the signal from Standstill to Standstill needs to be considered. This can have a significant influence in the fatigue damage calculation. Figure 2 shows a schematic of an operating cycle from Standstill to Standstill. In this figure also steady state conditions as SNL ($\Delta\sigma_{\text{SNL}}$), DPL ($\Delta\sigma_{\text{DPL}}$) and RSI ($\Delta\sigma_{\text{RSI}}$) are shown, these will consequently be considered with their mean stress in the steady state operating condition. The envelope cycle ($\Delta\sigma_{\text{Cycle}}$) is built through Full Load and the minimum peak during a Stop or Load Rejection. Through the Rainflow counting of the entire signal the other transients as Loadchange ($\Delta\sigma_{\text{Loadchange}}$) and Start ($\Delta\sigma_{\text{Start}}$) are included in the result of the fatigue calculation.

Figure 2. Operation Cycle schematic (based on [3])

Operation Cycles can be built for any scenario of turbine operation. The following Operation Cycles from Standstill to Standstill are defined:

- Start $\rightarrow$ Load $\rightarrow$ Stop
- Start $\rightarrow$ Load $\rightarrow$ Load Rejection
- Start $\rightarrow$ Load $\rightarrow$ Synchronous Condenser Operation $\rightarrow$ Load $\rightarrow$ Stop

Through the implementation of a load ramp to Full Load a worst case condition is generated in every Operation Cycle. For machines with frequent regulation for different loads additional Loadchanges can be implemented. This multiplies the result of the Rainflow counting for $\Delta\sigma_{\text{Loadchange}}$. Figure 3 shows different Operation Cycles for the example project for two different Start procedures. A major influence on the envelope cycle is the Start sequence and the sequence for the closing event. This confirms the results of Gagnon [3] that both Starts and closing events are of interest for optimization. Especially during the design process of turbine designs with many Operation Cycles a risk assessment for transient events is essential.

4. Optimization

As already identified, an Operation Cycle is driven by its maximum and minimum peaks that can be located in any transient event. In the examples shown in Figure 4 the Start sequence and the Shut-down sequence have been identified as driving factor with regard to fatigue damage. The prediction and optimization of both transient events results in a robust machine. The start optimization has been discussed in previous publications from Voith and others e.g. [4]-[7]. Through a modification of the governor laws the acceleration is controlled in a way that the stress is minimized. Figure 4 shows the results of a strain gauge measurement with a rough Start and an optimized Start in comparison to the
Figure 3. Example Operation Cycles

prediction. Through a SIMSEN (Software EPFL) simulation, the acceleration curves can be calculated and the Dynamic Stress Intensity derived to predict the intensity of the amplitudes. Through variations of the control system parameters, the best solution can be iterated to fulfill the requirements for time, stress and further machine requirements. Figure 4 shows that the amplitudes can be reduced to a minimum that is in the range of the SNL amplitudes for this example, which corresponds between both SG signal and Dynamic Stress Intensity. Through the minimized amplitudes the Start is not relevant in the reduced envelope cycle anymore and the fatigue life is increased (compare Figure 3). On the other hand, the Start time is increased and therefore a best compromise has to be established. For existing machines, the options for improvement are closely related to the governor capabilities. For new designs both design optimization and advanced governor laws improve a machine that is capable of many Operation Cycles.

Besides Start-up optimization, the envelope cycle that includes Shut-down events, as Stop, SCO and Load Rejection is of interest. Especially for LR it is a complex multi-objective optimization problem, as overspeed, waterhammer and time till next grid synchronisation are of further interest. For further discussion, the signal is divided into a mean stress and a dynamic part (Figure 5). The mean stress is displayed through a fine grey line. Both mean and dynamic parts are dependent on design, machine characteristics and control system parameters. The mean stress during such an event decreases to a minimum (\( \sigma_{\text{mean, min}} \)) with closing gates and is a key factor to be controlled. Different machines show a different magnitude of this effect in the strain gauge measurements.

By using an analytical approach, projects with different specific speeds have been investigated. For each project different closing events have been measured. For example, different Load Rejections, Stops and transition into SCO. The data afterwards has been normalized to machine data, design and operation characteristics. Figure 6 shows the results of 5 different measurement campaigns with the normalized characteristics on the abscissa and the minimum reached mean stress on the ordinate. The projects have different specific speed, size, head and power. Nevertheless a linear trend is established for this promising approach. Yet a scatter band cannot be totally neglected, but the knowledge about the main driving factors is available. With the included scatter band and additional safety factors, the method adds significant value to the risk assessment of new machines or for the adaption of an existing design for flexible operation. With further strain gauge measurements, the method will be refined and further proven.

The minimum peak of the envelope cycles is the sum of mean stress and dynamic stress amplitude,
Figure 4. Scaled strain gauge time signal of different Start-ups

Figure 5. Scaled strain Gauge time signal for two Load Rejections

as the mean stress already has significant impact for improvements the dynamic stress cannot be neglected. An approach that utilizes the dynamic stress intensity seems feasible and is investigated. The dynamics are influenced by both the system control parameters and the design itself, this results in a complex multi-objective optimization process.

Figure 5 shows the results of a strain gauge measurement of a machine where two Load Rejections were tested. The first Load Rejection (LR1) features a simple closing law. The second Load Rejection has a two slope closing law to keep the maximum overspeed but the dynamic and mean stress are both reduced.

Figure 6. Trend curve for minimum mean stress of closing events
For new machines all contributing parameters are available whereas for existing machines a change of the governor logic is most feasible. Existing governors, however, might lack of the needed flexibility in programming in the case of a Load Rejection it might be required to add modifications to the mechanical governor due to safety reasons. The optimization of a Stop is less complex.

5. Summary
With the Operation Cycle approach it is ensured that envelope cycles which are closed across event boarders are not missed in a Rainflow counting that is part of the fatigue calculation. Operation Cycles are defined through all loads from Standstill to Standstill. Potential to increase the fatigue life of a machine with many Operation Cycles can be localized in transient events as Start, Stop and Load Rejection. The optimization of Start-up can now be optimized based on a calculation and afterwards proven through a measurement. Through the Dynamic Stress Intensity and trend curves for closing events risks for new designs can be minimized and existing machines assessed. Ongoing investigations and the evaluation of further strain gauge measurements will refine the established calculation method. The Operation Cycle approach shows that a fatigue calculation adds significant value to the risk assessment of variable machines. For flexible machines that are operated in long time in Part Load operation additional measures need to be taken and added to the fatigue assessment. A reasoned strategy can, however, lead to a robust design that already has sufficient fatigue life and does not need further optimization of e.g. governor laws. Hence, the design is always a compromise between different goals. With increasing knowledge of the rough operating conditions, a fatigue life assessment enables operators to adapt their operation to their needs including a cost, risk and maintenance assessment.

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