On the Comparison of Hydroelectric Runner Fatigue Failure Risk Based on Site Measurements

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Abstract. The fatigue reliability of a turbine runner is closely related to its dynamic behavior. Over the past few years, Hydro-Québec has performed measurement campaigns on many of its turbine runners. These measurements led to the evaluation of the fatigue risk level of each runner in various operating conditions, which allows operating conditions with a higher risk of crack propagation to be avoided. This paper presents the results for turbine dynamic behavior assessed in steady-state conditions. Stress levels at strain gauge locations are used to evaluate the risk of fatigue cracking based on the Kitagawa-Takahashi diagram. Results show a good correlation between the calculated risk of cracking and real cases of cracks found in runners. Furthermore, the results comparison highlights a apparent tendency for recent designs to be more prone to cracking at speed-no-load operating condition than older designs. The paper gives an overview of the methodology used and discusses the conclusions derived from the sample of turbine runners available for this study.

1. Introduction
Increased penetration of solar and wind power in the energy market is changing the way hydroelectric powerplants are used around the world. Flexibility of operation is becoming a driving factor in this new market as hydroelectric generator-turbine units (GTU) are increasingly used for ancillary services instead of base load. This new paradigm implies more start-stops for GTU, which are more frequently used at speed-no-load as well as in other off-design conditions. At the same time, many GTU fleets in North America and Europe are attaining their design life and must be replaced or refurbished. Thus stems the need for a better understanding of the mechanical behavior of turbines on the whole operating range and an accurate relationship between turbine runner degradation and actual operating conditions.

Since fatigue is one of the main degradation mechanisms of turbine runners that eventually lead to blade cracking, it is important to understand this mechanism and correctly assess the risk of developing a crack in such structures. This can be done at the design stage using numerical simulations coupled with past strain measurements on similar turbines at—or after—commissioning or with strain measurements made directly on-site on the actual runner. Because large hydraulic turbines are custom designed for a particular powerplant, each design has a different stress “signature”, i.e. the load spectrum differs from one turbine design to another. Notice that in the case of rehabilitation...
projects for existing powerplants, even runners of the same design may exhibit different behaviors [1, 2]. Because each runner is different and it is not yet possible for simulations to efficiently predict the dynamic stress at every load condition, an assessment using strain gauge measurements is necessary.

Hydro-Québec's first strain gauge measurement campaigns on turbine runners date back to the 1990s, but since 2010 they have become central to fatigue risk assessments of both old and new runners. Such measurement campaigns are nowadays conducted on the vast majority of new runners at Hydro-Québec. During these campaigns, start-up procedures can be improved in order to minimize fatigue damage [3-5]. But most importantly, they allow the company to quantify the risk of fatigue failure for every turbine in the fleet and to modulate turbine operation, taking into account the damage incurred to the runner.

To date, fatigue risk assessments have been performed on 15 runners in the Hydro-Québec turbine runner fleet. Counting runners of the same design—and assuming they have a similar fatigue behavior—these 15 runner designs represent more than 50 runners, totalling over 7 GW of installed power. This paper briefly describes the methodology used to carry out this assessment and presents the obtained results. General observations and comparisons are then made along with a general discussion on how this newly gathered information can be used.

2. Fatigue Risk Assessment Methodology

The analysis is based on the Kitagawa-Takahashi diagram (see Figure 1) onto which a probabilistic approach has been developed to quantify the probability a given defect will cross the limit-state between propagating and non-propagating defects [6-8]. This diagram illustrates how classical approaches based on S-N curves can be linked to damage tolerance approaches based on fracture mechanics. In this approach, the following parameters are subject to uncertainty:

- $\Delta\sigma_0$: Fatigue endurance limit
- $\Delta K_{\text{onset}}$: Stress intensity factor of the high cycle fatigue onset (assumed equal to $\Delta K_{\text{th}}$)
- $\Delta\sigma$: Stress range
- $a$: Defect size

![Figure 1. Kitagawa-Takahashi Diagram](image)

Gagnon et al. [8] took a conservative approach to determine material properties defining the safe and unsafe zones using an uncertainty interval. Later, Thibault et al. [9] used the available experimental data to define a most probable interval within this uncertainty interval. These intervals are shown in Figure 2 and the material properties are listed in Table 1.
The purpose of the present study is to provide a quick comparison of results from many measurement campaigns. The analysis process is simplified for this purpose. The maximum dynamic stress range is used directly without uncertainty assessment or extrapolation to the hot spot. Hence, dynamic stresses might be underestimated. Furthermore, a circular surface defect is used because it has only one parameter, length $2a = 3$ mm. This defect is assumed to be present at the maximum dynamic stress location measured by the strain gauges and with a perpendicular orientation to the stress direction. Crack propagation from transient operating conditions is not considered in this paper. Note that transients could also be analyzed by this approach. The driving force, if large enough, will propagate a small defect [3-5]. If propagation occurs, the isoprobability hill in the diagram of Figure 1 will be moved toward the right, thus increasing the risk of failure with each transient event.

Using the material properties defined in Table 1, five zones of increasing risk of crack propagation during operating condition are defined as shown in Figure 3. The risk levels are graded from “A” to “E”, “A” being the lowest risk.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
 & Most Probable Interval & Uncertainty Interval \\
\hline
$\Delta K_{\text{onset}}$ & Min value 2.2 MPa·m$^{\frac{1}{2}}$ & 2.0 MPa·m$^{\frac{1}{2}}$ \\
 & Max value 3.9 MPa·m$^{\frac{1}{2}}$ & 6.0 MPa·m$^{\frac{1}{2}}$ \\
\hline
$\Delta \sigma_0$ & Min value 81 MPa & 55 MPa \\
 & Max value 278 MPa & 550 MPa \\
\hline
\end{tabular}
\caption{Material Properties}
\end{table}
3. Measurement Campaigns

Given the complexity of the loading in structures like hydroelectric turbine runners, the only reliable means of obtaining an estimate of the loading spectrum is through field measurements. These measurements are usually carried out during commissioning of new runners or on old runners to diagnose problems or extend useful life. In conjunction with the development of methodologies for fatigue risk assessment [7-2], Hydro-Québec developed the capability to carry out these measurement campaigns in order to assess the state of its runner fleet [13]. The group of runners for which Hydro-Québec has measurements includes runners commissioned from the 1980s up to 2019, with specific speed $N_q$ values ranging from 60 to 120, as shown in the results (Table 2).

In this methodology, the maximal peak-to-peak uniaxial equivalent stress range on the runner blades for each measured permanent regime operating condition and for all available runner datasets is needed in order to assess fatigue risk. In cases where the location on the runner blade is instrumented with a uniaxial strain gauge, this is done using Hooke’s law for tensile stress, which accounts only for the material modulus of elasticity. However, for cases instrumented with strain gauge rosettes, the principal stresses are used to assess the maximal peak-to-peak stress range. Principal stresses are obtained by accounting for both the material modulus of elasticity and Poisson’s ratio [14]. The obtained maximum peak-to-peak stress range over all available datasets is used as an input for the fatigue risk assessment. Each value is estimated at the measurement location, with no transposition at the hotspot [15] or time extrapolation [16] in order to simplify the study. Note that both the proximity of the strain gauge to the hot spot and the type of gauges installed can be used qualitatively in the assessment to help classify the runner and interpret the risk assessment results. For a more rigorous assessment, static and dynamic stress extrapolations to the hotspot have to be made [15]. The latter,

![Cracking Risk Levels](image)

**Figure 3.** Cracking Risk Levels
however, implies complex numerical simulations [7-2]. Figure 4 shows an example of strain rosette data and the calculated principal stresses.

![Strain Gage Rosette](image1)

**Figure 4.** Strain Rosette Data and Associated Principal Stresses

4. Results

The results for the fifteen units within the Hydro-Quebec runner fleet are shown in Table 2. The shaded region represents distributor openings at which units are usually not operated by Hydro-Quebec. Notice that most of the runners commissioned since 2010 present a high risk of fatigue failure in the part load region in which they are not usually operated as well as at speed-no-load where the runner is operated at least for synchronization with the network.

| Unit | Year of commissioning | Specific speed $N_s$ | Speed range (r.p.m) | Distributor opening (synchronized) |
|------|-----------------------|---------------------|---------------------|-----------------------------------|
| 1    | 1980s                 | 100                 | 20%                 | A A A A C B B C C C C C C C C C |
| 2    | 1980s                 | 100                 | 25%                 | A A B C B B B A A A A A A A A A |
| 3    | 1980s                 | 60                  | 30%                 | B C C C B C C C C C C C C C C |
| 4    | 2000s                 | 80                  | 35%                 | A A C C C C C A A A A A A A A A |
| 5    | 2000s                 | 60                  | 40%                 | A A A A A A A A A A A A A A A |
| 6    | 2000s                 | 80                  | 45%                 | B C C C C C C A A A A A A A A A |
| 7    | 2010s                 | 90                  | 50%                 | B D D D D D D D D D D D D D D D |
| 8    | 2010s                 | 120                 | 55%                 | D D D D D D D D D D D D D D D D |
| 9    | 2010s                 | 80                  | 60%                 | E E E E E E E E E E E E E E E E |
| 10   | 2010s                 | 100                 | 65%                 | C C C C C C C C C C C C C C C C |
| 11   | 2010s                 | 80                  | 70%                 | D D D D D D D D D D D D D D D D |
| 12   | 2010s                 | 80                  | 75%                 | D D D D D D D D D D D D D D D D |
| 13   | 2010s                 | 100                 | 80%                 | D D D D D D D D D D D D D D D D |
| 14   | 2010s                 | 60                  | 85%                 | C C C C C C C A A A A A A A A A |
| 15   | 2010s                 | 110                 | 90%                 | B C C C C C A A A A A A A A A A |

Detailed results are presented in Figure 5 for Units #1, #3, #9 and #12. On each diagram, we observe the location of every measured operating condition in the Kitagawa-Takahashi diagram considering the five risk levels. These diagrams enable the analyst to qualitatively use information about the uncertainty of any parameters to decide if a given runner should be considered more critical than another. They become a simple graphical tool to assist decision-making.
5. Discussion

We observe that Units #1 and #3 in Table 2 have high dynamic stresses (mainly risk level “C”) in their usual operating range. This is in accordance with the fact that, historically, these units have repeatedly cracked and been repaired since their commissioning. Unit #1 has cracked regularly at the crown/trailing edge junction since commissioning. The cracking mostly stopped after addition of an optimized stress relief in the problematic area, but a few cracks were still detected afterward. Note that the stress measurement campaign took place after the addition of this stress relief. Unit #3 has had one blade crack frequently at the trailing edge near the band, with the crack propagating through the band, as well as some cracking at the crown.

These two units show that stresses in Zone “C” can be detrimental to turbine runner reliability. Notice that Unit #9 has dynamic stresses in risk levels “B” and “C” within its usual operating range. This runner, while still relatively new, should be closely monitored since cracking issues are to be expected.
given the history of Units #1 and #3. At a lower risk level, Unit #12, which has dynamic stresses in risk levels “B” and “C” within its usual operating range, should also be monitored in the future.

In Table 2, we observe that most of the recent designs have high dynamic stresses at speed-no-load and at partial loads. This makes us wonder if given operator requests for high efficiency, new designs have been optimized for rated power output at the expense of partial load conditions. This might not seem a problem for GTU that normally only experience these conditions transiently during start up and shut down. However, with the current market trend demanding increased flexibility, it might become a problem in the future. Furthermore, GTU might also need to be operated at speed-no-load for extended periods for network (rotating reserve) or environmental (river minimum flow) considerations. In these cases, the expected operating scheme should be clearly specified in the contract technical specifications to ensure that the runner design properly matches potential future uses.

6. Conclusion
In addition to the possibility of identifying which units must be monitored closely in terms of cracking risk issues, Table 2 is the first step toward the optimization of operation and maintenance of turbine fleets. On one hand, turbine reliability can be improved by avoiding damaging operating conditions and modulating the operation of the entire fleet in order to minimize the overall damage while trying to maximize the monetary benefits. On the other hand, inspection intervals can be adapted to the assessed risk with the goal of timing inspections to minimize the risk within a given budget. Moreover, the assessed risk can be used to better plan GTU rehabilitation projects over the years. Combining fleet operation modulations with rehabilitation project planning will allow the utility to optimize its reliability and flexibility to maximize profitability.

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