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Influence of load spectrum assumptions on the expected reliability of hydroelectric turbines: A case study

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ABSTRACT

A lack of observed data can lead to significant discrepancy between estimated and actual fatigue reliability. In this study, the load spectrum derived from the strain measurements and operation history of a hydroelectric turbine are used to identify the information necessary to avoid major bias in the estimated fatigue reliability of such structure. Our results demonstrate that a limited number of parameters need to be considered. Any further simplifications may lead to major reliability estimate discrepancies. Furthermore, we observe that the parameters which influence initial reliability hide the influence of other parameters on the reliability failure rate associated with the structure's life expectancy. We conclude that a typical sensitivity analysis made on parameter values needs to be complemented with a sensitivity study on the chosen assumptions in order to properly evaluate the risks associated with the operation of hydroelectric turbines.

1. Introduction

Using oversimplified loading spectra can generate significant bias in fatigue analysis because of neglected features when compared to the actual load sustained by the structure. However, observed data are often lacking during the design of a structure or before measured values are available. In such cases, both the designer and the analyst have to rely on simplified loading assumptions. The lack in the literature of either standardized load spectra or observed data from existing hydroelectric turbine runners make it difficult for the construction of such *a priori* assumptions. For large Francis hydroelectric turbine runners, every runner is considered a prototype. Generally speaking, the loading patterns used during the design phase simply cannot be based only on previously observed data from similar designs. This often leads to a difference between estimated reliability and actual reliability. Such errors, if unacknowledged, might influence design choices leading to a risk of higher maintenance costs or warranty issues. The nature, consequences and probability of these errors are often not considered in reliability assessments. We believe that the possibility of such errors generates uncertainties which should be acknowledged in a attempt to minimize the risks associated with the operation of these large rotating structures. This is in line with the risk description proposed by Aven [1] in which the probability and the consequences of an event are not sufficient to describe risk. Uncertainties which include assumption credibility also need to be addressed. In many cases, the acknowledgement of such uncertainties may justify the loading spectrum experimental validation in cases where life expectancy is considered an important risk factor. Such observations would be an important step toward the safe operation and standardization of load spectra [2]. In this study, our objective is to define the main damaging features observed on an existing hydroelectric turbine runner and to quantify their effect on the reliability assessment of such structures.

Structures like large hydroelectric turbine runners often have limited inspection possibilities combined with high downtime costs. For these structures, we consider that cracks only need to be repaired after the onset of High Cycle Fatigue (HCF). This statement relies on two basic assumptions:

1. Significant crack growth will be induced after HCF onset and crack growth will then be proportional to operation time rather than the number of low cycle fatigue (LCF) events.
2. A crack needs to be repaired as soon as possible in order to minimize costs only if significant growth is expected.

A typical design assumption is that the stress experienced by the runner blades goes from zero to a given operating condition

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stress level to zero during a typical load cycle [3]. This simple loading pattern, shown in Fig. 1, is similar to the representation of combined HCF/LCF loading commonly used in the literature [4,5].

This loading pattern loosely matches the strains observed during a typical loading cycle on hydroelectric turbine runner blades. However, when compared with the measured loading shown in Fig. 2, this load pattern lacks transient events like turbine's startups and shutdowns. Given their amplitudes, these transients have a non-negligible influence which might generate significant bias on life expectancy [6,7]. In the industry, the study of such phenomena is recent and is not mentioned in the hydroelectric turbine runner life expectancy literature review compiled by Sabourin et al. [8].

The influence of the LCF and HCF part of Fig. 2 loading sequence can be observed on crack growth simulation from [6] shown in Fig. 3. In this figure, the crack propagation results obtained using the measured strains from Fig. 2 are presented. We observed a slow crack propagation if a minimal time is spent at maximum opening (LCF only). However, during normal operation, we could expect almost 24 h of operation at maximum opening for each loading block (HCF). The loading HCF component which as an amplitude lower than the onset threshold do not contribute to the crack growth initially. However, the crack will reach a point, identified as the HCF onset, after which crack growth speed increases rapidly due to the loading HCF component contribution [4]. This contribution will growth exponentially if we consider the strain amplitude constant as shown in Fig. 2.

Life expectancy cannot be defined by the loading pattern alone. It must be combined with other information to generate a representative loading spectrum suitable for life assessment. The information needed to derive a loading spectrum for a hydroelectric turbine runner is typically:

1. The list of all the allowed steady-state conditions.
2. The list and expected number of transient events (startups, shutdowns ...).
3. The location of every critical area on the runner blades.
4. The stresses (static and dynamic contents) for each allowed steady-state and transient operating conditions at each critical area.
5. The residual stress levels at each critical area.

Using these, the loading spectrum is generated and combined with both material fatigue properties and expected defect size to obtain a reliability estimate. Our objective in this study is to highlight the results discrepancy between the *a priori*loading assumptions and observed data. For this purpose the data from an existing structure for which we have both measured strains at a critical location and an operation history are used to derive simplified load spectra. The reliability results obtained with these spectra are then used to establish guidelines regarding the essential features needed in the loading spectrum to minimize bias due to simplifications while keeping the number of parameters to a minimum. Such guidelines should help limit the number of assumptions needed and facilitate the analysis when observed data are unavailable.

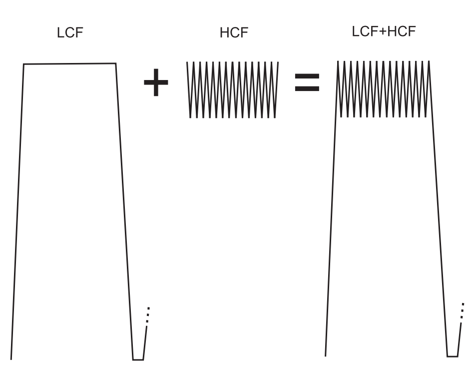

Fig. 1. Schematic example of combined LCF + HCF loading.

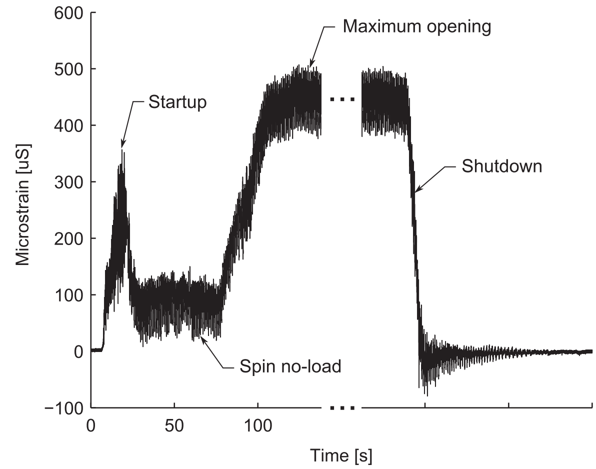

Fig. 2. Measured loading sequence.

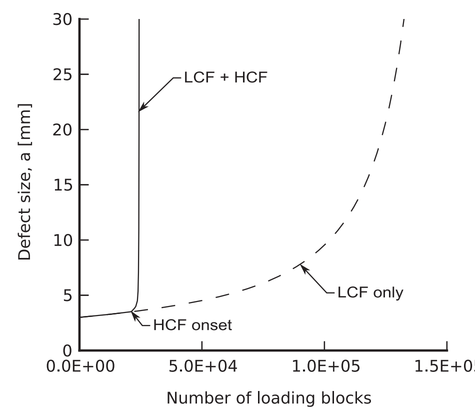

Fig. 3. LCF vs. LCF + HCF crack propagation results.

The paper is structured as follows: first, the turbine runner reliability model and the methodology are defined. Next, a case study is proposed based on observed data. Finally, reliability results are presented followed by a discussion on the importance of each parameter in the design, maintenance and operation of large hydroelectric Francis turbine runners.

2. Reliability model

To assess the reliability of a structure, we must first define a proper limit state for our application. In this study, Linear Elastic Fracture Mechanics (LEFM) theory will be applied since it is commonly used for the crack propagation of hydroelectric turbine runner blades [8]. According to LEFM, crack growth can be modeled as follows:

$$\frac{da}{dN} = C\Delta K^m, \quad \Delta K > \Delta K_{th} \tag{1}$$

in which a is the crack length, N the number of stress cycles, C a material constant, ΔK the stress intensity variation, and the exponent m also a material constant. In LEFM, no propagation occurs below a defined stress intensity variation level ΔK_{th}. The stress intensity factor variation ΔK is defined using the following: