Optimization of turbine startup: Some experimental results from a propeller runner

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Abstract. The turbine startup is a transient event generating high amplitude stress cycles in runner blades which might reduce significantly the life expectancy of the runner. Our goal is to use the increased range of possibilities offered by newer governing system to optimize the wicket gates control pattern in order to reduce the amplitude of the strain transient in the runner blade during startup. In this paper, we present our success in defining an optimal wicket gates control pattern for the startup of a newly commissioned propeller runner.

1. Introduction

The turbine startup is an event that can generate high amplitude transient stress cycles in runner blades. These high amplitude stress cycles might reduce significantly the life expectancy of the runner. To circumvent this problem, we can either optimize the design of the runner or optimize the governor's startup sequence parameters. Currently, we do not have accurate numerical model to predict the blade response during startup sequence. This renders difficult blade geometry optimization accounting for wicket gate opening control during the design of the runner. In an effort to understand the link between the turbine runner control system and blade response Hydro-Québec decided to carry out some in situ experimental strain measurements on prototype runners. This measurement campaign follows previous work by Hydro-Québec on the influence of startup on life expectancy [1, 2], the stochastic simulation of startup transient [3] and the numerical simulation of startup transient [4]. This is in relation with work published by Gummer [5] on cracking problem due to startup transients. Needless to say that startup is not the only transient which can influence fatigue reliability. Many other transient phenomenons have an impact on runner life [6]. Among these transient phenomenons, we will mention the load rejection transient [7] and the often neglected shutdown transient.

The experimental measurements presented in this paper were made on a propeller runner. The startup optimization was done during the commissioning of this runner and we had no previous experience with this specific design. During the optimization, different startup control patterns have been compared in order to evaluate their capacity to reduce the transient response of the blade. Our goal was to maximize the fatigue reliability [8] of the runner by using the full range of possibilities offered by the runner control system during the startup sequence. In this case, we succeeded to remove almost completely the startup transient with minimal impact on the startup time as shown in Figure 1.
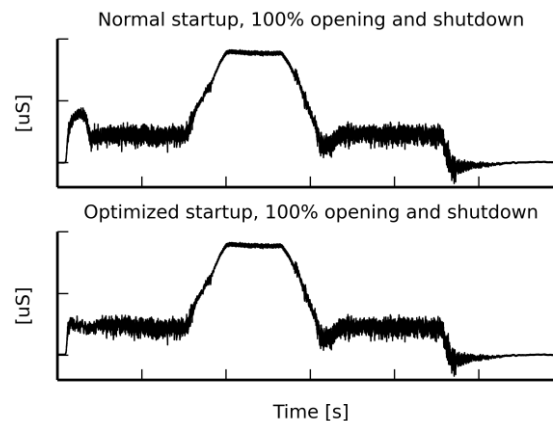
Figure 1. Comparison between blade strain
responses with and without startup optimization.

Newer governing systems used for turbine control offer an increased range of possibilities when compared to older systems. Our first step was to look at the optimization possibilities offered by these governing systems in order to define an optimization domain. The optimization domain was then adjusted for mechanical and operational limitation. Our objective was not to cover the whole optimization domain but explore some chosen possibilities.

The paper is structured as follows. First, optimization domain offered by the runners governing system presented and the chosen startup control pattern for the experimental measurement defined. Next, we present the experimental data obtained, the relation between opening rate and startup time. Last, we discuss the applicability and limitation of the presented results.

2. Governing system startup parameters

The typical governing system has a limited number of adjustable parameters. The parameters which influence the amplitude of the stress transient are:

1. Opening limit
2. Fold back speed
3. Fold back opening

With newer governing systems other parameters can be included to generate more complex control patterns as shown in Figure 2. The two (2) on the left represent the standard wicket gates control patterns and the two (2) on the right show patterns offered by newer governing systems that we want to investigate. However, it was not possible to generate the bottom right pattern on the unit studied.
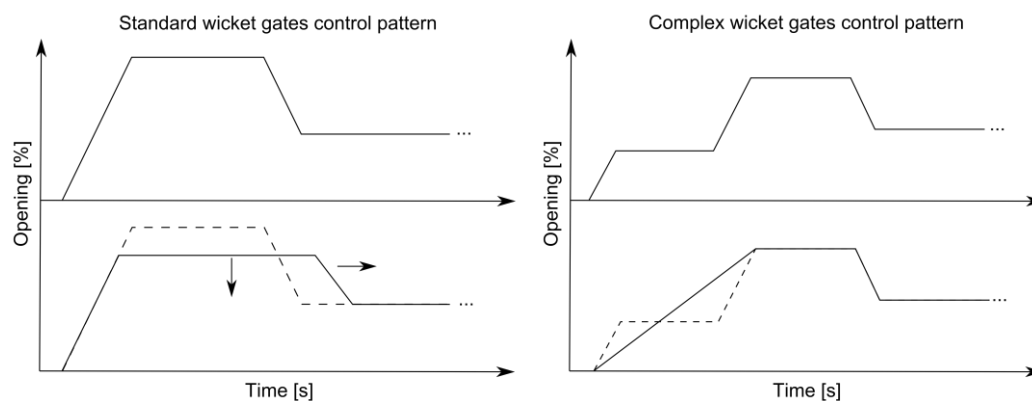

Figure 2. Governing system control patterns.

The objective is to attain synchronous speed in an acceptable time interval for the synchronization of the unit. This open some optimization possibilities in the startup sequence since maximum synchronization speed is not the main objective. The parameters used in IEC 61362 [9] to defined synchronization speed are presented in Figure 3.
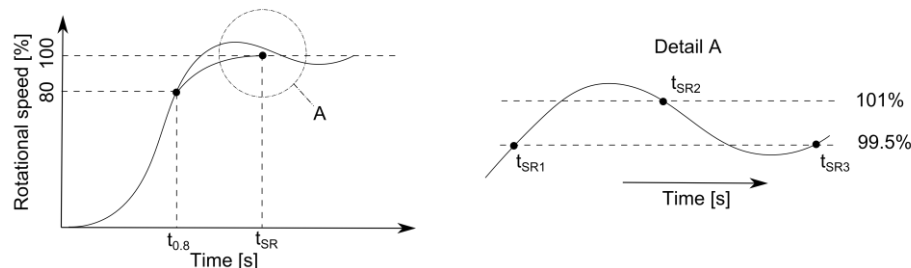

Figure 3. Startup speed as per IEC 61362 [9].

In this paper, the time to reach 80% of the synchronous speed is $t_{0.8}$ and the time to reach the synchronization range is t_{SR}. We use t_0 defined as 0.1% wicket gates opening as reference to determine $t_{0.8}$ and t_{SR}.

A priori, we expect lower startup opening limit to reduce the stress transient amplitude and to lengthen the time to reach synchronous speed. On the other hand, more complex control pattern are expected to lower the startup transient with less influence on the startup speed. The normal governing system settings for the propeller runner studied in this paper are the following:

1. Opening limit = 40% wicket gates opening
2. Fold back speed = 85% of synchronous speed
3. Fold back opening = 25 % wicket gates opening

Prior to the experimental testing, one of our hypotheses was that rotational acceleration, torsion and strain transient might be correlated. This was supported by the work of Gummer and Etter [5] in which they solved a high blade strain problem by controlling the acceleration during the startup sequence. This was only partially validated by our experimental results.

3. Experimental results

The experimental testing was carried out by Hydro-Québec during the commissioning of a propeller runner on a run-of-the-river power plant in Quebec, Canada. We tested seven (7) different wicket gates control patterns. The tested control patterns are summarized in Table 1.

Table 1 Wicket gates control patterns

Opening Limit	Fold back speed 1	Fold back opening	Fold back speed 2	Fold back opening 2
40	85	25	-	-
35	85	25	-	-
30	85	25	-	-
25	85	25	-	-
20	85	25	-	-
15	21	30	85	25
15	21	40	85	25

Note: Opening in % of max. opening and speed in % of synchronous speed

An overview of the results obtained is presented in Figure 4-5. The Figure 4 left shows the normal governing system setting for the studied runner. We observe, on the blade strains, that there is a transient period where the observed strains rise above the ones observed at Spin-No-Load (SNL) when

the rotational speed is stabilized after reaching synchronous speed. As we lower the opening limit toward 25%, the strain transient diminishes until the strain do not rise above the one observed at SNL. This is our optimal control pattern shown in Figure 5 left. Lowering the opening below 25% is suboptimal since we generate a strain plateau below the SNL level and lengthen the startup time as shown in Figure 5 right. We show one example of the more complex startup control pattern in Figure 4 right. We observe that the strains observed during the 40% plateau are not reduced compared to the top left results. Nonetheless, the maximum shaft torsion is reduced due to lower acceleration.
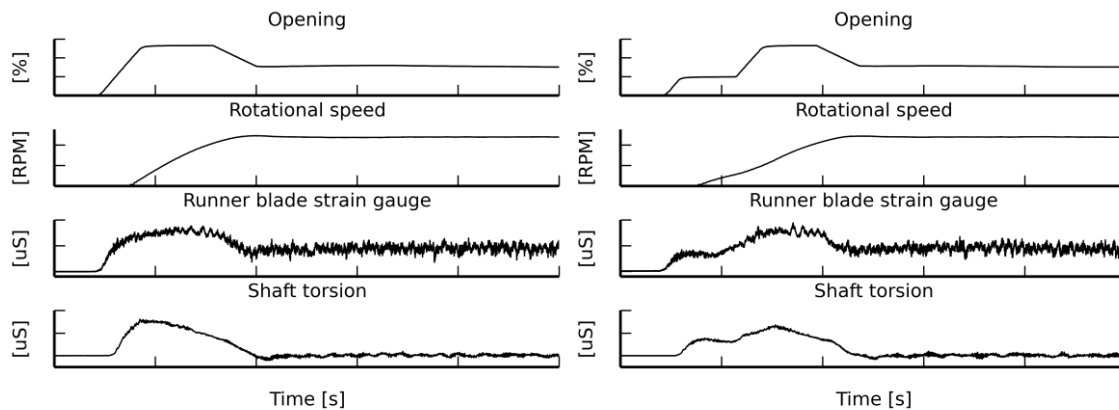

Figure 4. Comparison of wicket gates control patterns. (left) Startup at 40%. (right) Startup at 15% then 40%.
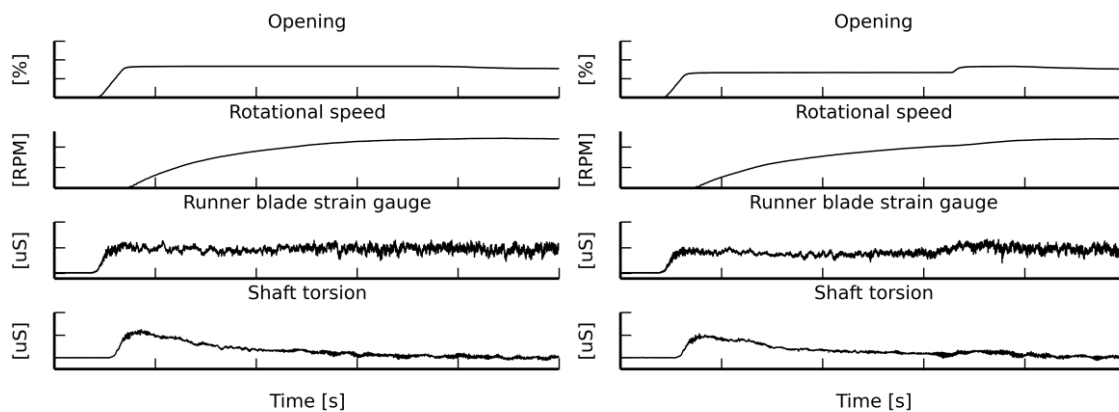

Figure 5. Comparison of wicket gates control patterns. (left) Startup at 25%. (right) Startup at 20%.

Overall, we observe, as expected, a similitude between rotational acceleration and shaft torsion as shown in Figure 6. However, even if we can observe a reduction of both the acceleration and torsion with a more complex control pattern, this does not translate to a reduction of the maximum blade strain observed in Figure 4. Furthermore, it was not possible to discriminate the optimal wicket gate control pattern from the suboptimal one at 20% opening from either maximum rotational speed acceleration or maximum shaft torsion only.
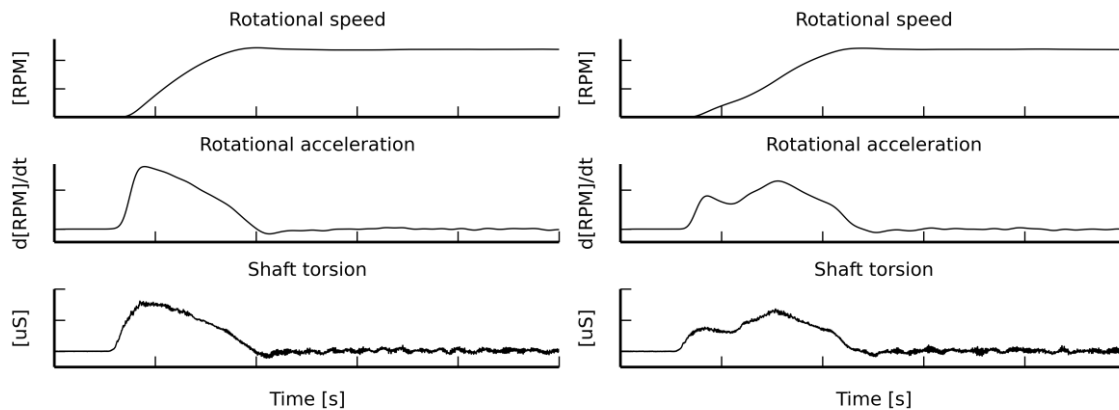
Figure 6. Acceleration vs torsion. (left) Startup at 40%. (right) Startup at 15% then 40%.

The startup time results for each wicket gate control patterns are shown in Table 2. We present only the first two points in time where the rotational speed enter the synchronization range: t_{SR1} and t_{SR2}. We observe that even if startup times are longer than for the normal startup parameters at 40% opening, we never reach unacceptable value for any of the wicket gates control patterns.

Table 2 Startup time results

Opening [%]	$t_{0.8}$ [s]	t_{SR1} [s]	t_{SR2} [s]
40	10.3	13.6	20.0
35	11.5	21.4	40.5
30	13.5	25.4	44.9
25	17.3	31.6	54.6
20	22.9	37.0	49.3
15, 30	16.3	28.6	44.2
15, 40	14.0	17.4	24.3

Note: t_0 is defined as 0.1% wicket gates opening

4. Discussion

One of the first questions we ask ourselves is: can we find an optimal startup control pattern where we completely remove the strain transient for any type of turbine runner? From our results we can say yes but this only apply to the runner tested. We believe that our conclusion might extend to similar design but we will need more data to confirm this. Nonetheless, if we compare the data from our propeller runner with the data from a Francis runner inside the same run-of-the-river facility [1] as presented in Figure 7, we observe significant difference in dynamic behavior. However, a similar tendency is observed in which the strain almost disappear when the opening limit get closer to the SNL wicket gates opening.
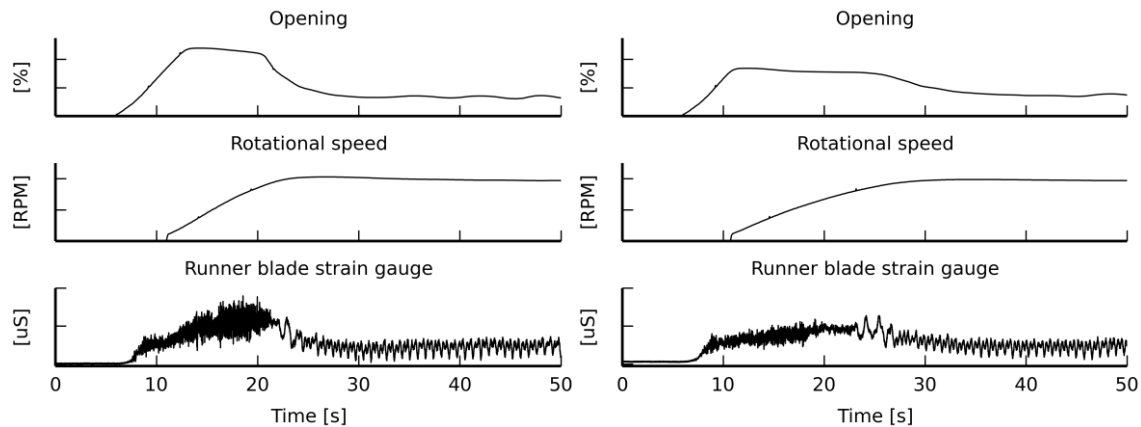
Figure 7. Francis runner #1 data. (Left) Startup 1. (Right) Startup 2.

This behavior observed in Figures 4, 5 and 7 where the strain diminishes with lower startup opening limit does not translate well to all runners. If we look at the data from Figure 8, we observe that for this Francis runner the strain transient happens in the first few rotation of the runner and that the amplitude of the transient augments when we lower the startup limit opening. This reinforce our assumption that every runner or at least group of similar runners might behave differently. This is particularly important for Hydro-Québec because we operate different power stations with different head and types of runner from a wide array of manufacturers. Furthermore, we also need to account for the fact that old and new runners have different design even in the same facility.
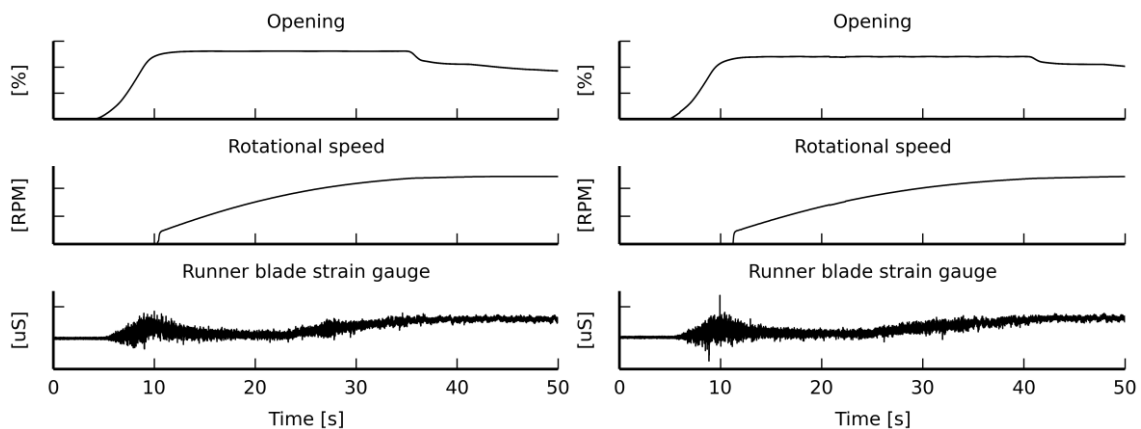

Figure 8. Francis runner #2 data. (Left) Startup 1. (Right) Startup 2.

These raise another question: Can we optimize the startup sequence using indirect measurements to eliminate the cost associated with blade strain measurement campaign? Our hope would be to find a suitable indirect measurement method or a combination of indirect measurement methods that would enable an optimization of the startup transient without the time and cost of runner blades instrumentation. However, as of this study, such method are not available and the only valid option is the direct measurement of blade strains. As more data become available we which to overcome this difficulty.

5. Conclusions

From the prototype experimental results presented in this study, we have confirmed the following:

1. The normal governing system parameter settings lead to high runner blade strain transient during startup.
2. Optimization of the governing system settings is possible without significant compromise to the startup speed.
3. When compared together different designs and types of runner have different dynamic behavior during the startup transient

More specific to the propeller runner studied, we learned that:

1. Startup transient can be reduced to a level where it can be completely neglected.
2. Suboptimal settings are possible where we generate a strain plateau below SNL during startup.

At the time of the study, we did not succeed to find a combination of indirect measurements able to detect the optimal startup settings. However, we believe that the optimization using indirect measurement is possible but maybe specific to each design and type of runner.

Future research should look for similitude between runner behaviors in order to reduce the need for direct strain measurement on the runner blade. Furthermore, when looking at Figure 1, we observe that their may be as much gain in fatigue life and reliability from the optimization of the shutdown transient than the startup transient once it is reduced to negligible level.

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