A look at Francis runner blades response during transients

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Abstract. Data shows that the mechanical response of Francis runner blades is sensitive to power plant control systems. To demonstrate this, we have explored two such systems: wicket gates opening and air admission. The proper control of these systems does more than warrant safe operation; they can also be used to minimize the strain cycle amplitudes during transients such as: startups, shutdowns and load rejections. Proper control parameters settings should minimize the equipment risk of fatigue failure without negative side effects on other components and objectives. With the help of measured examples from Hydro-Québec power plants, this paper demonstrates that a better understanding of these systems is needed in order to move beyond costly trial and error fine-tuning methodology.

1. Introduction

During the last decades, investigations related to turbine transient response were limited. The main interest in this field was safety concerns. For runner blade dynamic behavior, the focus was then on steady state operations. However, more recently, an increased interest in runner blades response during transients is observed due to their importance for fatigue and life assessment [1]. While the literature on the subject shows that both the amplitude of the response and the number of transient events play an important role in evaluation of fatigue failure risk, plant operators can only limit their amplitudes using the plant control systems; their occurrence being, for the most part, related to energy demand hence unavoidable [2, 3].

With the energy market deregulation, transient events are now more and more common. Their numbers being often well above previous historical values which can reduce significantly the equipment residual life [1, 4]. Research has shown that the dynamic amplitudes of most transients can be influenced using the turbine control systems [1-7]. By looking at the two types of simplified blade response observed in hydroelectric runner shown in figure 1, we observe that the startup and shutdown transients have a direct influence on the largest cycles contributing to crack growth in runner blades [8]. Notice that both types of response can be observed on the same blade at different locations due to the change in deformed shape from one operating condition to the other. In figure 1, the change are illustrated between SNL to maximum opening but could be generalized for any operating conditions. During the life of the turbine, four types of transients are typically observed: startups, shutdowns, load changes and load rejections. Of these, load changes generally don’t generate significant stress response other than static stress change from one condition to the other. On the other hand, a load rejection, which is an emergency procedure with some similarity with shutdowns, often generates much larger stress amplitudes. Even if uncommon, load rejections generate in some cases significantly
more damage than any of the others transients [6, 7]. Furthermore, shutdowns and load rejections can generate safety issues related to waterhammers.

Figure 1 Runner blades simplified strain response spectra [8]. (left) Type 1. (right) Type 2.

This means that for a turbine runner having acceptable dynamic behavior, a plant operator could adjust the control system parameters to minimize the equipment risk of fatigue failure without negative effect on other components and objectives. In an effort to understand this link between turbine control system and runner blades response, experimental data available from strain measurements on Hydro-Quebec runners were reviewed along with the ones available from the literature. The objective is to highlight how to improve runner fatigue reliability by using the full range of possibilities offered by the turbine control systems. This requires an understanding of the influence these systems have on the runner blade mechanical response which comes from a combination of periodic excitations, hydraulic instabilities, self-excitation, sudden change in operating parameters, water hammer, etc. In doing so, it will be possible to identify which ones are more sensitive to specific control system parameters.

The results of this study are presented as follows. First, the control system parameters available to plant operator in order to influence the transient events are introduced. Then, the runner blades mechanical response in regards to the control parameters during startup transients is analyzed. Next, shutdown and load rejection optimization possibilities are presented. Finally, the multi-objectives aspect of transient optimization is considered with not only runner blades but all the components of turbine-generator assembly.

2. Control systems
The wicket gates’ opening is the main parameter which regulates the operation during transient events. The speed governor typically has a limited number of adjustable parameters for safety purpose. However, outside those specific parameters, the governor operation can be modified by the manufacturer or plant operator at a relatively low cost. The typical adjustable parameters for the wicket gates opening sequence are:
1. Opening limit
2. Fold back speed
3. Fold back opening

With some governing systems, the opening rate or speed is also adjustable and can be easily used to influence the runner response during the transient. Notice that the opening rate is not always directly controllable. However, it can always be adjusted indirectly by physical modifications to the system configuration or some of its components. Nowadays, newer governor can often be reprogrammed to generate even more complex control patterns. In figure 2, the two control patterns on the left represent
how the typical wicket gates control parameters can be adjusted and the two on the right show other patterns which were investigated by Hydro-Québec [3].

Governor actions are triggered by the rotating speed. The aim is to reach synchronous speed in an acceptable time interval for the unit synchronization. The parameters used in IEC 61362 [9] to define synchronization speed are presented in figure 3. The opening sequence is as follows: first the gates open with a prescribed speed until they reach an opening limit then, after the rotating speed reaches the fold back speed, the wicket gates are limited to a fold back opening which is maintained until near synchronous speed for synchronization with the grid. Since fast synchronization is not the main objective, many optimization possibilities are available in the startup sequence parameters. The IEC recommendation is that the ratio $T_{SR}/T_{0.8}$ should be within 1.5 and 5, in which $T_{SR}$ is the time to synchronous speed and $T_{0.8}$ is the time to reach 80% of synchronous speed. Synchronous speed is achieved when the speed is within a 99.5% ~ 101% boundaries as shown in figure 3.

The wicket gates opening is also used to control the shutdown transient. The objective of the shutdown sequence is to safely stop the runner rotation. In order to do so the runner need to be unsynchronized from the network without going in over-speed. Typically, power is first decreased until Speed No Load (SNL) condition is reached. Then the turbine is unsynchronized and wicket gates are closed. Finally, when the rotating speed is low enough, the brakes are applied. This can happens more or less rapidly without any impact on safety. This is where optimization possibilities appear. Parameters like the wicket gates closing slope, slope changes, transition between them or cushioning on the completely closed position could be used to minimize strain transient while maintaining safe operation. Unfortunately, these parameters are not as easily adjustable as the startup parameters. This tends to limit experimentations.

In a way similar to shutdown sequence, wicket gates operations are also automated for safety during load rejections. The goal is to return the runner to synchronous speed or in some instance to completely stop the turbine when sudden grid desynchronization occurs during operation. Control
parameters for load rejection are similar to those used for shutdown sequence. In general, two wicket gates closing speeds are used, a rapid one used to limit overspeed followed by a second slower one to limit pressure surge before the wicket gates reach a completely closed position. The closing speeds are related to safety concerns but have significant margins for fine tuning. Load rejection is a more complex and interesting multi-objective optimization problem for which the results should for the most part also be applicable to the shutdown sequence.

Last, there is an often overlooked parameter which is the air admission system. The system is generally passive and designed to reduce pressure fluctuation and vibration due to hydraulic instability at part load or to solve hydraulic problem during load rejection. It is not usually designed to be fine-tuned during operation. Nonetheless, air admission should not be neglected because it has a significant impact on the runner dynamic behavior, vibrations and pressure fluctuations. We believe that this system should also be exploited to maximize the life of the runner.

3. Startups

The interest for startups optimization is not new and has been discussed previously by the authors and others researchers [1-7]. Despite these efforts, control parameters are still mostly defined using trial and error on site. However, developments are being made in the numerical simulation of such transient [10]. In previous work, we have shown that modifying the wicket gates opening pattern did influence not only runner blade response but could also help attain other objectives which means that fine-tuning startup can be seen as a multi-objective optimization problem [3]. In the case of the propeller runner that was studied, some changes in the opening pattern did not lower significantly the maximum stress cycle amplitude but proved to reduce maximum shaft torque during startup. Direct comparisons with various Francis runners are difficult since the data available are different. However, we can visualize this multi-objective problem using one of our dataset where the effect of the opening limit and slope was studied for a given standard control pattern. Figure 4 shows an overview of the strain experienced by the runner blades for default startup parameters and optimized startup parameters. Notice that, with regard to the dynamic behaviour definition presented in figure 1, we observe a type 2 response spectrum at this sensor location [8].

![Default startup with an opening limit of 20% and slope of 2%/s. (right) Optimized startup at 10%-2%/s.](image)

Figure 4 (left) Default startup with an opening limit of 20% and slope of 2%/s. (right) Optimized startup at 10%-2%/s.

Comparisons of opening limit and slope scenarios for the maximum strain range and pressure range in the spiral case are shown in figure 5. In this figure, the diameters are proportional to the maximum dynamic ranges observed during each startup. Notice that each startup was replicated twice which gives an idea of the repeatability for one startup to the other. The approximate time required to reach synchronous speed is indicated for the default startup scheme (20%-2%/s) and the two strain optimum. If the pressure fluctuation is also used for multi-objective optimisation, then only one optimum
remains. Notice that this optimal startup requires twice as long synchronisation time compared to default parameters. Nonetheless, it remains within acceptable values for the studied facility.

**Figure 5** (left) Max. strain cycle range. (right) Max. spiral casing pressure fluctuation.

Considering only the maximal strains cycle, there seems to be an equivalent impact of lowering the slope or opening limit. However, to minimize the pressure fluctuation, lowering the opening limit clearly has more impact than the opening speed. To investigate this, let us look at the startup with 30% opening limit and 2%/s opening speed in figure 6. These parameters generate the highest number of pressure fluctuation spikes. Notice how large pressure fluctuations are correlated to wicket gates closing. In each instance, the closing slope is maximal and is not correlated with the motion amplitude. Furthermore, these fast closing rate generates pressure spikes of the same order of magnitude of those of a total load rejection.

**Figure 6** Startup at 30%-2%/s

Similar behaviour is observed in the left part of figure 7 for the startup with 20% opening limit and 0.5%/s opening speed. However, for the strain optimum with 10% opening and 2%/s opening speed the pressure spikes have completely disappeared. This is because the opening limit moves to a higher value rather than a lower value during fold back which removes the main wicket gates closing event during the startup. Nonetheless, this happens at the expense of the time needed to reach synchronous speed which is longer. A compromise could be obtained if the closing rate was a controlled startup parameter.
To differentiate the severity of different startups, maximum value is a good indicator, but a more rigorous way is to look at the whole rainflow response spectrum. This gives a complete overview of the fatigue cycles contained in a given time series. In figure 8, four startup schemes, replicated twice, are presented. It shows that the rainflow spectrum of one of the worst startup (30%-2%/s) is highly similar to the default startup (20%-2%/s). It also shows that the two optimal startups in terms of strain (20%-0.5%/s and 10%-2%/s) are almost identical even if they seem to have different time signature (figure 7). Interestingly enough, for the two optimal startups, the reduction in severity is across the whole spectrum which confirms results observed in figure 5.

We would advise against the shortcut that longer startup time always translates to lower stress level. Longer transient also means more time over which hydraulic phenomena can appear. In figure 9, strains measurements from another Francis runner at Hydro-Québec illustrate this. In this case, sustained high strain cycles appear with slower opening and longer time to synchronous speed. This is thought to be related to hydraulic instabilities having enough time to establish themselves and only happens if the operating parameters stay compatible with the phenomena long enough.

**Figure 7** (left) Startup at 20%-0.5%/s. (right) Startup at 10%-2%/s.

**Figure 8** Rainflows comparison.
4. Shutdowns and load rejections

The shutdown transient is often neglected since it doesn’t generate as much high amplitude strain cycles compared to others transients like the startup and load rejection. However, as can be seen in figure 1, since it contributes to the largest strain cycle in the response spectrum for many turbines, it cannot be neglected. The control scheme for shutdowns is not as standardised as for the startups. Power plant operators can choose to go to SNL condition and then initiates the shutdown sequence. However, this is automated and can be requested from any operating condition. Sometime it is automated to happen slowly as shown in figure 10 left or so fast that SNL operation is hardly seen as shown in figure 10 right. Notice that the shutdown in figure 10 left comes from the same unit as the data in figure 4.

We currently don’t have examples of shutdown optimisation since the parameters are more difficult to modify compared to the startup. However, a change in shutdown transient amplitude will directly influence the largest damaging cycle in the response spectrum of runner blades. Hence, the potential for fatigue damage minimization is important and extended equipment life should be expected.

A similar transient, but often richer in term of dynamic behaviour and safety concerns, is the load rejection. Load rejections are not part of normal operation but can be significantly more damaging than other transients when the control parameters are not adjusted properly [5-7]. Since the turbine stays in off-design operation longer, reaches speed well above synchronous one and starts with significant hydraulic energy, the probability of generating undesirable hydraulic phenomena having damaging effect on the equipment is significant. Some hydraulic phenomena can induce auto-excitations when their frequency is near a natural frequency of the system thus generating sustained...
high amplitude strain cycles as long as both stay compatible. During the load rejection, change in
control parameters like wicket gates closing speed and use of multiple speeds have shown the potential
to remove or greatly reduce this auto-excitation [7].

There is a direct link between change in wicket gates motion and strains in runner blades. Sudden
changes can rapidly modify the flow rate and can be assimilated to waterhammers [11]. The effects on
the structure response of such changes are visible in figure 11 when the speed changes and in figure 12
right when wicket gates completely close. In the later, the observed behaviour is highly influenced by
the presence of air.

During load rejection, air admission systems are often used to prevent vacuum in the draft tube as
opposed to wicket gates which are used to limit over pressure in the spiral case. Furthermore, air
admission is also used as a measure to dampen pressure fluctuations during startups and part loads.
The presence of air in the fluid has a non-negligible influence on the response of nearby structures like
runner blades. Figure 12 presents the response for two subsequent load rejections at 75% of the rated
power. The one on the left is with normally working air admission system and the one on the right is
with intentionally partially blocked air admission system. This unit has three distinct air admission
systems and the main one was closed for testing. On the left, more medium range strain cycles are
observed on the runner and those are spread across the over-speed region. Comparatively, on the right
we observe lower amplitude cycles across the overspeed region and there is one sharp high amplitude
transient associated with the moment when wicket gates reach the completely closed condition. Notice
that the spiral casing pressure fluctuations are almost identical for both cases and that the draft tube
pressure fluctuations are only slightly increased. For this unit, the air admission system was design to
solve problem related to vacuum in the draft tube. For the condition presented, the response of the
turbines runner blades is significantly influenced by the change in air flow and pressure fluctuation
stay within acceptable limits. Altogether with the wicket gates opening, it is thought that the air flow
in the air admission system could be controlled to influence the structure response without prejudice to
its main function if a multi-objective optimization approach was to be used.
5. Discussion
First, it is important to mention that almost every transient examples presented in this paper, even those with non-optimal behaviour, are considered acceptable in regard to design and operational requirements. However, we believe that a smart power plant operation goes beyond simply ensuring acceptable operation. As discussed previously, non-negligible gain in life expectancy and probability of failure can be expected by fine tuning the turbine control systems. Most of the time, the cost of such changes are relatively low compared to the expected gains, even when a dedicated measurement campaign is needed. To carry such endeavour, all the components of the power plant should be considered in a multi-objectives optimization. This should include more than only blade dynamic strain amplitude. As shown in this paper, parameters like pressure fluctuations, unit vibrations, shaft torque, etc. should be considered. Also, while some of the experimental and numerical knowledge needed to do such fine-tuning is being developed for startups transients, they are still not well defined for shutdown and load rejections. In the end, such knowledge should reduce the need of costly trial and error methods.

Another important point is that air admission systems seem to have never been considered as a mean to extend the life of a runner. Such systems are generally used to reduce pressure fluctuations or solve dynamic problems but, as shown in this study, they often also operate automatically outside of the required operating region and could have a wide array of possible parameter values over which their desired effects could be obtained. We believe that these systems should not be considered only as a safety measure but also as a mean to maximize runner life and ensure reliable power plant operation.

6. Conclusions
In this paper, three types of transient events were identified for which the power plant control systems can be optimized to extend the life expectancy while maintaining reliable operation of the runner. These transient events are:

1. Startups
2. Shutdowns
3. Load rejections

Beside these, load change is another type of transient that does not generate high enough strain cycles to justify its study in term of optimization possibility.
Mainly two parameters from the power plant control systems have been investigated and could be used to influence significantly the life of the equipment without compromising their primary functions. These are:

1. The wicket gates opening
2. Air admission

Wicket gates opening control settings have already shown their capability to both reduce dynamic strain on the components and solve undesirable dynamic phenomena. On the other hand, the air admission system also demonstrated a significant impact on strain and other dynamic phenomena. However, for the time being, we still lack the knowledge and experience to predict its influence at the level of detail needed for optimization. We believe that a better understanding of these systems and how they could be fine-tuned is needed in order to move beyond costly trial and error methodology. Although this paper deals with Francis turbine, most of its content should also be true for other turbine types.

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