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On-site measurements of the dynamic behaviour of Pelton turbines in the context of predictive maintenance

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Abstract. The operating modes of pumped storage power plants, such as that of the Forces Motrices Hongrin-Léman (FMHL) in Switzerland, have drastically changed over the past decades due to the emergence of new renewable energies. The number of starts and stops experienced by machines increased significantly leading to broader fatigue cycles on the different parts of the machine. Therefore, the development of predictive maintenance tools is paramount to increase the availability and reinforce operational safety of the power plant. In this context, vibration measurements were performed on a 60 MW Pelton turbine of one of the ternary units of the FMHL power plant during dynamic and steady state operations. Non intrusive instrumentation has been deployed including accelerometers on the bearing. Comparing the ramp-up and ramp-down of the Pelton turbine, a hysteresis of the vibration level for a similar power has been observed. A reduction of the vibration levels when an additional injector is engaged during the ramp-up is observed. This reduction correlates strongly with the load reduction on the buckets when the total flow rate is distributed over more injectors, leading to a smaller flow rate per injector.

1. Introduction

For a few decades, emerging new renewable energies have been influencing strongly the electrical grid and have been modifying the way hydroelectric power plants are operated [1]. Thanks to their flexibility, hydraulic turbines are perfectly suited to compensate grid fluctuations. An increased flexibility implies more starts and stops experienced by the turbines which lead to broader fatigue cycles [2] [3]. For Pelton turbines, maximal stresses occur during start-up phases [4][5][6] when the runner starts to rotate and the jet impinges the standstill buckets. Repeated cyclic loading might lead to fatigue cracks in the region of stress concentration. These cracks are very insidious as they could remain unnoticed for a while and suddenly propagate leading in the worst cases to bucket detachments.

The Forces Motrices Hongrin-Léman (FMHL) pumped-storage (PSP) power plant in Switzerland

is composed of four horizontal ternary groups with 60 MW Pelton turbines and 60 MW five-stage centrifugal pumps [7]. The power plant was commissioned in 1971, and the original Pelton runners are still in use. However, fatigue cracks appeared earlier than expected on one of the runners, which forced operators to reduce the time between maintenance for safety reasons. Nowadays, offline non-destructive testing remain the only way to detect fatigue cracks before they propagate and lead to serious damages. These expensive methods cause downtime during the entire procedure, resulting in a loss of revenue for the power plant owner. Therefore, the development of predictive maintenance tools is paramount to increase the turbine availability and to reinforce operational safety.
The four ternary units at FMHL PSP will undergo a complete replacement in the coming years by replacing the Pelton runners. As the unit 3 of the FMHL PSP will be refurbished first, a vibration fingerprint was conducted in September 2021 on this group to evaluate the dynamic behaviour of the machine operating with the original runners. In this study, the main results of this vibration fingerprint are presented. The injectors opening and closing sequences are discussed in section 3, and their influences on the vibration level measured are presented in section 4.

2. Methods

2.1. Unit characteristics

Each ternary unit at the FMHL PSP is composed of 2 horizontal Pelton runners, each supplied by two injectors. Measurements have been performed on unit 3 of the FMHL PSP, the characteristics of which are described in Table 1. Both Pelton runners and the generator are connected to the main shaft. The five-stage pump shaft is decoupled from the main shaft during operations in turbine mode. The main shaft is supported by three hydrostatic bearings. In Figure 1, bearings are named from left to right: "1EX" for exciter bearing, "2TU" for turbine bearing, and "3AL" for alternator bearing.

Table 1. Main characteristics of one Pelton turbine at the FMHL PSP.

Maximal head	$[m]$	878
Unit discharge	$[m^3/s]$	8
Output	$[MW]$	60
Rotational speed	$[rpm]$	600
No. of runners	$[-]$	2
No. of injectors	$[-]$	4
No. of buckets per runner	$[-]$	22
Angle α for injectors 1 and 3	$[deg]$	55
Angle β for injectors 2 and 4	$[deg]$	25

2.2. Instrumentation

Two types of permanent sensors on the bearings allow for real-time vibration monitoring of the unit. Proximeters record the shaft position relative to the bearings in x and y directions. Absolut vibrations in x direction are measured by one velocimeter placed on each bearing, they are labelled "PA" in Figure 1. The acquisition frequency for the velocimeter was set to 2 kHz and their sensitivity is 50 $mV/mm/s$. Uni-axial accelerometers "ACC" were installed in x and y directions on the bearings of the turbine and on the bearing of the alternator. A triaxial accelerometer was placed on the old exciter bearing "1EX". However, the signal-to-noise

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ratio was found to be too low; thus, no analysis was performed with this latter accelerometer. Accelerometers have a sensitivity of 100 mV/g and their signals were recorded at an acquisition frequency of 12.8 kHz. The pipe between the unit valve and the injector number 1 was equipped with an ultrasonic flow-meter. The nozzle flow characteristics was reconstructed based on the injector positions provided by the plant's SCADA system. The hypothesis was made that the nozzle law is equivalent for the 4 injectors.

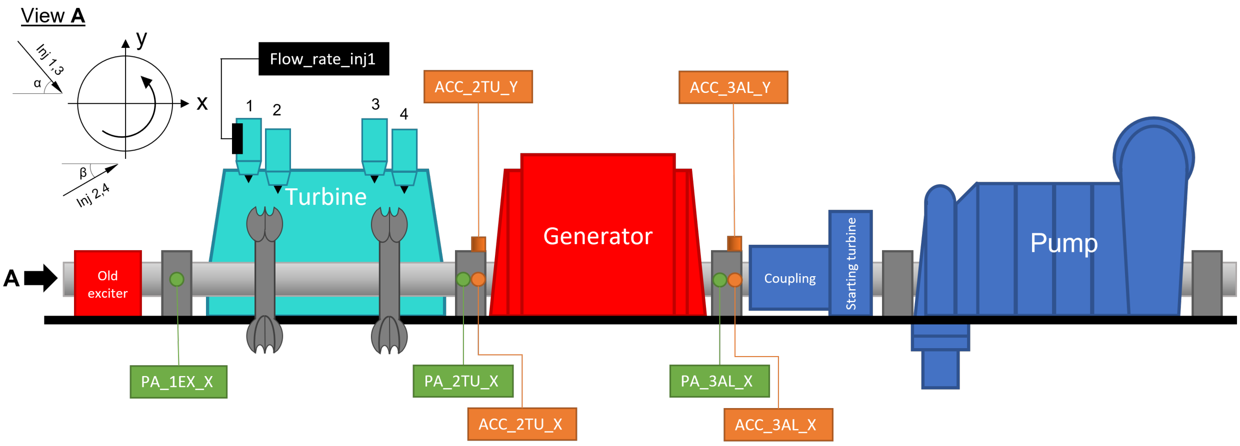


Figure 1. Schematic representation of a ternary unit at FMHL power plant. Permanent sensors are labelled in green, extra sensors are labelled in orange.

2.3. Operating programme

The turbine was manually operated according to the program in Figure 2. The first 10 minutes, the turbine was started and operated for 8 minutes at 3 MW which represents the minimal load. Then, the power was increased gradually and kept constant for 15 minutes steady state steps each 10 MW (10, 20, 30, 40, 50, 60). Next, the turbine was shut down following the standard procedure by decreasing the power from 60 to 0 MW. Once the shaft was at rest, the turbine was started again, but this time by increasing the power dynamically from 0 to 60 MW. Finally, 15 minutes steady state steps were performed in ramp-down mode each 10 MW (55, 45, 35, 25, 15, 5). This programme allows for comparisons between steady state and dynamic ramp-up and ramp-down. For both ramp-up and ramp-down phases the maximal power increasing-decreasing rate is ± 20 MW/min.

3. Injectors opening and closing sequences

Figure 3 displays the opening (a) and closing (b) sequences for dynamic ramp-up and ramp-down operations, respectively. The opening sequence is the following: injector 3, injector 4, injector 1, injector 2. The closing sequence is the opposite, meaning that injector 2 closes first. These sequences were implemented in 2010 during the refurbishment of unit 3. From the commissioning of the power plant in 1971 until 2010, the 4 injectors were operated simultaneously in the whole power range (0-60 MW). The aim of the new sequences is to optimise the efficiency of the turbine for small loads.

In Figure 3, coloured dots and triangles stand for injector positions during steady-state operations. During ramp-up operations, the injector positions for steady state operations are always slightly smaller than for dynamic operations. The opposite is observable during ramp-down where the steady state injector positions are always above the dynamic operations. These

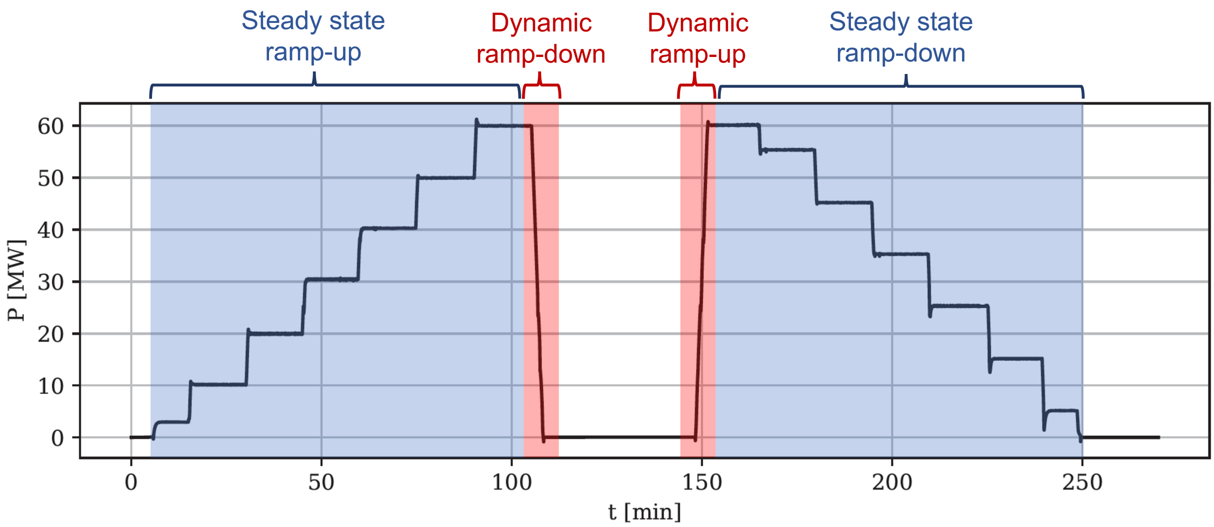


Figure 2. Operating programme during the measurements.

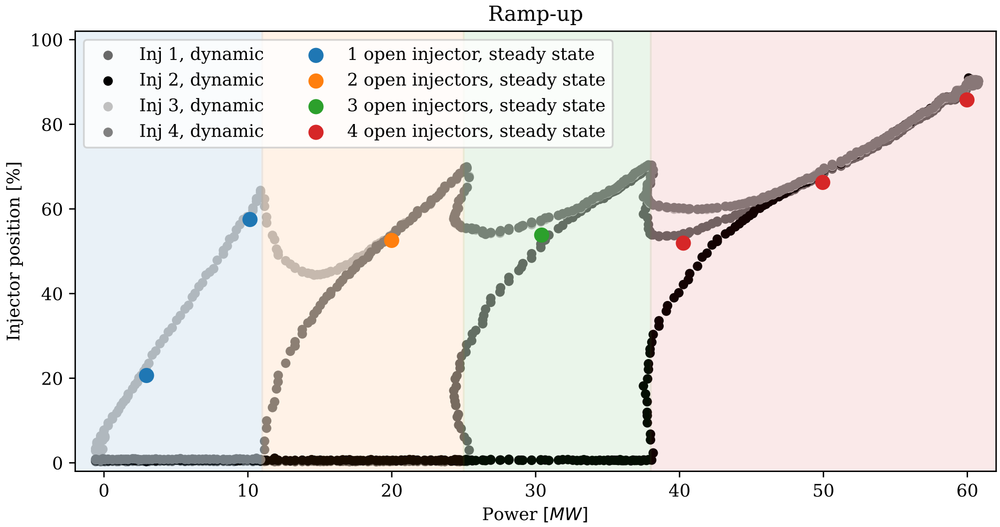
differences can be explained by two phenomena. The first one concerns the controller that regulates the injector positions following a power target. The actual power always lags behind the power target which explains the gap between the actual power and the injector position. Thus, during steady state operation, the power target matches the actual power, resulting in slightly smaller or greater injector positions during ramp-up and ramp-down operations, respectively. However, the greater gaps between steady state and dynamic operation observed in Figure 3a for powers above 25 MW and in Figure 3b for powers below 30 MW are due to a second phenomenon. During the closing of an injector, it still contributes to the power generated until its complete closure. Therefore, when one injector is either closing or opening, the positions of the remaining injectors do not correspond to a steady state operating point. These positions are greater during ramp-up, and smaller during ramp-down. In addition, the head also influences the injector positions for a given power. During this study, the head variation was small enough to exclude its influence on the injector positions.

In Figure 3 the background colours stand for the power ranges with one, two, three, and four injectors engaged. However, the power values at which injectors are opened or closed are different for ramp-up and ramp-down operations. For instance, during ramp-up operation, the injector no. 4 opens at 11 MW whereas during ramp-down operation, it closes at 6 MW. If the injector no. 4 would open and close at a fix power (e.g. 11 MW), when operating the turbine at 11 MW, slight variations in the generated power would induce the repeated opening and closing of the injector. Thus, this hysteresis is intentionally introduced to avoid repeating commutations of the injectors at a fixed power value. In Figure 4, the red bands display these hysteresis by highlighting power ranges where two injector configurations exist. In case of operation inside one of these bands, the number of injectors engaged is path-dependent.

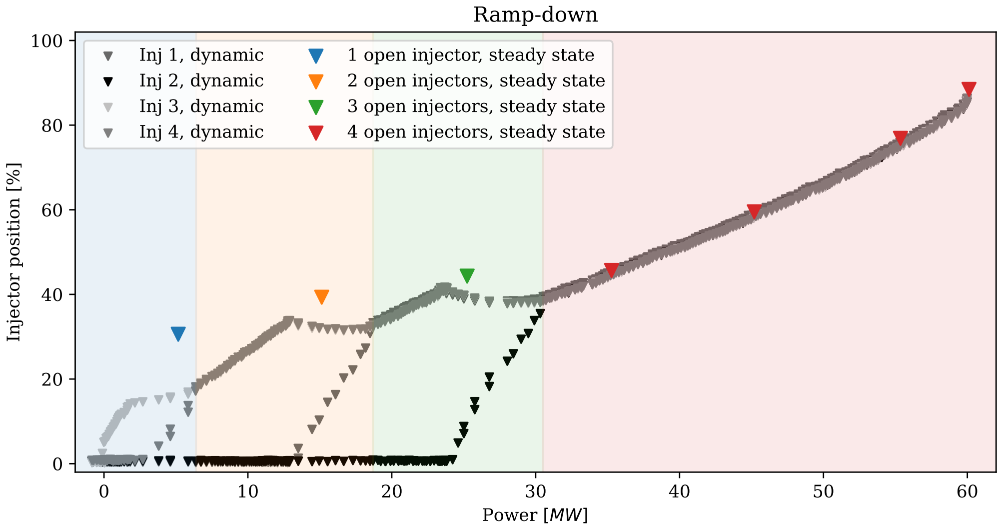
4. Vibration measurements

Figure 5 displays the comparison between steady state and dynamic operations for 2 velocimeters and 2 accelerometers. The RMS vibrations are normalised according to the maximal RMS vibration value during dynamic ramp-up.

In Figure 5b, reductions in the vibration intensities are observed during the opening of an



(a)



(b)

Figure 3. Injector opening sequence during dynamic and steady state power ramp-up (a), and ramp-down (b). Background colours stand for the number of injectors opened for a given power range (blue = 1, orange = 2, green = 3, and red = 4).

injector. These drops are only visible during dynamic ramp-up operations (coloured dots) and could be observed for the 3 injector openings, under powers of 11 MW, 25 MW, and 38 MW. In Figure 5d, however, a clear drop is only visible under a power of 25 MW during the transition from 2 to 3 injectors. These drops range from 10 % to 15 % of the maximal vibration intensity.

The main source of excitation for Pelton turbines is the periodic impingement of the jets on the buckets [8][9]. According to [10], for a theoretical bucket output angle β = 180°, the jet impact force on the buckets can be estimated according to Equation 1, where Q_c is the flow rate through the injector, ρ the density of water, C_{jet} the jet velocity, and the peripheral speed

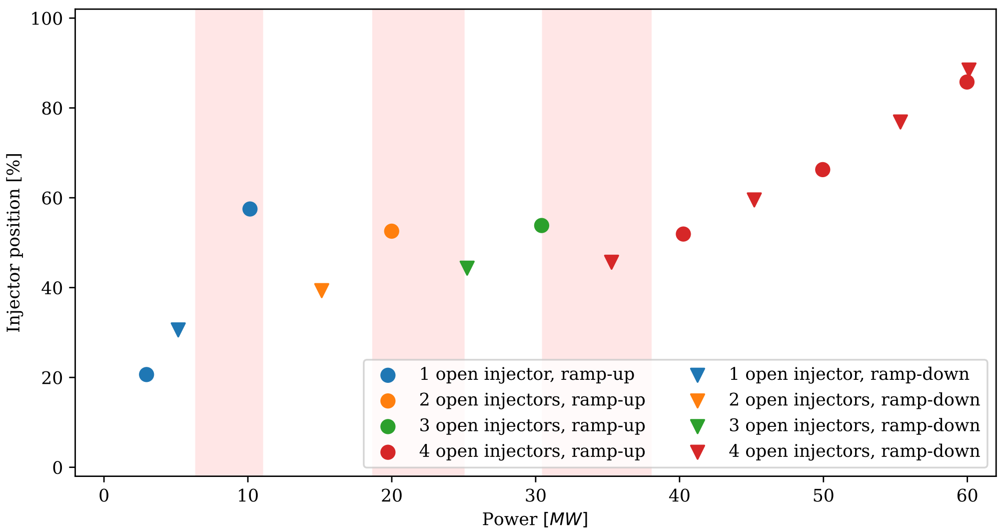


Figure 4. Injectors opening positions during steady state operations. The red bands display the power range where two injector configurations exist.

coefficient $k_m = 0.45 - 0.48$.

$$F_{bucket} = 2Q_c\rho C_{jet} \cdot (1 - k_m)^2 \tag{1}$$

The jet velocity C_{jet} is related to the net head according to $C_{jet} = \sqrt{2gH}$. Head variations due to losses in the waterway are assumed to be negligible on the jet velocity. Therefore, F_{bucket} is mainly driven by the flow rate Q_c, which is itself a function of the injector position according to the injector law (not provided here). According to Figure 6, the flow rate per injector Q_c drops while opening an injector to keep a constant total flow rate Q_{tot} through the turbine. Transitions are insured by the controller and are visible in Figure 3 in the transition regions. The drops in the vibration intensities observed in Figures 5b, and 5d are related to the flow rate reduction Q_c occurring when a new injector is open, and thus, related to the force reduction F_{bucket} acting on the buckets.

It is interesting to note that even though the resulting force produced by two opened injectors on the same runner is almost only oriented in the x direction, the influence of the flow rate per injector is also captured by the accelerometer "ACC_2TU_Y" sensor placed in y direction. Indeed, Figure 7 displays drops in the vibration intensities when opening an injector during dynamic ramp-up operations (coloured dots), mainly under powers of 25 MW and 38 MW. In contrast, these drops are less pronounced for the velocimeter "PA_2TU_X" (Fig. 5a) and almost not captured by the velocimeter "PA_3AL_X" (Fig. 5c). Velocimeters are recommended for low frequency vibration monitoring whereas accelerometers are suited for higher frequencies. The periodic excitation produced by the jets is dominant at the bucket passing frequency of 220 Hz (results not presented in this study). This frequency is calculated by multiplying the rotational frequency (10 rps) by the number of buckets (22). This relatively high excitation frequency might explain why velocimeters fail to capture the vibration-level drops during an injector opening. This hypothesis, however, still needs to be confirmed by further investigations.

Steady state operating points displayed by the black dots and triangles in Figure 5 also show a strong correlation between the flow rate per injector and the vibration level. Above 40 MW, ramp-up and ramp-down steady state points quasi overlap on the same curve. In this power range, the four injectors are open independently from the path followed. For lower powers, different injector configurations exist, vibration levels are thus dependent on the number of injectors engaged. Both dynamic and steady state curves are path dependent and reveal a shift in the vibration level between ramp-up and ramp-down operations below 40 MW.

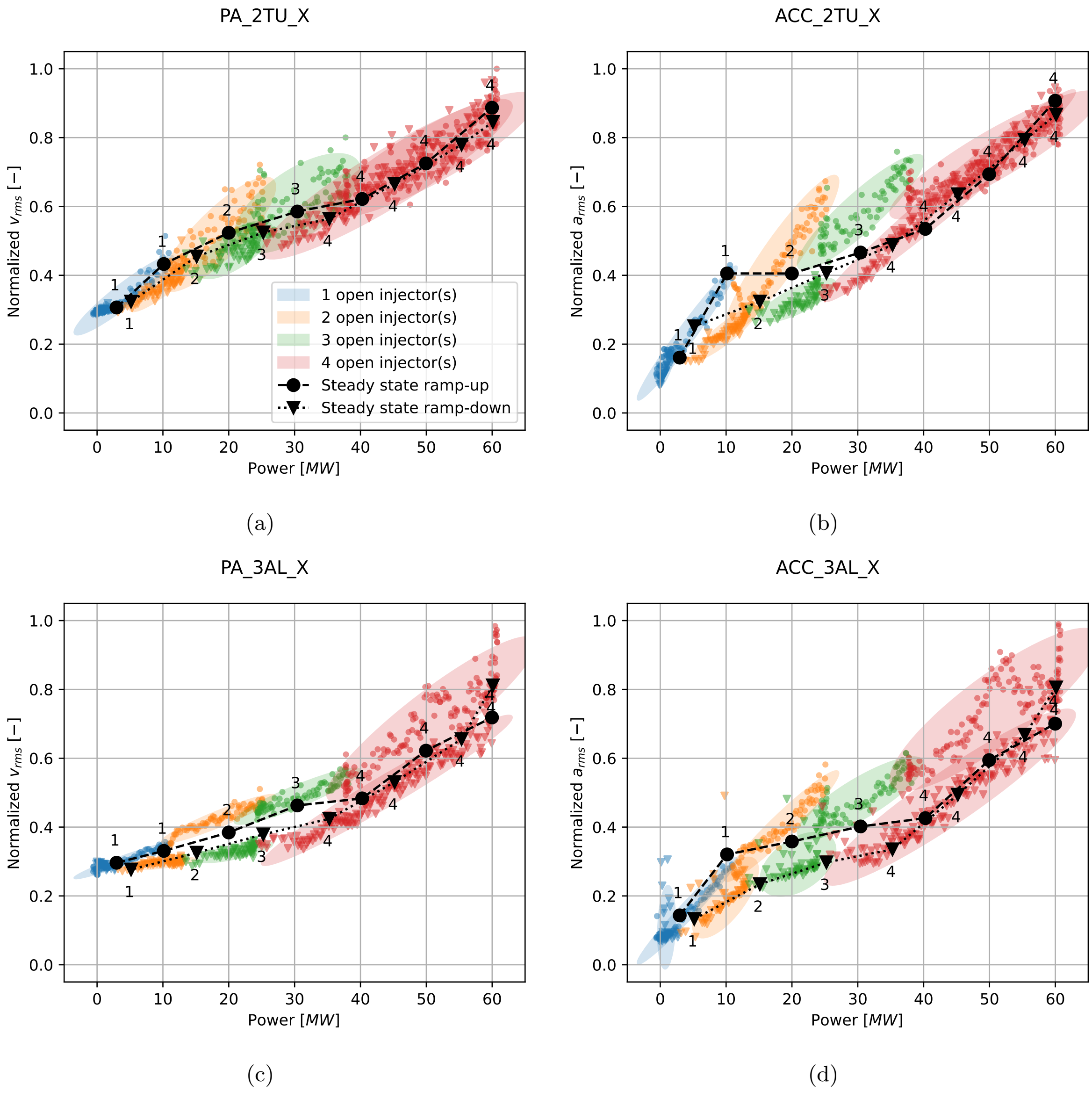


Figure 5. Normalised RMS velocity measured by velocimeters on the turbine bearing (a) and on the alternator bearing (c). Normalised RMS acceleration measured by accelerometers on the turbine bearing (b), and on the alternator bearing (d). The four sensors record vibrations in x direction (see Fig. 1). Coloured ellipses represent 2σ confidence interval for dynamic measurements during ramp-up (coloured dots) and ramp-down (coloured triangles). RMS normalised vibration for steady state operations are displayed by black dots (ramp-up) and black triangles (ramp-down) where numbers indicate the number of injector engaged.

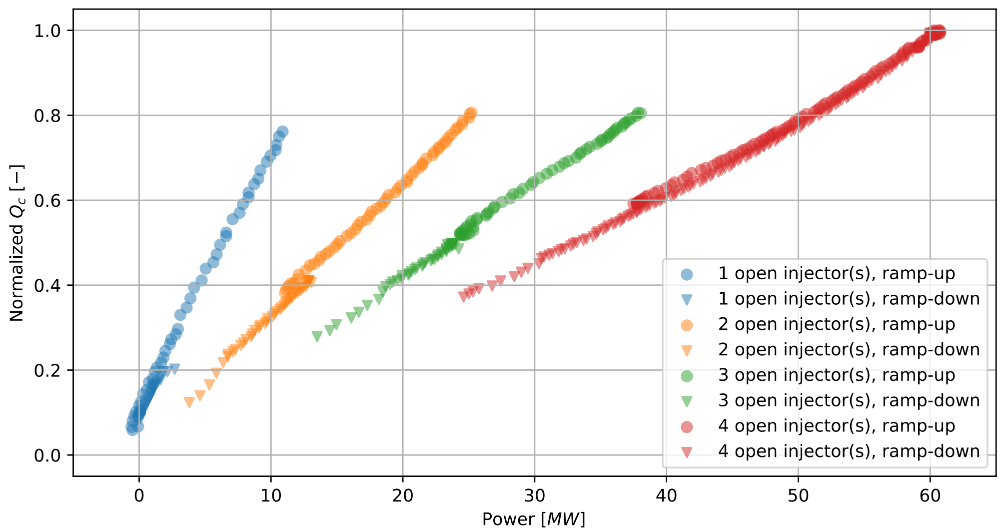


Figure 6. Normalised flow rate per injector Q_c during dynamic ramp-up and ramp-down operations.

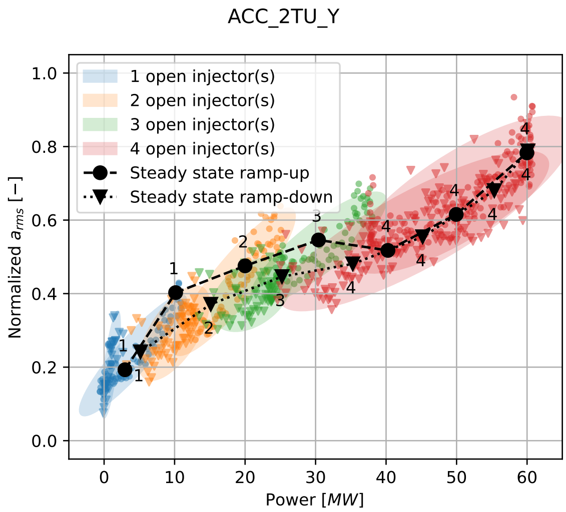


Figure 7. Normalised RMS acceleration measured by the accelerometer placed on the turbine bearing in y direction.

Stress experienced by the buckets are composed by the fluctuating stress produced by the jet and also by the constant centrifugal stress due to the bucket mass in rotation. For a given total flow rate Q_{tot}, and thus for a given power, F_{bucket} is smaller in the configuration with more injectors engaged. For the Pelton turbines at FMHL PSP, this is true for powers below 40 MW where different path-dependent injector configurations exist. The configuration which minimises the load on the bucket is the one with the highest number of injectors engaged. This configuration does not necessarily satisfy both the smallest load on the bucket and the highest efficiency. In addition, below 25 MW, and during ramp-up operation, only one runner is supplied with water which might contribute to an accelerated fatigue of the runner material in comparison to the second runner. Nevertheless, the precise characterisation of the load reduction when choosing a configuration which maximises the number of injectors is not straightforward. Further analysis is necessary to characterise the real benefit of operating a Pelton turbine following fatigue minimising operating curves instead of targeting the best efficiency. Moreover, a similar analysis was investigated numerically in [5] for back-to-back startups. Strain measurement in the region of stress concentration could help determine the real influence of the flow rate per injector on the stress experienced by the buckets. Fatigue prediction models could then be applied to find the best trade-off between a better efficiency and a reduced loading of the bucket.

5. Conclusion

The influence of the injector opening and closing sequences on the vibration level of the Pelton turbines of the ternary unit 3 at FMHL PSP, operated according to a programme including dynamic and steady state ramp-up and ramp-down operations, has been evaluated in this study. The injector opening sequence presents a hysteresis between ramp-up and ramp-down operations. This hysteresis is indeed necessary to avoid repeating commutation of the injector when operating the turbine at a fix point corresponding to a transition in the number of injectors engaged. The number of injectors engaged for a given operating point depends on the power path followed to reach the operating point.

Accelerometers placed on the turbine bearing and on the alternator bearing capture drops in the vibration levels during ramp-up operations when a new injector is engaged. According to [10], the periodic force experienced by a bucket due to the impingement of the jet is proportional to the flow rate of the jet. These drops are then strongly correlated with a flow rate reduction per injector. Permanent velocimeters monitoring the vibration of the unit fail, however, to capture these drops accurately.

Below 40 MW, more than one injector configuration might exist for a given steady state operating point. This is due to the hysteresis in the injector engaging sequence which is path-dependent. The configuration with the highest number of injectors engaged tend to reduce the load on the buckets by splitting the total flow rate over more injectors. This configuration, however, is not necessarily the best operating condition in terms of efficiency.

Finally, further analysis will be necessary to assess the benefit of operating a Pelton turbine to minimise the load on the bucket by maximising the number of injectors engaged. Strain measurements could help to quantify the actual stress reduction when opting for a configuration which minimises the buckets loading.

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