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To cite this article: G Moraga *et al* 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1411** 012022

Diagnosis of the unstable behaviour of a Kaplan turbine before synchronizing to the grid

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Abstract. This work reports on a new Kaplan turbine that experienced an unstable behaviour during its start up. The unit experienced strong sound and vibration in that phase. To identify the origin of this unstable behaviour, a set of sensors were installed within the turbine. Subsequently, tests were performed to determine the response of the different sensors during the acceleration of the machine to the speed no load stage. Following a thorough analysis of the results, the problem was identified as the air admission openings of the head cover and their distribution. To address this issue, a reconfiguration of these openings was implemented and their performance was evaluated. Following this rearrangement, the vibrations in the head cover were significantly reduced and the unit was successfully commissioned.

1. Introduction

Under the context of the current environmental challenges, the importance of renewable energies has been increasing each year. Solar and wind energies, in particular, have been gaining significant popularity due to their cost-effectiveness and quicker construction times, in comparison to hydropower [1]. However, the intermittent nature of these energy sources leads to an inconsistent supply of energy, which represents a problem for the electrical grid stability. Because of this, during the last years, hydropower has been gaining importance not only due to its renewable generation capacity but also due to its ability to regulate the output to the electrical grid to satisfy the power demand. The increasing reliance on hydropower for grid stability has spurred the refurbishment of existing power plants and the construction of new ones all over the world.

Each hydraulic turbine is designed to operate at a specific head and flow rate, which makes every turbine a unique machine. Consequently, it is common for new problems to emerge during their commissioning. Often, the causes of these problems need to be identified, and the issues must be rectified on-site. Moreover, due to issues encountered during the design, manufacturing, assembly stages, or the operational condition itself, unexpected problems [2–4] can occur during the commissioning tests. One of the most harmful operations during the commissioning is the operation at speed no load [5]. This operating condition is characterized by a stochastic flow with the presence of vortex structures, provoked by the swirling flow resulting from small guide vanes opening [6]. These structures, primarily originating in the vaneless space in the distributor, can induce strong pressure pulsations, potentially exciting critical components of the unit [7,8].

In this work, a Kaplan turbine experiencing high vibration and noise amplitudes is reported. These strong vibrations were detected within the head cover zone during the commissioning tests, while the machine was accelerating to speed no load. The origin of this problem was investigated and determined. A solution to mitigate this problem was proposed, tested and validated.

2. Case of study

2.1. Powerplant

In 2022, a 45 MW hydraulic powerplant was refurbished in Angola in an electrical isolated area. This powerplant is composed by three 15 MW Kaplan units with a head of approximately 19 m. Each turbine runner has 5 blades and a diameter of 3.3 m.

2.2. Air admission system

Due to the slight instability of the electrical grid where this power plant is located, frequent load rejections can be triggered. Consequently, hazardous effects, such as the separation of water columns, may occur due to the sub-pressure reached in the inlet of the draft tube after a sudden closure of the distributor. To mitigate this effect, the head cover of each unit has been equipped with an air admission system. This system allows atmospheric air to enter the runner chamber through several openings in the head cover (see figure 1a). These openings are connected to check valves, which allow the passage of atmospheric air once a certain level of sub-pressure is detected (see figure 1b,c).

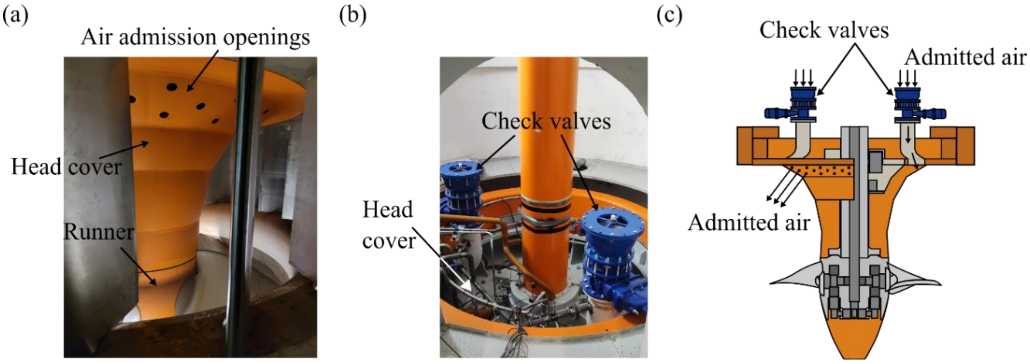

Figure 1. Air admission system: (a) Air admission openings, (b) Check valves, (c) Air admission system.

2.3. Problems detected

After the first unit was successfully assembled and installed, it was prepared for commissioning. During the acceleration to the nominal rotation speed, a loud noise was perceived within the head cover zone when the machine reached approximately 50% of the nominal speed. At the same time, strong vibrations were detected in the head cover, with the most intense vibrations occurring in the axial direction (perpendicular to the plane of the head cover). Previous studies, based on experimental modal analyses, suggested that the excitation of the runner blades could be the origin of the problem. However, despite modifications to these components and testing of various combinations of blades and guide vane openings, the vibration levels remained high. Consequently, the machine could not be commissioned satisfactorily for several months.

3. Tests on the unit

3.1. Instruments used

To carry out this investigation, a comprehensive array of sensors was installed throughout the unit. For the sake of brevity, only the most relevant sensors for this work are summarized below and schematically shown in figure 2.

During the conducted tests, operation signals, such as rotating speed, were acquired from the turbine built-in Supervisory Control and Data Acquisition (SCADA) system. To record all the signals from the installed sensors and the SCADA, a data acquisition system Brüel & Kjær Type 3053-B-120 was utilized and set to record an acquisition frequency of 4096 Hz. While, accelerometers Kistler 8752A50, with a sensitivity of 10 mV(ms^{-2})$^{-1}$, were used to measure the vibrations in the machine (ATT and A11 in figure 2a), a microphone PCB 426B03, with a sensitivity of 12.5 mVPa^{-1} was used to study the loud noise perceived (MICRO in figure 2a). To analyse the pressure pulsations on the machine, pressure measurements were also conducted. A submersible pressure sensor Keller PAA-23SY series, with an operative range from 0 to 20 bar (absolute) and a sensitivity of 400 mVbar^{-1}, was used to measure the pressure in the head cover (PTT in figure 2a). While, a submersible pressure sensor Keller PAA-23SY series, with an operative range from 0 to 2 bar (absolute) and sensitivity of 5 Vbar^{-1} was employed to measure the pressure in the draft tube (PDT in figure 2a). Because of the access to the draft tube was provided through a small chamber between the spiral chamber and the draft tube, the installation of the sensor PDT was not a trivial task. Firstly, to install this sensor, the machine had to be emptied. Next, PDT was installed in the access from the small chamber to the draft tube (as shown in figure 2b). The cable of the sensor was threaded through the access to the chamber prior to sealing it. After, this wiring was attached to the wall of the spiral chamber and guided towards an access to the head cover zone in one the stay vane (see figure 2c). From this access the wire was conducted to the zone where ATT and A11 were installed (schematically shown in figure 2a).

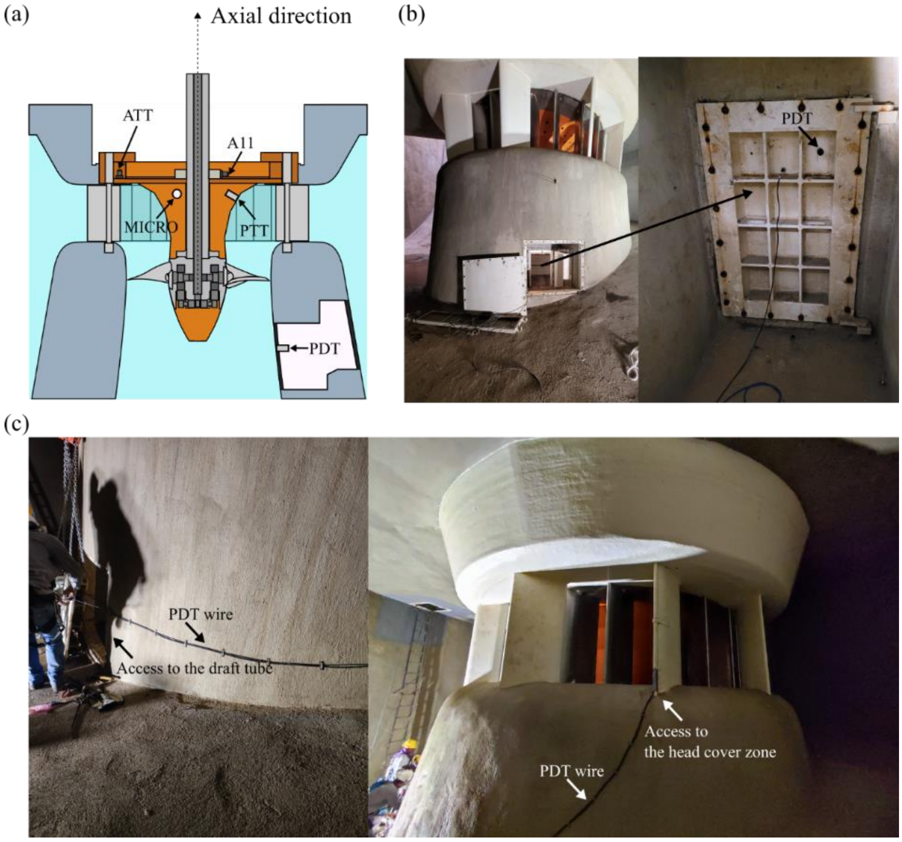

Figure 2. (a) Location of the sensors in within the unit: ATT: Accelerometer in the head cover structure, A11: Accelerometer in the turbine bearing in radial direction, MICRO: Microphone in the head cover, PTT: Pressure sensor in the head cover and PDT: Pressure sensor in the draft tube. (b) Pressure sensor installed in the draft tube. (c) Wiring of PDT towards the head cover zone.

3.2. Operation test

In order to determine the origin of the strong vibrations, an operation test was performed. Once the machine was filled with water and prepared to start-up, the runner was setup to a fixed opening position and the guide vanes of the unit were slowly opened, accelerating the machine from a standstill condition to its nominal speed. Several combinations of runner – guide vanes openings were tested.

4. Results

As previously explained, the unit was tested and measured during its acceleration to nominal rotating speed (NRS). As shown in figure 3a, the unit was slowly accelerated from standstill to NRS to identify when the issue arises. When the machine reached approximately 15% of the NRS, a slight increase in the vibrations amplitude was detected by the accelerometer on the head cover (see figure 3b). After this and just before the machine reached 50% of the NRS, the vibrations amplitude drastically increased (see figure 3b,c), with the highest measurements taken by the accelerometer installed in the head cover structure (ATT in figure 2). Although these vibration amplitudes decreased when the unit was reaching the NRS (after second 700 in figure 3), they remained excessive (according to ISO 20816–5:2018) while the machine was operating at speed no load. This behaviour persisted across all tested configurations for runner and guide vanes openings.

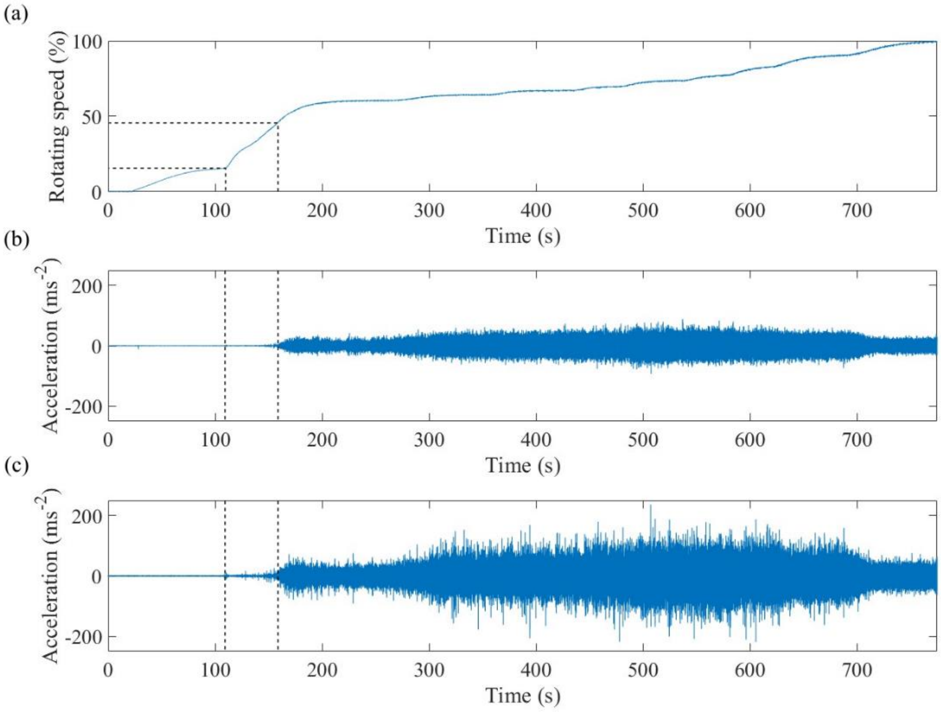

Figure 3: Acceleration to nominal speed: (a) Rotating speed as a percentage of the NRS, (b) Response of A11 (RMS = 1.716 ms^{-2}) and (c) Response of ATT (RMS = 2.624 ms^{-2}). All the RMS values were calculated at NRS.

The sound pressure and pressure pulsations were also analysed. Similar to the response of ATT, the noise detected from the head cover slightly increased after the machine reached 15% of the NRS (see Figure 4b). This increasing was also detected by the pressure sensor in the head cover and the draft tube (see figure 4c,d). As shown before with the installed accelerometers, the amplitude of the noise and the pressure pulsations significantly increased when the unit reached 50% of the NRS. Regarding to the pressure pulsations, it can be seen that the highest amplitudes were measured in the head cover (see figure 4c).

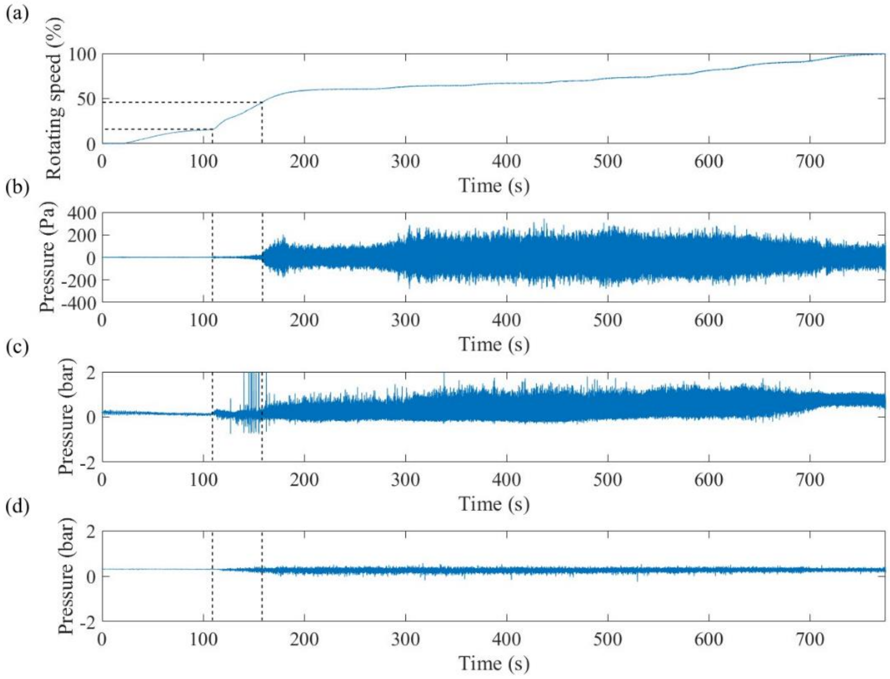

Figure 4: Acceleration to nominal speed: (a) Rotating speed as a percentage of the NRS, (b) Response of MICRO (RMS = 32.912 Pa), (c) Response of PTT (RMS = 38.886 mbar), and (d) Response of PDT (RMS = 28.221 mbar). All the RMS values were calculated at NRS.

According to the results from the measurements carried out, the most intense pressure pulsations occurred in the head cover of the unit. In consequence, the highest vibration amplitudes were detected in this structure by the sensor ATT. Although pressure pulsations, resulting from fluid-structures instabilities and self-excited vibrations in the runner, could induce strong vibrations in the head cover, these pulsations should be detected by the sensor PDT, whose response was not significantly high. Moreover, it is possible to see in figure 3 and figure 4, that the general response of the sensors installed in the head cover (PTT, MICRO, ATT and A11) is stronger than the one installed in the draft tube (PDT). This suggests that the origin of the problem could be located in the head cover.

Considering that the strong sound and vibrations could be caused by the excitation of the head cover of the unit and given that these issues consistently arose at specific moments during the acceleration to NRS, it was concluded that the problem could be a fluid-structure interaction instability between flow and the head cover structure. Therefore, modifications on the head cover had to be done so solve these strong vibrations problems. These modifications are explained in the following section.

5. Implemented solution

5.1. Modification of the air admission system

After analysing the head cover structure, shown in figure 5a, it was concluded that the passage of the water through the air admission openings in the head cover could have been exciting its structure, leading to the excessive vibrations detected by the sensors installed on it. However, as the air admission system is of paramount importance to prevent the water column separation and its dangerous rejoint, the head cover was modified in order to mitigate the fluid-structure interaction between flow and the head cover, without eliminating of the aeration openings. For this, the original openings (schematically shown in figure 5b) were sealed and replaced with five new openings (schematically shown in figure 5c). These new air admissions were nearly ten times the size of the original ones. Additionally, the orientation of these openings was altered from the original design, with the new ones positioned to face the axial direction. Lastly, the air admission valve was calibrated to open only when a certain level of sub-pressure is reached.

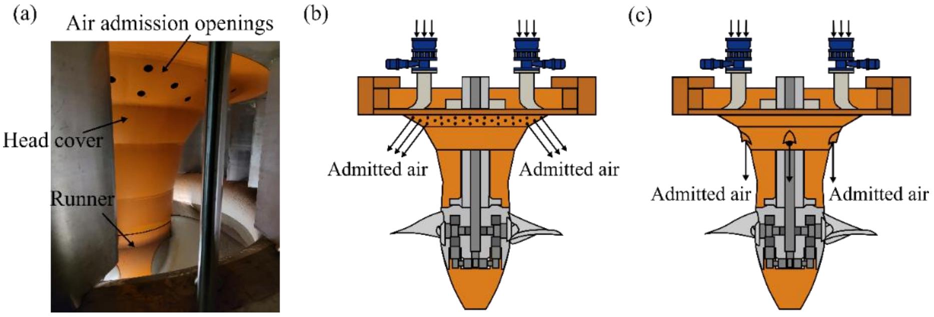

Figure 5: Air admission openings: (a) Picture of the original head cover of the unit, (b) Scheme of the original head cover and the passage of the air admitted and (c) Scheme of the modified head cover and the passage of the air admitted.

Once the head cover of the unit was modified, a new start-up test was conducted and new measurements were taken. The unit was accelerated from standstill to its nominal rotating speed (as shown in figure 6a). In this case, start-up was faster than the one shown in the past section (see figure 6b). It can be observed that following the modification of the head cover, the pressure pulsations on this structure decreased significantly (see figure 6c,d). In consequence, the strong vibrations and loud noise were also substantially reduced, decreasing up to 90.28% and 95.03%, respectively. (see figure 6e-h).

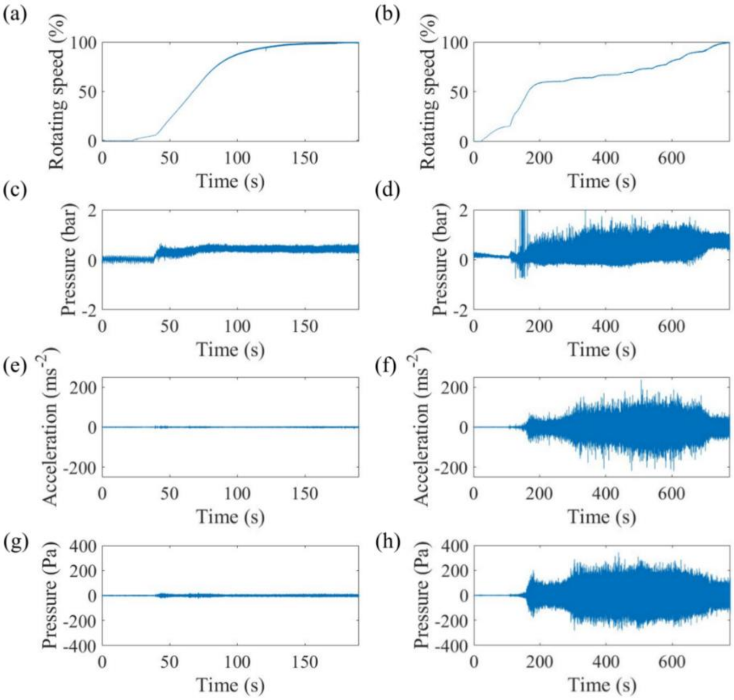

Figure 6: Start-up test after modifications of the head cover. Rotating speed as a percentage of the NRS: (a) After modifications and (b) Before modifications. Response of PTT at NRS: (c) After modifications (RMS = 51.937 mbar) and (d) Before modifications (RMS = 38.886 mbar). Response of ATT at NRS: (e) After modifications (RMS = 0.255 ms^{-2}) and (f) Before modifications (RMS = 2.624 ms^{-2}). Response of MICRO at NRS: (g) After modifications (RMS = 1.634 Pa) and (h) Before modifications (RMS = 32.912 Pa).

5.2. Performance of the air admission system after the modifications

To evaluate the performance of the new air admission system (AAS) configuration, three situations were compared by analysing the response of the pressure sensor installed in the head cover (PTT):

- The first situation involved an emergency stop triggered by the SCADA due to excessive vibration levels in the head cover (see figure 7a). This event took place during the initial commissioning tests prior to any modifications to the structure. At this point, the machine was operating at NRS, with no-load, and the AAS was not activated. The approximate flow rate in this situation before the closing of the distributor was approximately 5.69 m^3s^{-1}.
- The second situation was another emergency stop that occurred during a failed attempt to connect the machine to the electrical grid (see figure 7b). This event occurred during the commissioning tests after modifications were made to the head cover. In this case, the machine was operating at NRS, with no-load, but with the AAS activated. The approximate flow rate in this situation before the closing of the distributor was approximately 2.68 m^3s^{-1}.
- The third situation was a programmed load rejection during the final commissioning tests (see figure 7c), to test the behaviour of the machine under these conditions. Here, the machine was operating at NRS, at maximum load, and with the AAS activated. The approximate flow rate in this situation before the closing of the distributor was approximately 81.25 m^3s^{-1}.

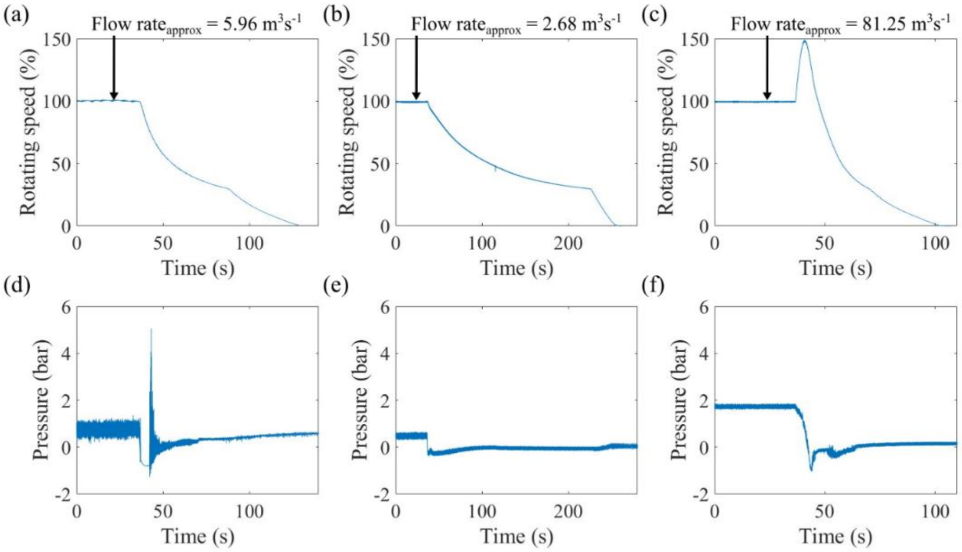

Figure 7: Variation of pressure after a sudden closing of the distributor (relative pressure). Rotating speed as a percentage of the NRS: (a) No load and AAS disabled, (b) No load and AAS enabled and (c) Maximum load, load rejection and AAS enabled Response of PTT: (d) No load and AAS disabled, (e) No load and AAS enabled and (f) Maximum load and AAS enabled.

Upon analysing the PTT sensor during the first situation (figure 7d) it was observed that the pressure in the head cover dropped nearly 1 bar (meaning close to the absolute 0) quickly after the distributor suddenly closed. This was followed by an abrupt pressure increase of nearly 6 bar after a few seconds, possibly due to the restoration of the column of water inside of the unit. In the second situation (figure 7e), a quick pressure drop of nearly 0.8 bar was detected after the distributor suddenly closed. However, with the AAS activated, a pressure increase of nearly 0.3 bar was detected in the head cover after a couple of seconds. It is important to note that the activation of the air admission system is the only difference between the first and second situations.

In the third situation (figure 7e), a pressure drop of 2.7 bar was measured by the PTT sensor. This was followed by a sudden increase of 0.7 bar in the head cover after a second. It is noteworthy that before the load rejection, the machine was operating at maximum load, and therefore, a much higher flow rate was circulating through the machine. Consequently, without the AAS activated, the pressure drop and increase due to the water column restoration could be much higher in magnitude. However, because the air admission system was activated, the pressure increase after the drop was 8.5 times smaller than that in the first situation (see figure 7d). It also can be noticed that the static pressure prior to closing the distributor (see figure 7f) is significantly higher than in the other two situations (figure 7d,e). This difference can be attributed to the energy losses experienced by the flow when it passes through the distributor and runner chamber.

From this analysis, it can be observed that the air admission system plays a crucial role in mitigating the hazardous effects of water column separation and rejoining. Moreover, the modifications implemented in the head cover of the unit, not only mitigated the issue of intense vibrations but also effectively prevented significant pressure fluctuations following a sudden closure of the distributor, whether due to an emergency stop or a load rejection.

Following the tests and analyses conducted on the head cover, the machine was successfully commissioned and commenced its commercial operation without any significant issues.

6. Conclusions

In this work, a case of a Kaplan turbine unit experiencing an unstable behaviour is reported. During its commissioning tests, the unit exhibited excessive amplitude vibrations and noise in the acceleration to the nominal speed, which persisted under no-load conditions.

To diagnose and rectify this issue, a comprehensive array of sensors was installed throughout the unit, and operational tests were conducted. Thanks to the tests performed, it was determined that the source of the high amplitude vibrations was the head cover itself and not the runner blades as initially suspected. Upon analysing this structure, it was determined that the flow passage through the air admission system installed in the head cover could have been exciting the head cover, thereby provoking the high amplitude vibrations detected by the sensors in this structure.

The openings of the air admission system within the head cover were subsequently reconfigured, resulting in a drastic decrease in the amplitude of the head cover vibrations. Finally, the new configuration of the air admission system was tested during subsequent commissioning tests, successfully mitigating the significant pressure fluctuations resulting from emergency stops and load rejections.

Acknowledgments

Greco Moraga received funding from the National Agency for Research and Development (ANID) / Scholarship Program / DOCTORADO BECAS CHILE/2020 – 72210054 for his PhD scholarship. Alexandre Presas and David Valentin want to acknowledge the Serra Hunter Program of Generalitat de Catalunya. The authors want to express their gratitude to all ELECNOR staff in the analysed powerplant, which showed their highest commitment with the test performed there.

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