Vibration Monitoring of Hydropower Systems

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ABSTRACT

Excessive vibration in hydropower systems is often an indication of a failure of equipment that can lead to fatigue issues or complete shutdown of a system. Localizing the source of the vibration and identifying the cause is crucial to evaluating the structural integrity and ensuring its continued operation. At a hydropower plant in Arkansas, substantial vibration was being generated within one of the hydropower units when brought offline, when no flow should be occurring through the unit. On site personnel suspected that the vibrations were coming from the wicket gates, whose opening and closing controlled the flow of water through the unit. Observations lead to the belief that leakage-flow induced vibrations were being generated by a permanent gap between adjacent gates in the closed state. Within the hydropower unit, the wicket gates are fully submerged underwater, and visual inspection of the body of each gate requires the unit to be completely drained of water. Thus, a short-term monitoring program was designed to use accelerometers to measure the magnitude of vibration coming from the wicket gates using only the gate stems accessible along the outer ring of the unit. The source of the vibration was localized by investigating the energy of vibration produced from each wicket gate and where the vibration initiated as the gates transitioned from open to closed. The results of this study were verified during a later dewatering of the unit where gaps between adjacent gate pairs were measured. The results of this effort provide a method for localizing excessive vibration in hydropower units in need of maintenance.

INTRODUCTION

Condition monitoring is a process for monitoring the state of a machine or equipment in an effort to apply fault detection and predictive maintenance. This process may include many techniques such as acoustic, vibration, or thermal monitoring and provides a method of non-destructive testing (NDT) that allows for the identification of changes that may be indicative of developing damage in a system [1]. Without the ability to conduct predictive maintenance, maintenance will be forced to occur once a malfunction has caused the system to shut down, and thus condition monitoring is important for making informed decision throughout the service life of a system. The occurrence of vibrations at the component level can be an indicator of problems arising in a system. Vibration monitoring can be completed in several ways such as impact testing, where a component of the system is excited and the response is measured, or by measuring vibrations under the normal operational loading of the system. For hydropower systems in particular, monitoring and maintenance are imperative to their uninhibited function. The prevention of system failures can prevent loss of generation capacity or other structural issues. Hydropower systems support millions of end users; therefore, their upkeep is of the upmost importance and unplanned disruptive events are to be avoided.

Excessive vibration leading to failure is a major concern as parts begin to wear from accumulated fatigue damage, and may also cause human comfort issues [2, 3, 4, 5]. Nässelqvist, et al. [3] discussed how fatigue limits and the relationship between vibration and allowable loading on mechanical parts can be used to set alarm levels. Several studies have been conducted where vibration monitoring was used to ascertain the condition of a hydropower system. Most of the research available in literature is applicable to rotating components of hydropower systems, however there are studies that address non-rotating systems such as dams and spillways. Mateja, et al. [6] developed a long-term monitoring program for a concrete dam on the Sava River to measure the structural response under operational loads using laser Doppler vibrometers. A review of studies addressing flow-induced vibration of spillway gates was conducted by Ishii et al. [7]. For some spillway gates it was observed that significant vibration can be induced by water flowing under the bottom seal of the gate, which can lead to failure [6]. Although the available research is useful in developing approaches to identify vibration issues in operating hydropower units, it does not directly address the mechanisms of vibration in a non-operating hydropower unit. At the site examined in this current study, a short-term vibration monitoring program was executed when unexpected vibrations began occurring in one of the site's turbine units. The monitoring program involved taking vibration measurements under both operational loads and an offline state. This study aims to investigate the cause and location of vibration in a non-operating hydropower unit. A more detailed accounting of this study is available at [9].

BACKGROUND

The Ozark-Jetta Taylor Lock & Dam 12 is located in Ozark, Arkansas along the McClellan-Kerr Arkansas River Navigation System (MKARNS). On the powerhouse side, onsite personnel reported loud vibration being generated when one of the turbine units was brought offline. The powerhouse contains five 20 MW, slant axis turbines as depicted in Figure 1. Initial investigations conducted by the onsite personnel led to the belief that the vibration was originating from the unit's wicket gates. Each turbine consists of sixteen wicket gates oriented circumferentially around the penstock of the unit. Flow of water through the unit is controlled by the opening and closing of these wicket gates. Each wicket gate is 3.3 m tall and trapezoidal in shape with stems located at the top and bottom of the gate, as represented in Figure 2a. The bodies of the gates are partially hollow with internal stiffening ribs. The gate operating mechanism consists of the outer stems and an outer steel ring, which are connected using shear levers. The gates are opened and closed by rotating the outer ring, which rotates the stems and the wicket gates together in a coupled manner.

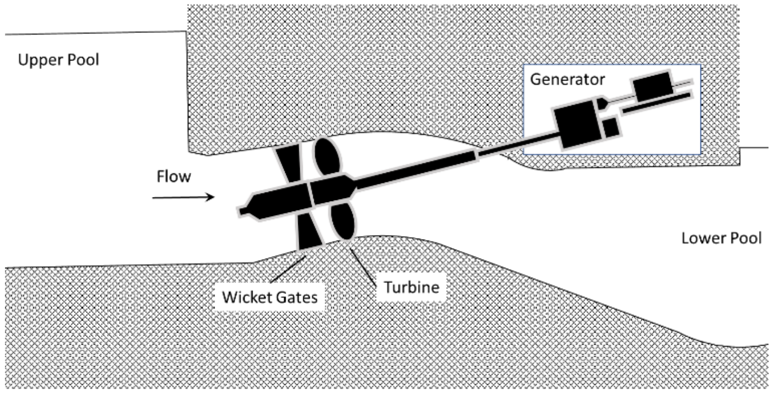

Figure 1. Turbine configuration

When fully opened, the gates are oriented parallel to the longitudinal axis of the penstock. When closed, they are nearly perpendicular to the longitudinal axis of the penstock, with a slight overlap between the edges of adjacent gates to create a seal. These positions, as shown in Figures 2b and 2c, are the extremities of a turbine's operation. The amount of closure between the gates controls the rate at which water flows through the hydropower unit, and thus the amount of power being generated. When the gates are opens and water is allowed to flow through the unit, turning the turbine and moving machinery, it is well documented and expected that vibrations will occur under operational loads. The issue that arose at this site is that vibrations occur when the wicket gates were closed, and no flow was passing through the unit. The vibration which occurred exclusively when the gates were closed was almost a humming sound, and was directly witnessed by the authors and onsite personnel. It was also witnessed during the operation and closing of a separate unit, that this same phenomenon occurs when debris becomes lodged between closing gates, preventing them from fully closing and properly sealing. In these instances, the gates are briefly opened and then closed to allow the debris to dislodge and pass through, ceasing the vibration. For the unit being investigated, this did not occur when the gates were cycled. This led to the belief that the vibration in the unit is caused by an excessively large gap between two adjacent wicket gates, resulting in water rushing through and exciting the gates. Because cycling the gates does not eliminate the vibration, it is expected that this permanent gap is due to damage, installation, or fabrication issues, resulting in leakage-flow induced vibrations.

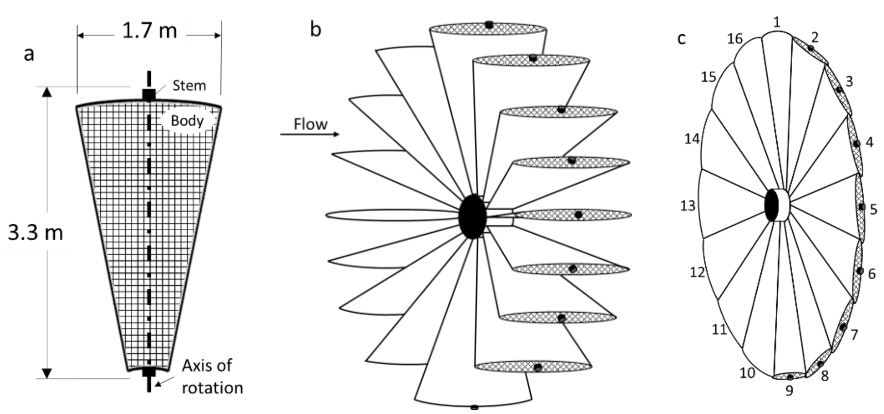

Figure 2. (a) Geometry of single wicket gate; (b) wicket gates in opened and closed (c) positions

LEAKAGE FLOW-INDUCED VIBRATION

In the context of this study, the term "leakage-flow" induced vibration is being used to broadly categorize the flow of fluid through a gap, not just for low velocity flows. The issue of leakage-flow induced vibration spans across industrial, hydraulic, and nuclear contexts in channel gates, valves, and other small openings [10]. Mulcahy [10] conducted a review of issues that arise in nuclear reactors due to leakage flow in valve systems and flow control gates and discussed methods to avoid the induced vibrations. Vortex shedding was determined to the common cause of these vibrations. Vortex shedding refers to the phenomenon where periodic flow develops as flow separation occurs around a bluff, and often flexible, body subjected to cross flow [10, 11, 12]. Vortex shedding is not limited to unstable shear layers and alternating vortices developing on either side of the body and has been seen to also occur for a single shear layer, such as a small gap under lift gates [14]. When a body is flexible, the existence of vortex shedding leads to the possibility of "lock-in" occurring, where the vortex-shedding frequency synchronizes with the natural frequency of the body [12, 13, 14]. When the shedding is due to non-linear fluid-structure interactions "lock-in" at the natural frequency of the body the activation of super-harmonic and sub-harmonic responses becomes evident [12, 13]. This synchronization has been studied in many contexts [12, 15].

In the context of this study, confirmation of whether vibration is present due to an excessive gap between adjacent wicket gates is determined by investigating the shedding frequency, under the assumption that vortex shedding is occurring. Experimentally, when the velocity at which the fluid is flowing through the gap is inaccessible and unknown, the system vibration information can be used to diagnose flow-induced vibrations. This method of diagnosis is common in industrial and nuclear contexts [12, 16]. For this current study, confirmation of vortex shedding caused by an excessive gap is completed by comparing the modal properties of a wicket gate extracted from a numerical model to the frequency content identified by a short-term monitoring program.

NUMERICAL MODEL

The modal properties of a single wicket gates in a closed position were investigated using a finite element model. The model was created in ABAQUS/Standard using as-built drawings provided by onsite personnel. Fabrication errors, material uncertainty, degradation over time, and damage from debris, etc., all contribute to changes in the condition of the gate between the physical gate and a numerical model; however, that is beyond the scope of this study.

To emulate a fully submerged gate with water rushing passed, an added mass component was incorporated into the model through the material density parameter [9, 17]. More detailed information on the development of the numerical model is available in [9]. An eigenvalue analysis was performed on the static gate system using the built-in Abaqus linear perturbation step and Lanzos Eigensolver to calculate and extract the frequencies of the system in the closed position.

The finite element model was built using solid geometry in three separate parts and tied together. The lower wicket stem, upper wicket stem, and the main wicket gate body containing stiffeners were assembled as shown in Fig. 3 and meshed with mostly quadratic tetrahedral elements and some quadratic wedge elements. The total number of elements in the model is 44605. The outer ring of the gate operating mechanism forcibly holds the gates in the closed position, therefore the boundary conditions applied across the entire surface of each stem restrains all degrees of freedom to simulate the gate being held in the closed position. Simulations were run to consider added mass in the torsional direction to extract the fundamental torsional frequency and in the weak axis bending direction to extract the fundamental flexural frequency. The first torsional mode was found to be approximately f_{1t} = 14.18 Hz, while the first flexural mode as shown in Figure 3b, was found to be approximately f_{1f} = 56.042 Hz.

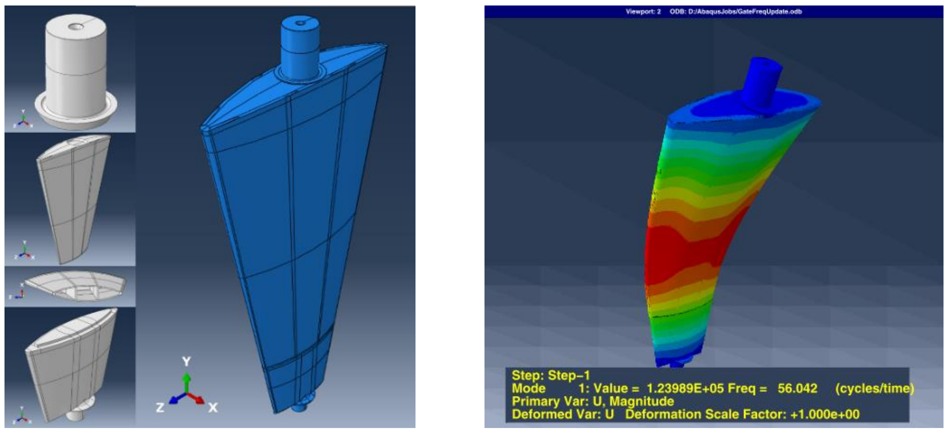

Figure 3. (a) Wicket gate model parts and assembled geometry; (b) first flexural mode

SHORT TERM MONITORING PROGRAM

As measurements of the flow within the penstock of the unit were inaccessible, vibration measurements were taken using accessible stems along the outer ring of the wicket gates. Accelerations were measured both longitudinally and radially to the penstock using two accelerometers per stem. Vibrations at each gate for each unit were measured three times for a duration of one minute. Details regarding the equipment and software utilized and the filtering applied to the collected data is available in [9].

Two units were selected to participate in the monitoring program. The first, referred to as Unit A, is the unit where significant vibration was noticeable, and the second, Unit B, was a separate unit where no significant vibration was noticeable. Due to the size of the units and limits in the number of accelerometers and cable length, measurements for the top and bottom halves of the units were conducted separately. The gates for each unit are numbered clockwise as shown in Figure 2c.

The vibration measurements are normalized by subtracting the mean from each signal and further filtered by applying a digital Butterworth high-pass filter with a cutoff frequency of 0.5 Hz. The frequency content was inspected using the power spectral density (PSD), $S_{xx}(w)$. Details on the calculation of the PSD can be found in literature on random vibration and digital signal processing, such as [18]. Parseval's theorem, or Rayleigh's energy theorem, equates the sum of the square of the magnitudes of a signal with the sum or integral of the square of its transform [19, 20].

Therefore, the arithmetic mean of the energy content is obtained by taking the root-mean-square of the area under the PSD, formally

$$G_{\text{rms}} = \sqrt{\int_{-\infty}^{\infty} S_{xx}(\omega)\, d\omega} \tag{1}$$

In addition to inspecting the energy content for each gate, the frequency vs time relationship was investigated using a Short-term Fourier transform (STFT) as the gates transitioned from opened to closed. The goal of this was to inspect how vibration propagated through the unit by pinpointing when and at which gate the harmonic vibration began. This was completed using the built-in STFT function in the SciPy library of Python [21]. More details on STFT are available in literature [22].

RESULTS AND DISCUSSION

The PSD for each gate at each unit were averaged in the frequency domain. The average PSD plots for the gates in Units A and B with the highest magnitude of vibration while offline are shown in Figure 4a and 4b respectively. The figures are shown in log-scale to aid in visualizing the order of magnitude of each gate's response. While the vibration is similar in both units, in that there are peaks at similar frequencies, the response in Unit A is two to three orders of magnitude higher. Note, as the vibration from Unit A were noticeable throughout the entire facility, it may even be the case that the vibrations measured at Unit B were actually generated from Unit A, but this cannot be conclusively determined. The PSD showed distinct frequency content at 57 Hz and harmonics of 57 Hz. This is close to the 56.042 Hz calculated for the first flexural mode by the numerical model, with only a difference of 1.7%. This difference can be attributed to uncertainties in boundary conditions, simplifications in the gate's geometry and connectivity, and the true condition of the gate. These results indicate that vortex-induced vibration of a gate is locking-in with the fundamental flexural frequency of the gate and activating super-harmonics due to the non-linear nature of the fluid-structure interaction [12, 13]. The G_{rms} values for each gate are calculated as (1). The vibration experienced in Unit A is orders of magnitude higher than that of Unit B. For the gates for which the results are shown in Figure 4, the G_{rms} is 0.2767 for Unit A and 0.0772 for Unit B. In addition, the maximum G_{rms} values in Unit A were found at gates 10, 11, and 12.

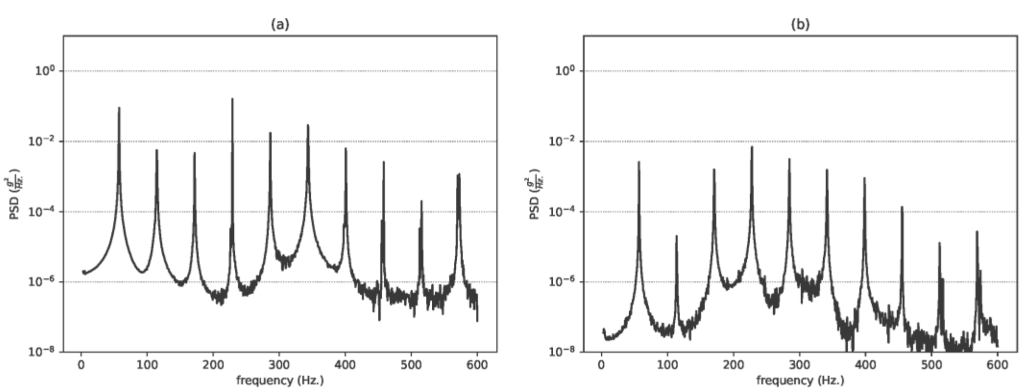

Figure 4. PSD of longitudinal vibration for each gate of (a) Unit A and (b) Unit B

To examine the frequency content as the gates transition from opened to closed, an STFT was completed for both Units A and B. The results of the STFT are shown as a heat-map in Figure 5, where the y-axis represents the frequency, x-axis represents the time during gate closing, and the color represents the magnitude of vibration at a particular frequency. In each of these cases, the gates close at approximately *t*=18s. For Unit A, clear harmonic vibrations become present after the gates reached the closed position. That behavior was not seen in Unit B. This supports the observation that the vibration is only occurring when the gates are closed for this specific unit. Because the gates are connected through the outer ring, it is expected that the vibration propagates from a single set of adjacent gates to the rest of the unit. Closer inspection of the frequency content as the gates close is used to identify the gate at which the harmonics begin. Gates 10, 11, and 12 were found to be the first where peaks at the fundamental frequency and super-harmonics of the fundamental frequency began to appear before it spread to the rest of the unit.

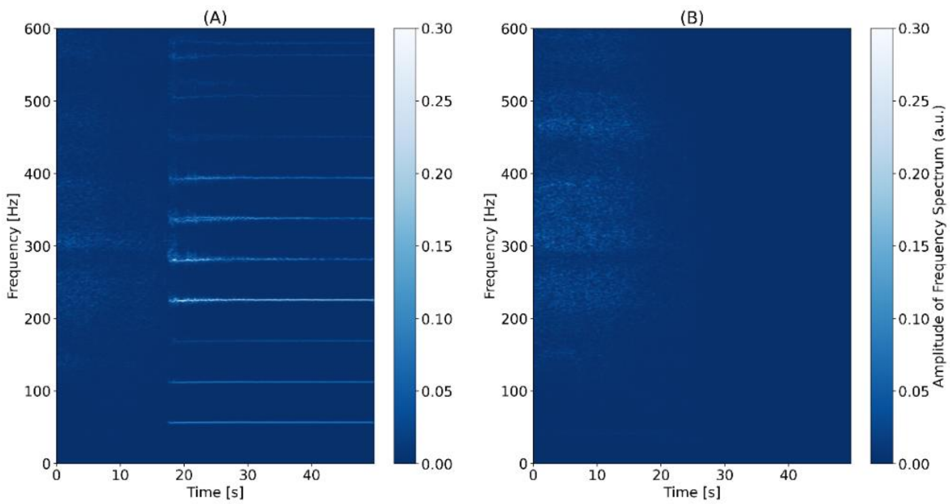

Figure 5. STFT of representative gates during closing for (a) Unit A and (b) Unit B

CONCLUSIONS

The evidence provided by the short-term monitoring program suggested that the large gap would most likely be found between gates 10 and 1 or 11 and 12. A later traditional visual inspection was performed on the wicket gates of Unit A, verifying these results. The gaps measured between gates 10 and 11 were indeed larger than anywhere else on the unit and double the allowable design gap. Thus, the results of this effort provide a method for condition monitoring to localize excessive vibration in hydropower units in need of maintenance. Examining the frequency content of the hydropower unit to measure the magnitudes of vibration and where they began led to the diagnosis of flow-induced vibrations. Although this study employed a short term-monitoring program, future investigations into hydropower design could expand upon this method to a longer-term monitoring program to detect faults as they develop or investigate the gap sizes and flow parameters that lead to lock-in harmonics.

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