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Frequencies of Nappe Vibration for Free-overfall Structures

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ABSTRACT

Under relatively low-head discharges, the occurrence of nappe oscillation, otherwise known as nappe vibration, may be observed on hydraulic structures with a free overfall, such as weirs, crest gates and fountains. This phenomenon, which has been early identified as undesirable and potentially dangerous on gates, is characterized by oscillations in the thin flow nappe cascading downstream of the crest. In addition, these oscillations produce a significant level of noise and acoustic pressure waves that increase the environmental and societal impacts of the structure. A review of the scientific literature shows a lack of consensus regarding the causes and source of the oscillations development. In this context of relatively poor understanding of the dominant processes, a detailed investigation has been undertaken to identify and quantify the nappe vibration mechanism. The research is being performed with a prototype-scale linear weir located at the Engineering Hydraulics laboratory of the University of Liège. The study employs high-speed cameras and audio equipment to characterize the nappe vibration. This paper presents first characteristics of the nappe vibrations gained from images and sound analysis, especially in terms of vibration frequency, for a quarter round and a half round weir crest. This study shows that frequencies measured by sound and image analyses are identical and depend on the crest shape, the fall height and the unit discharge.

Keywords: Spillway, nappe vibration, nappe oscillations, physical modelling, flow characterization

1. INTRODUCTION

When water falls in the form of thin sheet from a weir, a gate or a fountain, nappe vibration may occur (Casperson 1993; Naudascher and Rockwell 1994). These nappe vibrations are known to produce excessive noise that can be heard far away from the source and may cause problems such as vibrations in doors or windowpanes in buildings nearby such as reported in the case of Linville Land Harbor Dam rehabilitation (Crookston et al. 2014).

As regards to gates, the occurrence of nappe vibration has been attributed in part to the interaction between the flow and the air pocket between the gate and the nappe (Naudascher and Rockwell 1994). In fact, spoilers attached at the gate crest to divide the nappe and aerate the air pocket have proven to be an effective mitigation technique (Naudascher and Rockwell 1994; Sumi and Nakajima 1990; USBR 1964). However, vented nappe does not prevent the vibration occurrence in the case of free surface weir (Binnie 1972; Crookston et al. 2014; Crookston and Tullis 2012; Fulvey 1980). Effective mitigation techniques have been proposed to prevent the development of nappe vibration on free surface weirs. Anderson (2014) and (“Investigation into spillway discharge noise at Avon Dam” 1980) reports the effectiveness of crest roughness modification. Lodomez et al. (2016) assesses and optimizes practical geometric countermeasures (crest modifications) which do not modify the weir hydraulic efficiency.

Several studies have been conducted on nappe vibration mechanism. Schwartz (1966) investigated the influence of boundary layer conditions. Squire (1953) attributes nappe instabilities to shear forces that occur at the interface between the falling water and air, in a Kelvin-Helmholtz mechanism (Helmholtz (1868)). Casperson (1996) studied oscillation occurring on curved crest while Chanson (1996) suggested a pressure discontinuity at the weir crest as the cause of the phenomenon, with an origin of the vibrations at the crest. Casperson (1993) investigated the feedback mechanism played by the confined air chamber behind the nappe. Following the nappe vibration problems experienced after the rehabilitation of the Linville Land Harbor Dam, new investigations have been undertaken recently at the Utah Water Research Laboratory (Utah State University) (Anderson 2014; Crookston et al. 2014). They suggest that the nappe instability most likely arises at the weir crest. Indeed, the horizontal bandings on the nappe created by the oscillations are observed directly after the
flow separation from the weir crest. These recent observations with some conflicting results from previous analysis confirm the complexity of the studied hydraulic mechanism.

The present experimental study has been initiated on large-scale models to come up with generic scientific conclusions as well as a deeper systematic analysis of scale effects. This paper provides an overview of the preliminary results regarding the characterization of the nappe vibration.

2. EXPERIMENTAL SETUP

Figure 1 shows the experimental apparatus used and installed at the Engineering Hydraulics laboratory of the University de Liège. The prototype-scale linear weir is an elevated box divided in two identical weirs with a 3.50-m long crest. The air cavity behind the nappe can be confined or vented to the atmosphere. Indeed the weir located on the left bank is confined between two lateral walls and a back wall, one lateral confinement wall being transparent (Plexiglas) and others black multiplex panels. The other model is vented except on the shared lateral side. The models are used independently by obstructing with multiplex panels the unwanted crest. The fall is adaptable with a maximum value of 3.00-m.

Two weir crest geometries have been tested, a quarter round crest (15-cm radius and 15-cm long flat element) and a half round crest (15-cm radius), which are modelled with typical prototype dimensions of reinforced concrete weir (Figure 2).

Water is supplied to the model by means of two pipes connected to two regulated pumps. Butterfly valves help in controlling very low discharges. Water enters the reservoir through perforated pipes parallel to the crest and located on the bottom of the reservoir. As illustrated in Figure 3, a baffle wall of synthetic membranes has been inserted in the reservoir to ensure uniform velocity conditions upstream of the crest. The discharge is measured
with an electromagnetic flow meter installed on the supply piping, with an accuracy of 0.5% FS. The maximum unit discharge is $7.22 \times 10^{-2}$ m²/s (250 l/s in the model).

![Image](image.png)

**Figure 3.** Upstream view of the facility: reservoir, water supply pipes and baffle wall upstream of the right side crest.

The first nappe vibration characterization has been achieved by means of a free-field microphone (MCE 212) with a frequency range between 6 Hz and 20 kHz placed in front of the falling nappe (2 m downstream of the crest and at 2 m high to avoid water projection). Based on acoustic measurements, audio spectra analysis, carried out by means of the SYMPHONIE software suite, provides the dominant sound frequencies and their associated intensity (Lodomez et al. 2016). A second mean of characterization is a high-speed video camera (Go-Pro Hero 4 - acquisition frequency of 240 Hz) to capture images of the falling water. Image analysis enables to quantify the nappe oscillation frequency by the detection of horizontal bands in the falling water, assuming that these horizontal bands arise from the lighting on the undulating surface. Indeed, the use of spotlights lighting up from downstream the falling nappe allow to visualize these bands on images shot from 2 m downstream of the crest.

In this paper, the characteristics of the nappe vibrations, especially of the phenomenon frequency gained from image and sound analysis, are presented and discussed for four model configurations with varied crest shape and fall height. The main parameters of these configurations are listed in Table 1.

<table>
<thead>
<tr>
<th>Configurations</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crest length (m)</td>
<td></td>
<td>3.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crest shape</td>
<td>Quarter round</td>
<td>Half round</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fall (m)</td>
<td>3.00</td>
<td>3.00</td>
<td>1.00</td>
<td>0.50</td>
</tr>
<tr>
<td>Discharge range (m²/s)</td>
<td>0.015-0.07</td>
<td></td>
<td>0.01-0.06</td>
<td></td>
</tr>
<tr>
<td>Confinement</td>
<td>Confined</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**3. RESULTS AND DISCUSSION**

**3.1. Sound analysis**

As already mentioned, the first quantitative results have been obtained by acoustic measurements. These measurements have been performed to characterize the flow rate range for which the nappe vibration phenomenon appears. For various flow rates between 0.01 m²/s and 0.07 m²/s, an audio recording of 4 minutes has been made and processed to highlight the dominant frequencies in the audio spectrum.

For a common range of unit discharges, audio spectra of sound recordings are illustrated in Figure 4 for the four configurations studied. They clearly show for configurations A and C a local frequency peak up to a unit discharge of 0.045 m²/s. For configuration D, the local peak is visible for unit discharge of 0.015 m²/s and 0.03
m²/s and disappears for higher discharges while for configuration B, no local frequency peak is visible in the discharge range.

In Figure 5 the maximum intensity of the spectrum and its corresponding frequency (illustrated in Figure 4 by red circles) are reported as a function of the unit discharge. If the frequency is a local frequency peak, this frequency may be considered as the frequency of nappe vibrations. Therefore, the detection of local frequency peak and the bell-shaped evolution of the maximum intensity with the discharge in Figure 5 allow defining the nappe vibration flow range.

For configuration A, it can be noticed that the frequency of vibrations varies between 30.75 Hz and 35.5 Hz, for unit discharges between 0.015 m²/s and 0.07 m²/s. For configuration B, no local peak being detected, for all unit discharge tested, the maximum sound level and it corresponding frequency are therefore meaningless regarding nappe vibration phenomenon. Indeed, nappe vibrations do not appear for this configuration. Sound measurements will be confirmed by the flow visualization. For configuration C, the nappe vibration can be detected between 0.015 m²/s and 0.045 m²/s when a local frequency peak exists. Indeed, in some periods of tests, despite a slight buzzing sound, no vibration was heard, while at other times the vibrations could be clearly heard and viewed. If vibrations exist, the frequency of the peak is however variable with the discharge. Between 0.015 m²/s and 0.03 m²/s, dominant frequency is between 44 Hz and 44.5 Hz although a frequency of 51 Hz has also been detected for 0.02 m²/s. For 0.04 m²/s and 0.045 m²/s dominant frequency is equal to 41.25 Hz. This value corresponds to the frequency of the maximum intensity of the spectrum when nappe slightly buzzes between 0.015 m²/s and 0.03 m²/s. This finding leads to the conclusion that the nappe may vibrate preferentially between 41.5 Hz and 44 Hz in the range of 0.015 m²/s to 0.045 m²/s. Finally, Configuration D shows vibrations for unit discharge between 0.01 m²/s and 0.04 m²/s. In this unit discharge range, there are three types of vibrations: a first one around 36.75 Hz between 0.01 m²/s and 0.02 m²/s, a second one around 40.75 Hz between 0.02 m²/s and 0.03 m²/s and a third one around 34.5 Hz between 0.03 m²/s and 0.04 m²/s.

Figure 4. Audio spectrum of sound recording for A, B, C and D configurations, unit discharge between 0.015 m²/s and 0.06 m²/s.
### 3.2. Image analysis

Horizontal bands are the visible characteristics of the nappe oscillation phenomenon. For various flow rates and all model configurations, flow visualization has been conducted. Figure 6 shows the images obtained for the configuration A and B. For the quarter round crest, horizontal bands are clearly visible for unit discharges lower than 0.06 m²/s, which is in agreement with sound measurements. In fact, the flow visualization shows nappe vibrations for the same flow ranges as those derived from the sound analysis. In contrast, for the configuration B no horizontal band is visible except for 0.015 m²/s. This is consistent with sound measurements as a dominant frequency peak could only be identified in configuration B for low unit discharge. However, in that configuration the nappe is impacting the back wall. For higher discharge, nappe breaks up. This creates small aerated nappes, which do not vibrate. In Configuration C and D with smaller chutes (1.00-m and 0.50-m, respectively), horizontal bands can be detected on the whole crest width (Figure 7(a)) or by zone, depending of the lighting (Figure 7(b)).
Figure 6. Nappe vibration visualization for (a) 0.015 m²/s, (b) 0.03 m²/s, (c) 0.045 m²/s and (d) 0.06 m²/s for the configuration A on the left column and the configuration B on the right column.

Figure 7. Nappe vibration visualization for (a) 0.01 m²/s - Configuration C and (b) 0.02 m²/s - Configuration D

Assuming that the horizontal bands are due to the lighting on the undulating surface, the frequency of the horizontal bands has been determined by the extraction of information carried by a fixed set of pixels on a succession of images. The method is conceptually sketched in Figure 8. The undulating nappe surface, represented at three successive time steps, shows horizontal bands (lit or unlit bands) that move according to the flow direction. Then, for a fixed image frame, a chosen line of pixel carries information which varies depending on whether the pixels are on the saturated zone of the oscillation or not. This information is translated on each pixel of the line into a numerical value between 0 and 255 (images encoded in 8 bits). Then, the vibration frequency is calculated by means a Fast Fourier Transform of the fluctuation of this mean value of the line of pixels. The image analysis on 100 images (recorded at 240 Hz) is illustrated for the configuration D and a unit discharge of 0.02 m²/s in Figure 9. This figure illustrates (1) the chosen line of pixel, (2) the mean value of this line and (3) the FFT of the fluctuation of this mean value. Repetitive bands are clearly visible even if for the instantaneous image (Figure 7(b)) these bands are hard to see. Moreover, this pattern corresponds to an oscillating mean value of the pixel line. And, the dominant frequency is 36 Hz, corresponding to 15 bands passing through 100 images recorded every 1/240 second.
Figure 8. Conceptual representation of image analysis.

Figure 9. Image analysis on 100 images for Configuration D, a unit discharge of 0.02 m²/s.

The resolution of the image frequency calculation depends on the ratio between the acquisition frequency and the number of images frames. For an acquisition frequency of 240 Hz, a minimum of 480 frames have to be used to ensure a resolution of 0.5 Hz. For configuration A, C and D, the image analysis has been applied to unit discharges for which horizontal stripes can be observed. Indeed, for configuration B and a unit discharge of 0.03 m²/s and for configuration D and a unit discharge of 0.05 m²/s, the image analysis respectively in Figure 10 and Figure 11 provides no information regarding the nappe vibration phenomenon. Potential peaks are very low amplitudes and represent the noise of the signal. The number of chosen pixels lines (100 pixels per line) is at least 3 for each set of images. The number of sets of analyzed images is between 3 and 5 per unit discharge. The results are shown in Figure 12 and compared to relevant dominant frequencies detected by sound measurements. The frequencies derived from image analysis are identical to those resulting from sound measurements and do not depend on the considered pixels and images sets, excepted for configuration C, unit discharge of 0.01m²/s. The vibrations for the Configuration C do not appear systematically. Image analysis is thus reducing to few unit discharges. However, the derived frequency corresponds to the sound frequency measured at the same time.

As a consequence of this finding, it appears that the noise is linked to the oscillations in the falling nappe but, it cannot be explained by the impact of the nappe on the ground. Indeed assuming that the cause of noise is due to the impact, the sound frequency should be twice the visual frequency since the impact varies between two opposite particle of the cyclical nappe waves. Finally, the various behaviors observed for the 4 configurations suggest that the vibrations depend on the crest shape, the fall height and the unit discharge.
Figure 10. Image analysis on 480 images for Configuration B, a unit discharge of 0.03 m²/s.

Figure 11. Image analysis on 480 images for Configuration D, a unit discharge of 0.045 m²/s.

Figure 12. Results of sound and image analysis in terms of frequencies.
4. CONCLUSIONS

The research conducted on a prototype-scale linear weir model enables to describe the nappe vibration phenomenon, especially in terms of frequencies, by means of image and sound analysis. The main result is the obvious link between the frequency of the sound and the frequency of horizontal stripes in the thin flow nappe. For a prototype-scale linear weir with a 3.46-m long crest, a 3.04-m high chute and a quarter round crest, these frequencies are in the range of 31 Hz to 37 Hz. In contrast, for a vibrating half round crest configuration and a limited fall, the dominant frequencies vary with the unit discharge, in the range of 34.5 Hz to 44.5 Hz.

The tests made on half round crest clearly show that this type of crest shape is less likely to induce nappe vibrations. A possible explanation could be the variability of the detachment point of the nappe along the crest length which disrupts the oscillations alignment. The study is still ongoing with additional tests to determine potential parameters that characterize the initiation of nappe vibration.

5. REFERENCES


