Application of the Rossiter model for predicting the frequency of vortex shedding and surface oscillations in rectangular shallow reservoirs

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Abstract

Shallow reservoirs are ubiquitous in hydraulic engineering. Predicting the properties of the flow field in such reservoirs is instrumental to inform their design, operation, and maintenance. In previous research, oscillating jets were experimentally observed in rectangular shallow reservoirs, and we assess here the performance of a simple analytical model to predict the frequency of the dominating jet oscillation mode(s). The model couples the evaluation of the reservoir natural frequencies, with the Rossiter feedback loop formula. The analytical predictions are compared against experimental observations by reanalyzing an existing dataset. In many cases, the model predictions match the observations. Remaining discrepancies may result from experimental uncertainties, which could be reduced in future tailored laboratory tests, or from the dimensionless vortex celerity value used by the feedback loop model, which was not assessed experimentally.

Introduction

Shallow reservoirs are common hydraulic structures serving multiple purposes. They are used for stormwater management (Dufresne et al., 2009; Adamsson et al., 2003) and wastewater treatment (Izdori et al., 2019), as service reservoirs in water supply systems (Zhang et al., 2014), as constructed wetlands (Guzman et al., 2018; Persson & Wittgren, 2003), or as settling basins (Lakzian et al., 2020; Liu et al., 2013). Many of these reservoirs are rectangular or closely approximate this shape (Dufresne et al., 2009; Li & Sansalone, 2021; Liu et al., 2013; Tarpagkou & Pantokratoras, 2013; Zhang et al., 2014). Designing, operating, and maintaining these reservoirs are challenging. Minimizing sedimentation is crucial for storage facilities, while maximizing it is essential for sedimentation tanks. For example, efficient sediment trapping in stormwater reservoirs significantly affects the water quality (Guzman et al., 2018). Predicting sediment deposition patterns is essential for planning maintenance of storage facilities (Izdori et al., 2019).

Numerous experimental studies have examined the flow fields developing in rectangular shallow reservoirs, unveiling complex hydrodynamic processes despite the simple geometry (Adamsson et al., 2003; Camnasio et al., 2011; Dewals et al., 2008; Dufresne et al., 2009; Dufresne et al., 2010a; Peltier et al., 2014a). Depending on the reservoir aspect ratio and the hydraulic boundary conditions, distinct flow patterns were observed. For rectangular reservoirs with aligned central inlet and outlet channels, the flow field may involve a detached jet, a reattached jet, or a meandering jet (Miozzi & Romano, 2020; Peltier et al., 2014a, b). Sediment trapping and mixing efficiency vary significantly between these flow patterns (Adamsson et al., 2003; Camnasio et al., 2013; Dufresne et al., 2009, 2010b; Yan et al., 2020). Therefore, accurately predicting the flow field is crucial in engineering applications. Here, we investigate the potential to predict the oscillation frequency of a meandering jet in such a rectangular shallow reservoir with aligned central inflow and outflow channels.

The prediction of the peak oscillation frequency of a monophasic jet impinging a wall or the mixing layer at the interface between a semi-enclosed cavity and a mainstream has been performed for about 60 years (Table 1) using the so-called "feedback loop" formula, introduced by Rossiter (1964). This method is not predictive as several solutions exist for a given flow configuration (Heller et al., 1971). Therefore, Kegerise (1999) coupled the Rossiter formula with the calculation of the natural frequencies of the fluid domain to make the coupled model semi-predictive. Perrot-Minot et al. (2020) recently adapted this coupled model to an open-channel configuration. The authors were able to predict the peak oscillating frequency of the mixing-layer at the interface between a lateral isolated cavity and the adjacent mainstream. This frequency is equal to that of the vortex shedding along the mixing layer and that of the free-surface oscillations in the basin. For the feedback loop model to apply, two ingredients are required: a vortex street (along which vortices travel one after the other) and a downstream wall in the alignment of the vortex street where the vortices impinge. Figure 1 lists five geometrical configurations typically encountered in natural or man-made, riverine or urban water environments, for which the feedback loop formula could be applied to predict the vortex shedding frequency. Apart from the lateral cavity already considered by Perrot-Minot et al. (2020) (as sketched in Figure 1a), the other configurations are a reservoir (Figure 1b), a groyne field (Figure 1c), a sediment trap (Figure 1d) and the space between consecutive macro-roughness elements (Figure 1e). This list is certainly not exhaustive.

The aim of the present work is to assess the validity of the coupled model for the meandering jet at the center of a shallow reservoir, as shown in Figure 1b. Given the comprehensive dataset of meandering jet configurations provided by Peltier et al. (2014a), including measured oscillating frequencies, their observations were reanalyzed here and used as a reference for assessing the performance of the coupled model.

The paper is organized as follows. The first section presents the experimental procedure and the list of flow configurations. Both ingredients of the analytical model are then presented: first the calculation of the reservoir natural frequencies and then the Rossiter feedback loop formula. Finally, the predicted and measured frequencies are compared to assess the reliability of the model.

Data and methods

Laboratory experiments

Peltier et al. (2014a) performed laboratory experiments to characterize the flow field in a horizontal, smooth, rectangular shallow reservoir with one narrow inlet at the center of the upstream wall and one outlet of same width at the center of the downstream wall (Figure 2Figure 1: Examples of geometrical configurations in the riverine environment to which the present Rossiter model was applied by Perrot-Minot et al. (2020) (a), is applied in the present research (b) or could be applied in future works (c, d, e).

Figure). In a series of tests, the authors kept the reservoir width (L_y) and length (L_x) constant, with L_y = 0.985 m and L_x = 1 m. Two different inlet channel widths b were considered (b = 0.06 m and 0.08 m). The inlet discharge Q (adjusted by a valve in the pumping loop and measured with an electromagnetic flowmeter) and the water depth h (adjusted by a downstream tailgate) were independently varied to generate a large set of flow configurations. A meandering jet was observed in 26 configurations, which are considered herein. The corresponding hydraulic conditions, including the flow discharge Q, mean water depth h and corresponding Froude number F are detailed in Table 2.

The free-surface velocity field in the reservoir was measured by Peltier et al. (2014a) with a LSPIV method at a recording rate of 25 frames per second during more than 7 minutes, over an area of 1 m × 1 m with a final spatial resolution of 1 mm per pixel, e.g., 1000 pixels over the length and width of the reservoir. By applying a proper orthogonal decomposition of the velocity field, Peltier et al. (2014a) obtained the oscillation frequency of the most energetic modes of the impinging jet. The frequency of the first pair of modes is noted f_{vel} in Table 2, where subscript *vel* stands for "velocity measurements". These frequencies were previously compared against the predictions of a 2D shallow-water model by Peltier et al. (2015).

Besides, two water depth signals were recorded with ultrasonic sensors (uncertainty of 0.2 mm) located above the reservoir, near the inlet (US_1) and outlet (US_2) channels, as depicted in Figure 1: Examples of geometrical configurations in the riverine environment to which the present Rossiter model was applied by Perrot-Minot et al. (2020) (a), is applied in the present research (b) or could be applied in future works (c, d, e).

Figure . Each measurement lasted 122 seconds with a sampling frequency of 50 Hz, corresponding to 6100 sampling points. Detecting the peak values of the Welch spectra applied on these signals allowed us to estimate the peak frequency (noted f_{US}) of the free-surface oscillations. In some cases, the amplitude of free surface oscillations was too low to enable detecting a distinctive peak in the spectra and these cases are labelled "?" in Table 2. Conversely, in some configurations, two peaks were identified, indicating a bidirectional seiching (Engelen et al., 2020) and the two values are reported in Table 2.

As shown in Figure 3, the peak frequencies obtained by both methods match very well. This suggests that the same peak frequencies govern the oscillating jet and the free-surface oscillation, as described by Perrot-Minot et al. (2020) in an isolated lateral open-channel cavity.

Natural frequencies of the reservoirs

Following Rabinovitch (2009), the natural frequencies $f_{n_x n_y}$ of a rectangular open-channel basin are computed as:

$$f_{n_x n_y} = \frac{c_g}{2}\left[\left(\frac{n_x}{L_x}\right)^2 + \left(\frac{n_y}{L_y}\right)^2\right]^{\frac{1}{2}}, \tag{1}$$

where n_x and n_y are the number of nodes of the corresponding mode along, respectively, the x and y directions, L_x and L_y are the characteristic dimensions along each direction (Figure 2), and c_g is the celerity of the gravity waves computed as follows (Lamb, 1945):

$$c_g = \frac{g}{2\,\pi\, f}\tanh\left(\frac{2\,\pi\, h\, f}{c_g}\right), \tag{2}$$

with g the gravity acceleration.

Perrot-Minot et al. (2020) proposed to normalize the natural frequencies by the frequency f_{10} of the first streamwise oriented natural mode (with a single node along x axis). Eq. (1) thus reads:

$$\frac{f_{n_x n_y}}{f_{10}} = \left[n_x^2 + \left(\frac{n_y}{L_y/L_x}\right)^2\right]^{\frac{1}{2}}. \tag{3}$$

As L_x and L_y are kept constant in the present dataset (Table 2), the non-dimensional natural frequencies remain the same for all configurations. The first three values (with n_x and $n_y \leq 1$) are plotted in Figure 4 as a function of F; they appear as horizontal dash lines. Moreover, as in the present work the aspect ratio of the reservoir is close to unity (L_y / L_x = 0.985), $f_{n_x n_y} \approx f_{n_y n_x}$ so that $f_{01} \approx f_{10}$.

Feedback loop formula

As a vortex is shed at the upstream extremity of the jet, i.e., at the outlet of the inlet channel, it travels at a celerity noted c_v (where v stands for "vortex") along the jet towards the downstream wall. As the vortex impinges the wall, a gravity wave is generated and propagates with a celerity c_g (Eq. (2)) in all directions, including the direction back towards the jet upstream end where the gravity wave interacts with the vortex shedding process. The feedback loop formula is based on two assumptions: (i) that both processes have the same frequency and (ii) that both waves are in phase at the jet upstream and downstream ends. These assumptions are supported by the fact that the impinging jet generates the gravity wave at the downstream wall and that the gravity wave triggers the vortex shedding at the jet entrance. This implies that the time taken by a vortex to travel all along the jet from upstream to downstream (equal to L_x / c_v) added to the time taken by the gravity wave to travel back from the impinging wall to the jet entrance (equal to L_x / c_g) must be a multiple number (N) of periods of the feedback loop (or to the inverse of its frequency noted f_N), so that:

$$\frac{L_x}{c_v} + \frac{L_x}{c_g} = \frac{N}{f_N}, \quad (4)$$

As derived by Perrot-Minot et al. (2020), the mathematical expression of the feedback loop formula then reads:

$$f_N = \frac{N}{\frac{L_x}{c_v} + \frac{L_x}{c_g}}, \tag{5}$$

where f_N is the vortex shedding frequency, equal to the jet oscillating peak frequency and N a positive integer ($N = 1, 2, \ldots$). As for the natural frequencies (Eq. (3)), the feedback loop frequency can be normalized by the first streamwise natural frequency f_{10} as follows:

$$\frac{f_N}{f_{10}} = \frac{1}{\frac{c_g}{2L_x}} \frac{N}{\frac{L_x}{c_v} + \frac{L_x}{c_g}} = \frac{2N\mathsf{F}}{\frac{U}{c_v} + \mathsf{F}}, \tag{6}$$

where $U=Q/(bh)$ is the flow velocity in the inlet channel and $\mathsf{F} = U / c_g$ is the corresponding Froude number.

For a given configuration from Table 2, all parameters from Eq.(6) are known except for the vortex advection celerity c_v. Peltier et al. (2014a) did not measure c_v but empirical estimates of the ratio of c_v to U are available in the literature (Table 1). The ratio used herein is an average of the value reported for impinging jets (in air): $c_v / U = 0.70$. The solutions of Eq.(6) for $N \leq 4$ are plotted in Figure 4 as a function of F, where they appear as monotonically increasing curves.

Normalization of experimentally observed frequencies

Consistently with Eqs. (3) and (6), the measured peak frequencies are normalized by f_{10} and read:

$$\frac{f}{f_{10}} = \frac{f}{\frac{c_g}{2}\frac{1}{L_x}} = \frac{2fL}{c_g}. \tag{7}$$

The normalized peak frequencies measured with LSPIV (f_{vel} / f_{10}) and with the ultrasonic sensors (f_{US} / f_{10}) are finally added to Figure 4 as symbols.

Results

Identification of measured natural frequencies

Most measured peak frequencies (f_{vel} or f_{US}) in Figure 4 appear to be close to a natural frequency of the shallow reservoir (i.e., most symbols are located on, or relatively close to, a horizontal line). For the 26 configurations tested herein, 21 exhibit a peak frequency equal to f_{10} (along x axis) or f_{01} (along y axis), among which five also exhibit a f_{11} second peak frequency (and are thus in bidirectional seiching, with two dominating modes, see Engelen et al., 2020).

In the two configurations with the lowest Froude number ($\mathsf{F} < 0.2$), the measured frequency differs from any natural frequency. This is also the case for three other configurations with a larger Froude number but the currently available data (Peltier et al., 2014a), which were not collected for the purpose of the present study, does not enable pointing at a clear-cut explanation for this deviation.

Application of the coupled model

The coupled model (natural frequency and feedback loop formula) assumes that, for a given configuration, the peak frequency equals the frequency that best fits both a natural frequency and a solution of the feedback loop formula. Graphically, this coupling results in selecting the natural frequency located the closest to an intersection between a horizontal line (natural frequency) and a monotonically increasing curve corresponding to a specific N value (solution of the feedback loop formula).

For example, the coupled model predicts that for $\mathsf{F} = 0.2$, $f = f_{01}$ or $f = f_{10}$ and $N = 4$ as two intersections are observed for $\mathsf{F} \approx 0.2$: f_{01} and $N = 4$, as well as f_{10} and $N = 4$. The agreement of these predictions with the measured frequencies for the two flow configurations with $\mathsf{F} \approx 0.22$ (Figure 4) supports the validity of the coupled model. As another example, for $\mathsf{F} \approx 0.45$-0.47, three intersections are observed: $f = f_{11}$ and $N = 3$, as well as $f = f_{10}$ or f_{01} and $N = 2$. Figure 4 shows that for all configurations with $0.45 < \mathsf{F} < 0.5$ (except one), two peak frequencies were indeed measured, one about equal to f_{01} or f_{10}, and the second about equal to f_{11}.These data are also consistent with the predictions of the coupled model. The fair agreement between the predicted and measured peak frequencies suggests that the coupling between a natural mode and the feedback loop is indeed the physical mechanism controlling the jet meandering frequency.

In contrast, for $\mathsf{F} \approx 0.3$, three intersections can be observed at $f = f_{11}$ and $N = 4$, as well as at $f = f_{01}$ or f_{10} and $N = 3$. However, the peak frequency for the configuration with $\mathsf{F} = 0.31$ is measured at an intermediate value between these intersections. This discrepancy between the predicted and measured peak frequencies remains unclear from the currently available experimental data. Unfortunately, no ultrasonic sensor frequency peak (f_{US}) could be estimated for this configuration to assess the validity of the measured POD peak frequency (f_{vel}).

Besides, for $0.35 < \mathsf{F} < 0.4$, no intersection exists in Figure 4. However, the majority of frequencies measured within this range correspond to a natural frequency of the reservoir with a single node (f_{01} or f_{10}). Similarly, no intersection exists for $\mathsf{F} < 0.2$. For these configurations the measured peak frequency differs from any natural frequency, but they match a solution of the feedback loop Rossiter formula with $N = 1$ for $\mathsf{F} = 0.16$ and $N = 4$ for $\mathsf{F} = 0.18$.

Conclusion

The present work aimed at assessing the capacity of the model coupling the Rossiter feedback loop formula and the natural frequency of the reservoir to predict the peak frequencies of the meandering jet at the centre of a shallow reservoir impinging the downstream wall. The model was evaluated based on a set of 26 flow configurations measured in a rectangular reservoir with an aspect ratio close to 1. The results confirm that most measured peak frequencies are equal to a natural frequency of the shallow reservoir and are equal to the closest intersection between the natural frequency curves and the solutions of the feedback loop formula. Still, a few measured frequencies seem to differ from the predicted ones. The discrepancies between present measurements and model predictions may originate from the experimental data precision or from the model validity. Regarding the experimental data, the ultrasonic (water level) measurements from Peltier et al. (2014a) last only two minutes (at a sampling rate of 50 Hz), while Perrot-Minot et al. (2020) used 10-minute series of ultrasonic measurements (at a sampling rate of 200 Hz). Peltier et al. (2014a) data are thus expected to be of lower precision. Regarding the feedback loop model, the main unknown is the value of the vortex advection celerity c_v, taken here as $c_v / U = 0.7$ as proposed by the aeroacoustics literature on impinging jets, without specific experimental validation for free surface reservoirs (unlike in the case of the cavity configuration where this ratio was experimentally adjusted by Perrot-Minot et al., 2020). In future experiments, it would be valuable to better capture the spatial distribution of the free surface oscillations (as performed by Perrot-Minot et al., 2020) to enable discriminating between the various possible modes. Another inherent limitation of the coupled model is that it is not fully predictive in the sense that, for some configurations, several close intersections exist, and the model does not permit predicting which one will actually be occurring.

Data Availability Statement

All data and models used during the study appear in the manuscript and in Table 2.

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Table 1 : Literature review of the application of the feedback loop formula with the corresponding measured or selected ratio of vortex celerity (c_v) to the mean flow velocity (U).

Configuration	Reference	c_v / U
Impinging jets (in air)	Ho & Nosseir (1981)	0.62
	Tam et al. (1986)	0.7
	Powell et al. (1992)	0.64-0.75
	Panda (1999)	0.68-0.7
	Gao and Li (2010)	0.57-0.74
	Mercier et al. (2017)	0.54-0.61
Cavity (in air)	Rossiter (1964)	0.57
	East (1966)	0.35-0.6
	Block (1976)	0.57
	Ahuja & Mendoza (1995)	0.65
	Colonius et al. (1999)	0.57
	Larchevêque et al. (2003)	0.38-0.62
	Rowley et al. (2006)	0.625
Open-channel cavity	Perrot-Minot et al. (2020)	0.56

Table 2: Characteristics of the tested configurations along with the measured peak frequencies.

L_x (m)	L_y (m)	b (m)	h (cm)	Q (L/s)	F	f_{vel} (Hz)	f_{US} (Hz)	
1	0.985	0.08	1.80	0.25	0.41	0.228	0.220	
			2.74	0.50	0.44	0.259	0.269	
			5.56	1.53	0.47	0.509	0.391	0.537
			1.25	0.13	0.36	0.172	?	
			1.95	0.12	0.18	0.197	?	
			2.24	0.26	0.31	0.270	?	
			2.90	0.50	0.40	0.263	0.269	
			4.23	1.00	0.46	0.476	0.342	0.464
			5.40	1.46	0.46	0.557	0.391	0.537
			5.84	1.43	0.40	0.447	0.391	
			4.96	1.03	0.37	0.369	0.350	
			3.78	0.48	0.26	0.317	0.317	
			3.27	0.24	0.16	0.061	?	
		0.06	3.39	0.50	0.42	0.275	0.293	
			2.10	0.25	0.44	0.229	?	
			1.41	0.13	0.41	0.233	?	
			5.19	1.01	0.45	0.514	0.366	0.513
			2.12	0.13	0.22	0.246	?	
			2.55	0.27	0.35	0.259	?	
			3.44	0.50	0.41	0.280	0.293	
			5.06	0.98	0.46	0.378	0.366	
			6.69	1.50	0.46	0.412	0.415	0.586
			6.84	1.48	0.44	0.418	0.415	
			5.59	1.00	0.40	0.364	0.366	
			4.04	0.51	0.33	0.423	?	
			3.24	0.25	0.22	0.293	?	

List of figure captions:

Figure 1: Examples of geometrical configurations in the riverine environment to which the present Rossiter model was applied by Perrot-Minot et al. (2020) (a), is applied in the present research (b) or could be applied in future works (c, d, e).

Figure 2: Sketch of the rectangular shallow reservoir considered by Peltier et al. (2014a).

Figure 3: Comparison of the peak frequencies measured by LSPIV and POD (f_{vel}) and by the ultrasonic sensors (f_{US}), when available (Table 2).

Figure 4: Comparison between the coupled model and the measured data