Non intrusive measurement technique for dynamic free-surface characteristics in hydraulic jumps

F. Murzyn,[1] H. Chanson[2]

[1]ESTACA Campus Ouest, Parc Universitaire de Laval-Changé, Rue Georges Charpak, BP 76121, 53061 Laval Cedex 9, France; PH (+33) 2 4359 4715; email: fmurzyn@estaca.fr

[2]School of Civil Engineering, The University of Queensland, Brisbane 4072, Australia; PH (+61 7) 3365 3516; email: h.chanson@uq.edu.au

Abstract.

This paper concerns dynamic free-surface measurements performed in hydraulic jumps with Froude numbers between 3.1 and 8.5 using non intrusive ultrasonic probes. The interest was first focused on the characteristics of mean (η) and turbulent (η') levels of the air-water interface. Then they were coupled with phase-detection conductivity probes to assess the accuracy of the sensors. This allowed an accurate definition of the exact level detected by the ultrasonic displacement meters. The results showed a regular increase of the mean level over the jump (roller length). A peak of turbulent fluctuation was found on the roller whose amplitude depends upon the Froude number. Comparisons with previous studies showed a good agreement in terms of shapes and roller length estimation. Frequency analysis of the free-surface fluctuations revealed that highest frequencies in the jump are around 4 Hz. Based upon an autocorrelation analysis, the integral time scales of the air/water interface were found to be between 0.03 s and 0.12 s.

Keywords: Hydraulic jumps, Free-surface dynamics, Ultrasonic sensors, Measurements.

1. Introduction

A hydraulic jump is a rapid transition from a high-velocity to a low-velocity flow (super-critical to sub-critical flow). It is characterised by the interaction of strong turbulence with a free-surface leading air entrainment (bubbles, splashes and/or droplets). The hydraulic jump was extensively studied in the last decade including the experimental works of Chanson (2006, 2007, 2009), Mouazé et al. (2004), Murzyn et al. (2005, 2007), Kucukali and Chanson (2008). Mostly, these measurements were focused on the air/water flow properties (void fraction, bubble size, velocity…). Nevertheless, attention must be paid to the free-surface because, in the upper flow region, the recirculation area is characterised by large fluctuations affecting the dynamic of the flow. In the present study, these air/water interface properties were analysed with a new non-intrusive ultrasonic technique. Mean and

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turbulent levels of the free-surface were measured for Froude numbers between 3.1 and 8.5. The ultrasonic probes were synchronised with phase-detection conductivity probes enabling an accurate definition of the interface detected by the acoustic sensors. Finally, the free-surface frequency ranges were also discussed. The results were compared with previous studies showing good agreement and accuracy of these new probes.

2. Experimental arrangements and flow conditions

The experiments were carried out in a 0.50 m wide, 0.45 m deep horizontal rectangular flume with 3.2 m long glass sidewalls and a PVC bed at the Gordon McKay Hydraulics Laboratory of the University of Queensland. The water discharge was measured with a Venturi meter located in the supply line and it was calibrated on-site with a large V-notch weir. The free-surface measurements were recorded using six ultrasonic displacement meters (S1 to S6, Fig. 1) with a spatial accuracy of 0.18 mm and a maximum response time of 70 ms. The sensors were mounted above the flume and calibrated prior to the experiments. Data acquisition lasted 10 min with a sampling rate of 50 Hz. A simple filtering technique based on a threshold voltage was applied to remove all erroneous points from time series. In the present paper, Froude (1) and Reynolds (2) numbers respectively ranged from 3.1 to 8.5 and from 23,750 to 64,100. The inflow depth d_1 and jump toe location x_1 were constant (d_1 = 0.018 m and x_1 = 0.75 m). Figure 1 presents the experimental set-up with all relevant notations. Further details on the experiments were reported in Murzyn and Chanson (2007). A summary of the main experimental characteristics is presented in table 1.

$$Fr = \frac{U_1}{\sqrt{gd_1}} \qquad (1) \qquad\qquad Re = \frac{U_1 d_1}{\upsilon} \qquad (2)$$

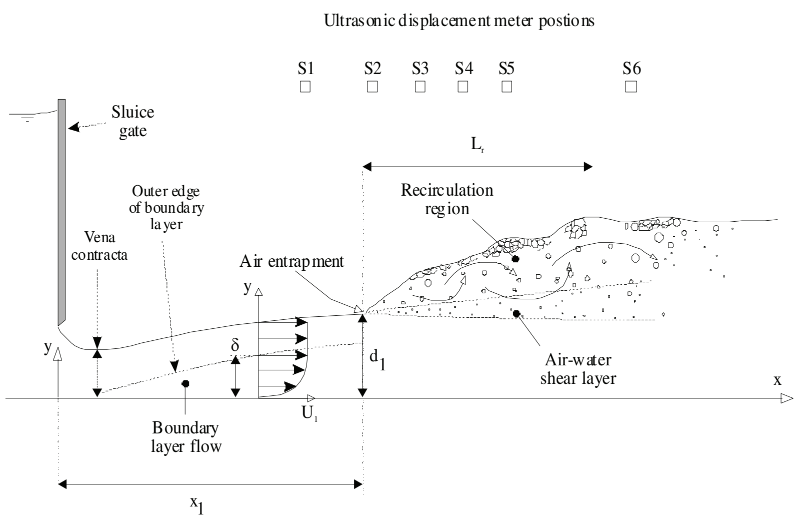


Figure 1. Sketch of the experimental set-up with all relevant notations

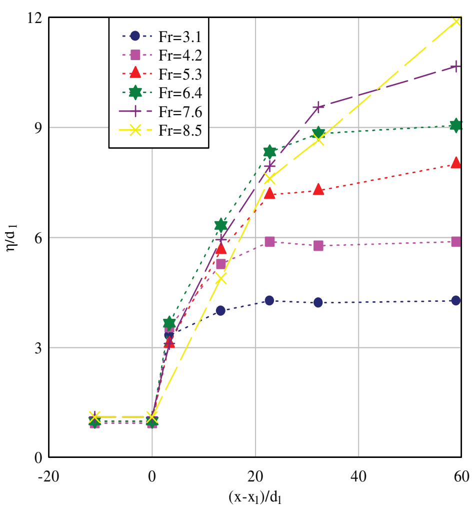
Test n°	x_1 (m)	d_1 (m)	W (m)	Fr	Re	L_r/d_1	η_{max}/d_1	η'_{max}/d_1
1	0.75	0.018	0.50	3.1	23750	15	4.28	0.33 (S2)
2				4.2	31850	21	5.89	0.55 (S2)
3				5.3	39800	27	8.00	0.69 (S2)
4				6.4	48600	33	9.06	0.86 (S3)
5				7.6	57050	N/A	N/A	1.04 (S3)
6				8.5	64100	N/A	N/A	1.47 (S5)

Table 1. Experimental conditions (N/A: not available)

3. Results

3.1. Mean and turbulent free-surface profiles

Figures 2 and 3 respectively present the dimensionless mean free-surface profiles as a function of the dimensionless distances $(x-x_1)/d_1$ and $(x-x_1)/L_r$ where L_r is the roller length.



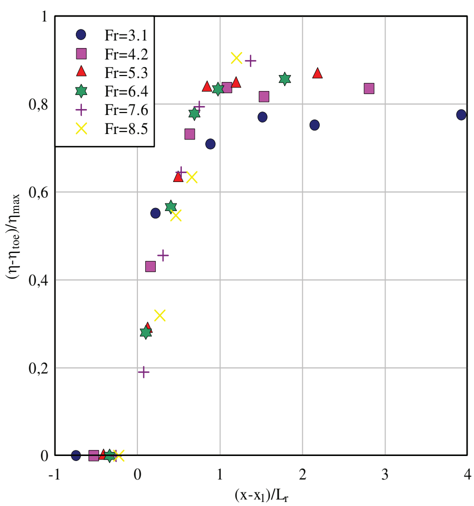


Figure 2. Free-surface mean levels in hydraulic jumps (left)
Figure 3. Similarity of free-surface profiles (right)

Figure 2 shows a regular increase of the mean level until a horizontal profile is reached (except for Fr = 7.6 and 8.5 for which the sixth ultrasonic displacement meter was not far enough from the toe). These shapes were in good agreements with flow visualizations (Mossa and Tolve, 1998) and previous experimental results (Mouazé et al., 2004 and Murzyn et al., 2007). Table 2 compares the roller length data with the estimated roller lengths using the correlation of Hager et al. (1990) and Murzyn et al. (2007). The results were comparable. Using the roller length, all profiles fitted into a self-similar shape (Fig 3).

Reference	Fr	L_r/d_1
Present study	3.1	15
	4.2	21
	5.3	27
	6.4	33
Hager et al. (1990)	2 < Fr < 8	$\frac{L_r}{d_1} = 8(Fr - 1.5)$
Murzyn et al. (2007)	2.0	7
	2.4	10
	3.7	18.5
	4.8	25

Table 2. Comparisons of roller lengths with previous studies

Figure 4 presents the turbulent fluctuations of the free-surface as functions of $(x-x_1) / L_r$ where η' is defined as the rms of the free surface output signal. For $(x-x_1) / L_r < 0$ (upstream of the toe), the turbulent fluctuations were closed to 0. Downstream of the toe ($(x-x_1) / L_r > 0$), they suddenly increased and a peak was found in the first half of the roller ($(x-x_1) / L_r < 0.5$). In this region, splashes, droplets and bubble ejections were more intense explaining these results. Downstream of this maximum, the free-surface fluctuations decreased monotically to a lower value. The decaying trend corresponded to a dissipative region where the free-surface recovered quietly. All the trends were also in good agreement with the data of Mouazé et al. (2004), Murzyn et al. (2007) and Kucukali and Chanson (2008). Note further that the turbulent fluctuation levels increased with Froude number (Murzyn and Chanson, 2007).

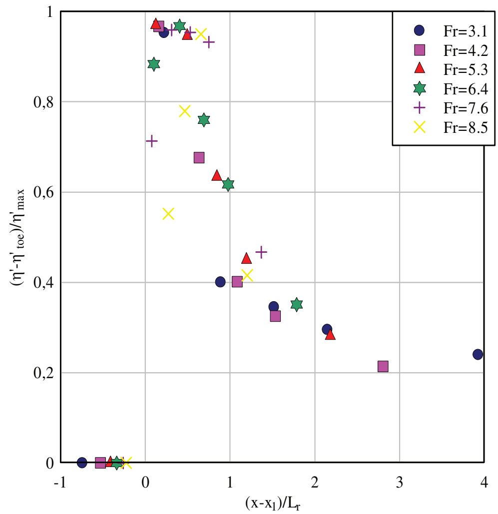
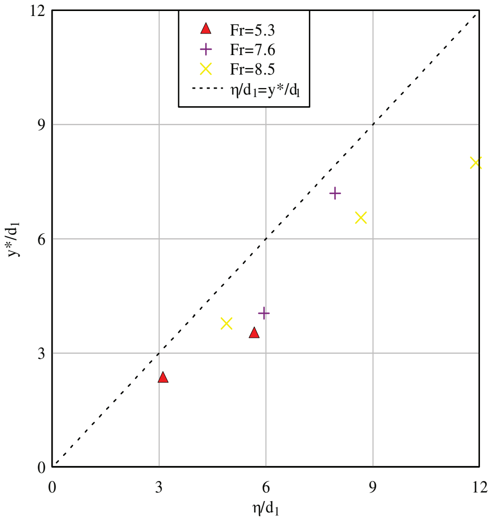


Figure 4. Turbulent fluctuations of the free surface

3.2. Accuracy of the acoustic sensors

The results were compared with detailed air-water flow measurements obtained using a phase-detection conductivity probe, to accurately define the exact position of the air/water interface detected by the ultrasonic sensors (Fig. 5). In Figure 5, the time averaged water level η is compared with y^* where y^* is the boundary between the turbulent shear layer and the upper flow region dominated by free-surface strong fluctuations, and deduced from vertical void fraction profiles (Fig. 6).



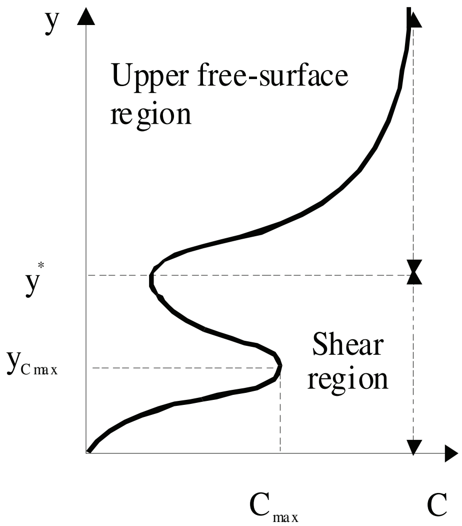


Figure 5. Air/water interface position compared to y^* (left)
Figure 6. Vertical void fraction profile in hydraulic jump with y^* position (right)

Figure 5 indicates that the free-surface levels deduced from the acoustic displacement meter are slightly above y^* for all conditions. The level of the free-surface detected by the acoustic sensor was within the upper free-surface region (recirculation region, Fig. 1) where the void fraction is generally larger than 60 % to 80 % and rapidly reaches 100 % (air). This was a very thin layer. Acoustic probes were thus able to accurately define the boundary between air and water in such flows.

3.3. Frequency analysis and time scales of the free surface

Some spectral analysis of the free-surface fluctuations were performed to obtain relevant information on the time scales of the flow developing in the upper free-surface. The Fast Fourier Transform (FFT) of the signal probe outputs was computed with a smoothing technique using a window of 20 points (Murzyn and Chanson, 2007). For all flow conditions, the results yielded the dominant frequencies of the free-surface fluctuations in the hydraulic jumps. Here, we present the Strouhal number (3) as a function of the dimensionless roller length $(x-x_1)/L_r$.

$$St = \frac{Fd_1}{U_1} \qquad (3)$$

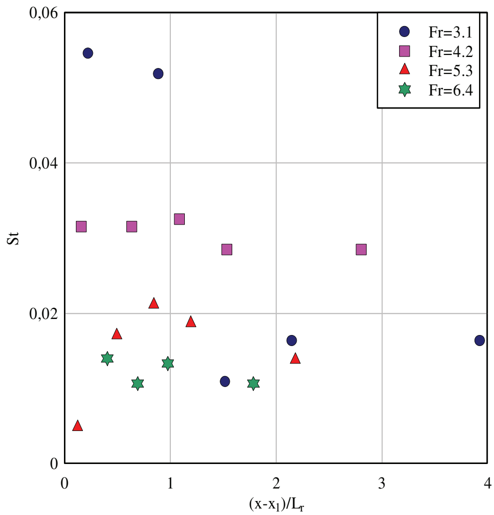


Figure 7. Strouhal number associated with free-surface fluctuations in hydraulic jumps

The results showed that the Strouhal numbers were between 0.01 and 0.06 which corresponded to characteristic frequencies of the free-surface between 1 and 4 Hz. For a given Froude number, the free-surface frequencies were larger and nearly constant in the roller. Downstream, they decreased with increasing the dimensionless distance to the toe. The lowest frequencies were found in the dissipative area where the larger time scales were observed according to flow visualizations.

Lastly, an autocorrelation coefficient (4) was computed on the acoustic sensor outputs to define a characteristic time scale (T_t) of the free-surface motion (5):

$$R_i(A,\tau) = \frac{\overline{\eta_{iA}(t)\eta_{iA}(t+\tau)}}{\overline{\eta_{iA}}^2} \qquad (4)$$

$$T_t = \int_0^{\tau_{max}} R_i(A,\tau)\,d\tau \qquad (5)$$

where τ_{max} is the time corresponding for which $R_i = 0$. The time scale T_t is a measure of the interval during which the output signal of the acoustic sensor is correlated with itself (Tennekes and Lumley, 1972). The results are presented on figure 8.

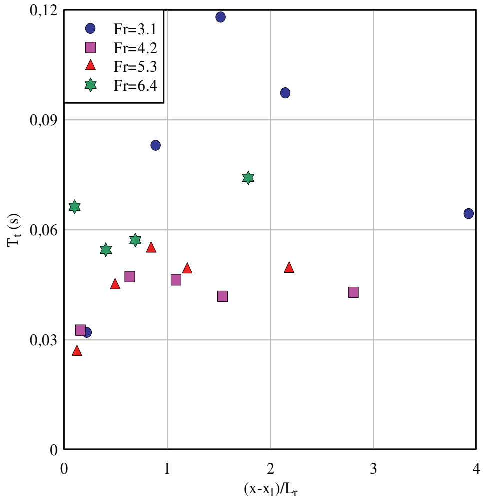


Figure 8. Autocorrelation time scales of the free-surface fluctuations

The time scale T_t ranged from 0.03 s to 0.12 s. It was nearly constant for a given Froude numbers in the dissipative area. The results were interesting because they bring information on the minimum sampling rate that must be used to fully describe the fluctuations of the free-surface.

4. Discussion and conclusions

To date, few experimental investigations tried to characterise the free-surface dynamics in hydraulic jumps. In the present paper, using a non intrusive technique (no disturbance of the flow), new results are presented:

- The mean free-surface levels regularly increased downstream of the toe until a certain distance (roller length). Beyond this limit, it remained nearly flat;
- The turbulent fluctuations of the free-surface exhibited a peak of intensity in the first half of the roller whose amplitude depend on the Froude number;
- The position detected by the acoustic sensor was found within a very thin layer in the upper part of the flow (recirculation region) where the void fraction rapidly reached 100 % (air);
- Frequencies of the free-surface fluctuations were not higher than 4 Hertz whereas the autocorrelation time scales were between 0.03 s and 0.12 s.

Comparisons with previous studies showed that the ultrasonic displacement meters were accurate in these highly turbulent flows. Indeed, the shapes of the mean and turbulent free-surface profiles, as well as the roller length estimates, were found to be in agreement with earlier studies, including Mouazé et al (2004), Murzyn et al. (2007), and Kucukali and Chanson (2008). The main advantage of the ultrasonic technique is that it is non intrusive. Thus, the sensors do not need to be continuously immersed and a simple calibration is required prior to experiments. Furthermore the data rate (50 Hz in the present study) can be larger than for most wire gages (20 Hz maximum). Altogether the ultrasonic sensor technique is particularly interesting to follow rapid and high fluctuations in these flows, although droplets and splashes may affect the output signal. This could be a limit for the study at larger Froude numbers but was not examined herein. Another issue deals with the integration surface for the measurements. As the emitted beam diverges, the integration surface increases with distance, leading to a lesser resolution. By setting the acoustic displacement meter as close as possible from the free-surface, it is expected that the problem could be minimised (nevertheless, it should not be too close to avoid any droplet or bubble from touching its sensitive part). The relationship between free-surface fluctuations and oscillations of the toe and/or bubble frequency may be interesting for future works as well as the influence of the Reynolds number on the flow dynamics. Finally, it is strongly believed that this work brings new, useful information for a better understanding of the physical processes involved in hydraulic jump flows.

5. Acknowledgments

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