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MEASUREMENT OF TURBULENCE PARAMETERS IN HYDRAULIC JUMPS USING ULTRASONIC SENSORS AND THEIR CORRELATION WITH MACROSCOPIC FLOW PARAMETERS

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Abstract.*The sudden transition from supercritical to subcritical regimes in channel flows is known as hydraulic jump. Some geometrical characteristics of the transition such as the length of the roller and of the jump itself can be associated to turbulence parameters in different positions of the flow. These are generally obtained from the fields of mean and fluctuating velocities, being usually: turbulence intensity, Reynolds stresses, and turbulent kinetic energy. The techniques commonly used to determine the velocity fields are: hot-film anemometry, particle image velocimetry, laser Doppler velocimetry, acoustic Doppler velocimetry, acoustic displacement measurements. The aim of the present study is to compare different methods, in order to verify the adequacy of the ultrasonic sensor to predict the mentioned lengths of the hydraulic jump and the roller. The study considers experimental data found in the literature. In particular, the ultrasonic sensor measures the position of the water surface, and previous studies indicate that the variation of this position can be used to study the macroturbulence characteristics. The ultrasonic meter presents the positive aspects of being a robust technique, relatively easy to use, and less expensive than the alternative methods. The results of the present study point to the adequacy of using ultrasonic meters for measurements in hydraulic jumps.*

Keywords:*hydraulic jump, length of the roller, length of hydraulic jump, free-surface position.*

1. INTRODUCTION

Considering a free surface, if the fluid motion is accompanied by a transformation of a dynamic state to another, it leads to a variation in the shape of the water surface. An example is the hydraulic jump, which is a phenomenon that occurs when a flow changes from a supercritical to a subcritical regime. The hydraulic jump is characterized mainly by a sudden rise of the free surface, accompanied by wave formation, water ejection, and air incorporation in the flow. The study of such phenomena becomes interesting in many aspects of applied engineering, such as in the design of hydraulic structures, in the understanding of maritime phenomena and in sediment transport in rivers and oceans. In this applied context, spilling breakers for example may be modeled throught hydraulic jumps with low inflow Froude numbers (Brocchini and Peregrine, 2001). In many hydraulic structures, the cited phenomenon is used as a mechanism of energy dissipation, as observed downstream of dam spillways.

Hydraulic jumps can be physically viewed as composed by two characteristics lengths: the roller length and the hydraulic jump lenght. The roller corresponds to the region that contains the recirculation motion of the fluid, such that the movement of the free surface is reverse to the movement of the main flow direction. Downstream of the roller, the flow initially remains affected by the hydraulic jump, and finally reaches a condition of normal turbulent open channel flow. The distance from the jump toe to the end of the transition zone is called the “hydraulic jump length”.

Because of the large flututuations of all observable parameters of hydraulic jumps, the mentioned lengths are difficult to be determined experimentally. This difficulty is magnified by the uncertainty that derives from the different definitions concerning both lengths among different researchers. In an attempt to standardize the different results found in the literature and to contribute with more experimental data, Simões,*et al.* (2010) proposed a methodology based on the measurement of the turbulent flucutations that occur at the free surface in channel flows. They firstly determined instantaneous positions of the free surface using ultrasonic sensors. The acquired data were then used to quantify turbulence parameters at the free surface, like the turbulence intensity and the Strouhal number.

Turbulence parameters of hydraulic jumps have been extensively studied only recently and, for this reason, they are relatively limited (Liu, *et al.*, 2004). The studies found in the literature and used in the present comparative analysis were choosen based on the description of the experimental arrangements, and on the conceptual arguments exposed by the authors. Among them, the following compose the main basis of this work: Gunal and Narayanan (1996), Liu, *et al.* (2004), Mouaze, *et al.* (2005), Lennon and Hill (2006), Murzyn, *et al.* (2007), Kucukali and Chanson (2008), Misra,*et al.* (2008), Murzyn and Chanson (2009), Chachereau and Chanson (2011), Brocchini and Peregrine (2011), Romagnoli, *et al.* (2012), and Zhang, *et al.*(2012).

Some of the mentioned authors have focused their attention in the investigation of the dynamics of the air-water interface, viewed as dependantof interactions between the large-scale eddies and the free surface.

Murzyn, *et al.* (2007) used wire gauges in their experimental studies. Besides determining the free surface and relevant turbulence profiles, they furnished free surface length scales for both longitudinal and the transversaldirections. The characteristic turbulence velocities were plotted using the diagram proposed by Brocchini and Peregrine (2001) that presents the different forms of turbulence as a function of turbulent velocities and length scales.

Kucukali and Chanson (2008), Chachereau and Chanson (2010, 2011), and Murzyn and Chanson (2009a, b), performed measurements with acoustic displacement meters, described as a non intrusive technique. Simultaneously, two-phase flow properties were recorded using phase detection probes (single-tip and double-tip conductivity probes). Their results include: free surface profiles, free surface fluctuations, spectral analysis of the data obtained with the phase detection probes and the acoustic sensors, integral turbulent time and length scales, and Strouhal numbers.

It is important to note, however, that none of the cited studies furnished a joint assessment of hydraulic jump lengths and turbulence, as proposed by Simões,*et al.*(2010). The authors established the end of the hydraulic jump as the section where the statistical parameters become independent of the longitudinal position.

Therefore, the aim of this paper is to present the positive aspects of the ultrassonic sensors as a tool for studying hydraulic jumps, throught a literature review and data comparison. The particular interest in hydraulic lengths is because of its practical application in the design of energy dissipators. The hydraulic jump length indicates the length of the hydraulic structure where the bed protection is necessary, represented by the concrete slab and the side walls of a convetional dissipation basin (Carollo, *et al.* 2007; Peterka, 1984). This study presents a comparative analysis of free surface profiles, flow frequencies, roller lengths and hydraulic jump lenghts.

2. POSITIVE ASPECTS OF USING ULTRASONIC SENSORS

The highly turbulent flow in hydraulic jumps leads to the formation of water droplets, splashes, air incorporation and free surface fluctuations. The source of vorticity and air bubbles entrainment is closely related to the oscillation breaking front at the toe of the jump, at the impingement point (Liu, *et al.*, 2004). This flow behavior hinders the measurement of flow properties, mainly in the roller region, which contains large scale eddies and where the peak of turbulence is observed.

Different techniques of velocitiy and position measurements in hydraulic jumps may be affected by the mentioned high turbulence, conducting to erroneous or biased data. The bubbly flow structure may also be a source oferrors, when using measurement techniques that do not respond adequately to the two phases condition (air-water).

The mentioned aspects may restrict the use of some techniques only for low inflow Froude numbers (with lower levels of turbulence than high inflow Froude numbers) or to impose post treatment to the data in order to evidence the flow characteristics under study, as occurs, for example, with optical and acoustical techniques as PIV (Particle Image Velocimetry) and ADV (acoustic Doppler velocimeter). The optical non intrusive techniques face strong technical limitations in such aerated conditions, due to the light diffraction caused by the bubbles (Mouaze, *et al.*, 2005). Robinson, *et al.* (2000) *apud* Liu, *et al.*(2004) found that the velocitiy measurements using ADV in highly turbulent and highly air-entrained flow are underestimated comparing to real velocities. Because of this fact, Liu, *et al.* (2004) confined their experiments to low inflow Froude numbers (F_1=2.0, 2.5, and 3.32).

The PIV technique provides velocity flow fields based on the movement of reflective particles present in the flow, with the use of pulsed lasers, consisting of a laser light source and a high speed camera (Simões, 2012; Lin,*et al.*, 2012). As challenges for the use of PIV in hydraulic jumps are the identification and tracking of the free surface (through image analysis) and the suppression of the scattering of the laser light by the air bubbles in the roller region (Lennon and Hill, 2006). In order to overcome such difficulties, Lin, *et al.* (2012) used PIV and BIV (bubble image velocimetry) to measure velocities in non-aerated and aerated regions respectively, finding different velocities for bubbles and water. However, more specific studies are needed to verify the applications of BIV in hydraulic jumps.

The influence of bubbles and water ejection not only affect adversely the PIV and ADV methods, but also the acoustic method focused in this paper. Murzyn and Chanson (2009b) used a simple filtering technique based on a threshold voltage to remove erroneous points from the time series. Chachereau and Chanson (2011) also removed spikes by a threshold technique, and discussed that some outputs included a few erroneous measurements for situations

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with large angles between the free surface and the horizontal, and the reflected beam did not return to the acoustic displacement meter head.

The problems related to the presence of the spikes in the output signals were circumvent by Simões,*et al.*(2010) using a simple statistical analysis. The data were inserted in box-plot diagrams (Fig. 1 and Fig. 2) and standard tools were used to localize discrepant values of the sample. Following the mentioned standard procedures, the outliers were localized above the superior limit ($qr_3 + \phi AIQ$) and under the inferior limit ($qr_1 - \phi AIQ$), where qr_3 and qr_1 are the third and first quartile respectively, ϕ is a constant equal to 1.5, and AIQ is the range between the third and first quartile ($AIQ=qr_3-qr_1$). This elimination criterium was followed carefully in order to avoid deviations from the experimental reality and it was applied just one time. The procedure was able to produce results that correctly represent the phenomenon. The same methodology was also used by Simões,*et al.*(2013) for the descriprion of the surface in skimming flows along stepped chutes.

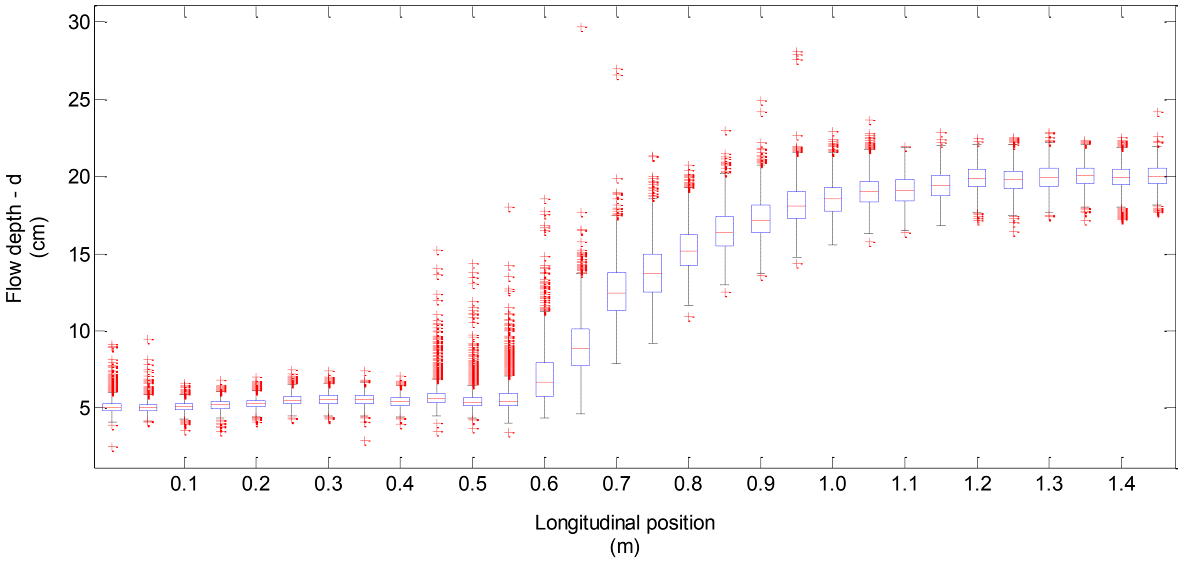

Figure 1. Box-plot diagram of raw ultrasonic sensor data with outliers, F_1 = 3.0 (first 30 positions). Adapted of Simões, *et al.* (2010).

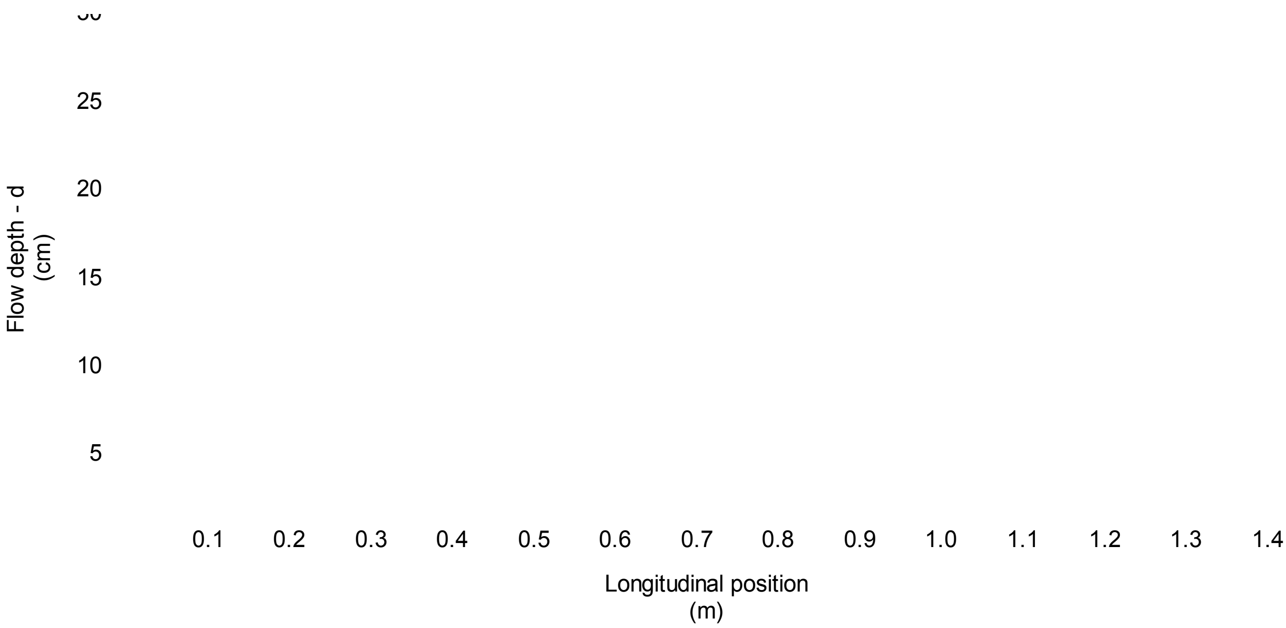

Figure 2. Box-plot diagram of altered ultrasonic sensor data without outliers, F_1 = 3.0. Adapted of Simões, *et al.* (2010).

The interesting study of Simões, *et al.* (2010) shows that for the cases in which the roller length and the jump length are studied based on free surface fluctuations, the use of ultrasonic sensor is promising. Besides it's a relatively easy and low-costing application, the post-treatment of raw data does not require a large calculation effort, as required by other techniques.

3. EXPERIMENTAL ARRANGEMENTS

The experimental methodology presented by Simões, *et al.*(2010, 2012 a,b), consisted in using an ultrassonic sensor in order to record the free surface position. The experiments were carried out inthe Laboratory of Hydraulic at the School of Engineering at São Carlos – EESC/USP, in a channel with 41 cm width and 61 cm height. The supercritical condition was formed downstream of a broad crested weir and the hydraulic jump position was controlled by a vertical sluice gate at the end of the flume. The flow rate was determined using a triangular weir located upstream of the channel.

The measurements were recorded for 67 different positions along the central line of flow containing the hydraulic jump, with a sample rate of 2000 measurements per position and a frequency of 50 Hz. The hydraulic jump studied by the mentioned authors was produced for an inflow Froude number of 3.0, and a specific flow rate of 0.11 m^2/s.The experimental results were compared to numerical simulations, presenting good sobrepositions between the experimental data and the free surface profiles simulated with different turbulence models.

Similar measurements were conducted by Simões, *et al.*(2013) for skimming flows in stepped spillways. The ultrasonic sensors were used to measure monophasic flow at the beginning of the spillway and biphasic flow after the inception point for aeration, showing that they may be adequately applied in both regions.

4. RESULTS

4.1 Free surface profiles

The free surface upstream of the hydraulic jump is quite smooth in relation to the mean flow level downstream of the impingement point. At this point the flow becomes highly turbulent, aerated, and the surface fluctuates around a mean level, presenting water ejection and waves that propagate along the flume. This change in the flow structure is accompanied by a sudden change in the free surface elevation, forming a steep slope at the front of the jump. Afterwards, the flow starts to stabilize and the free surface turbulence becomes similar to that observed upstream of the hydraulic jump. The level then approximates the subcritical uniform flow condition, according to the Bélanger equation.

Figure 3 shows results of mean surface profiles, considering data of various authors. In this figure, d/d_1 is the nondimensional water depth, x is the distance along the flume and x_1 is the position of the toe of the hydraulic jump with height d_1. In order to evaluate the technique used by Simões, *et al.*(2010, 2012b) only results for Froude numbers close to 3.0 are represented in the graph.

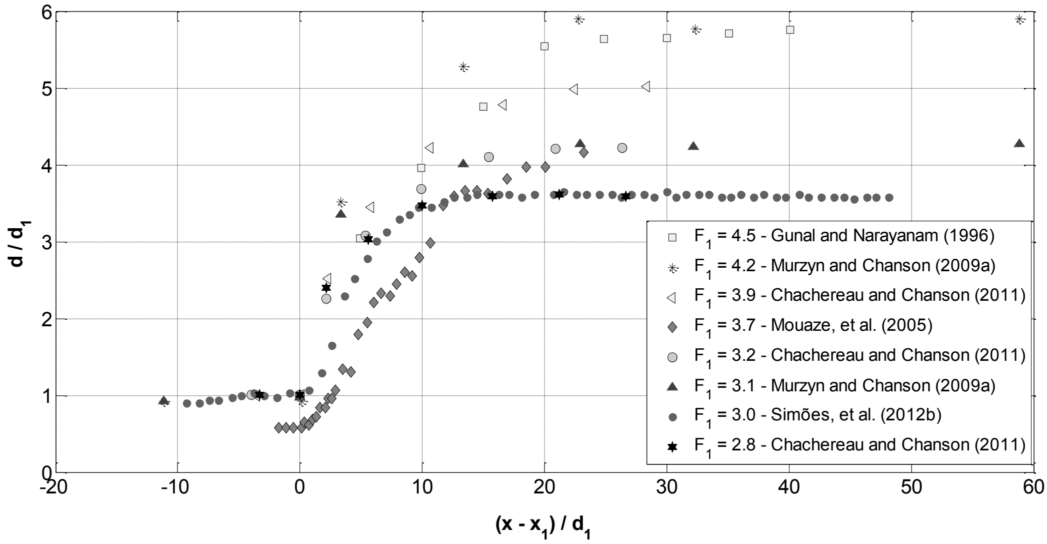

Figure 3. Mean free surface profiles.

Gunal and Narayanam (1996) carried out measurements of velocity using a hot-film anemometer for differents bed slopes. The mean depths at various positions along the channel were measured using a point gauge. The authors compared their results with predictions of a numerical model, and a good agreement between theoretical and experimental surface profiles was obtained for all studied Froude numbers and slopes. Mouaze, *et al.* (2005) performed measurements of the free surface using two homemade miniature resistive wire gauges. Murzyn and Chanson (2009a, b) and Chachereau and Chanson (2011) used ultrasonic probes to study the dynamics of the free-surface at the flume

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centreline. Besides presenting mean dimensioless profiles (d/d_1) as a function of ($x-x_1$)/d_1, Murzyn and Chanson (2009a, b) also used the dimensionless distance ($x-x_1$)/L_r with ($d-d_1$)/d_{max} with which all their profiles fitted into a self-similar shape. L_r is the roller length and d_{max} is the maximum depth.

Simões, *et al.* (2012b) represented the data using the vertical dimensionless axis d/d_c (d_c is the critical depth) as function of $x/(d_2-d_1)$. Accordingly to the mean free surface profile shown in Fig. 4, the position where d/d_c = 1.0 corresponds to the maximum dimensionless turbulece intensity $IR = w'/V_c$.

$w' = \sqrt{\overline{w^2}}$ Turbulent fluctuation intensity in vertical direction
w Difference between instantaneous vertical velocity and mean vertical velocity
$\sqrt{\overline{w^2}}$ Mean turbulent velocity
V_c Critical velocity
IR Relative turbulent intensity

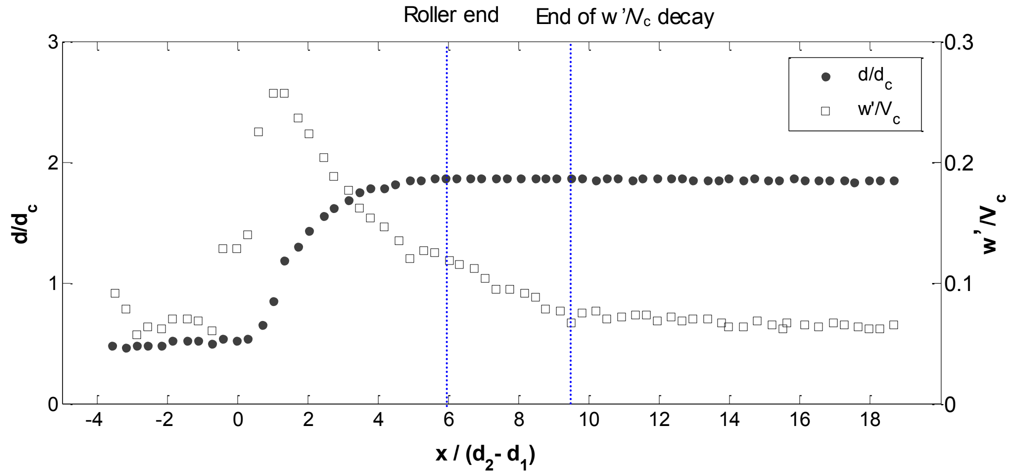

Figure 4. Free surface profile for F_1=3.0.
Adapted of Simões, *et al.* (2012b).

From Fig. 3 it can be observed that the data of Murzyn and Chanson (2009a,b), Chachereau and Chanson (2011) and Simões, *et al.*(2012b), who used ultrasonic displacement meters, presented similar behaviours, showing a growing trend for higher F_1 numbers. The profile obtained by Simões, *et al.* (2012b) for F_1 = 3.0 is almost coincident to the profiles for F_1 =2.8 and F_1 =3.0 of Murzyn and Chanson (2009a) and Chachereau and Chanson (2011), respectively. Comparing the F_1=4.2 and F_1=4.5, it is possible to observe that the last profile (obtained with wire gauges) presents slightly lower values than the first profile (obtained with ultrasonic sensor).

The majority of the data presented similar front slopes, but the data of Mouaze,*et al.*(2005) for F_1 = 3.7 are slightly different and inferior to other profiles with similar F_1. The possible cause of this difference may be related to the different measurement technique adopted by the mentioned authors, or may lay on the sample rate, which was 128 Hz during 5 seconds, while in other studies (Chachereau and Chanson, 2001; Simões, *et al.*, 2012b; Murzyn and Chanson, 2009a) the frequency was 50 Hz and a longer time sample.

4.2 Strouhal number

Throught a data analysis in time domain, it is possible to verify which frequencies exist in the raw signal obtained with certain equipment. The decomposition of the raw signal in time-frequency components can be made throught a Fast Fourier Transform. The dominant frequency (F) may becombined with the flow depth (d) and the velocity (V), resulting in a representative quantity of the flow turbulence denominated Strouhal number (Eq. 1).

$$St = \frac{F \cdot d}{V} \quad (1)$$

The determination of the Strouhal number is important in the study of hydraulic jumps because it is related to the turbulence flow structure. The oscilation frequency of the toe position, for example, is associated to growth and travel of large scales vortices in the jump (Long, *et al.*, 1991). The studies of Chanson (2011) demonstrated that the dimensionless frequency of the longitudinal toe position ($F_{toe}d_1/V_1$) ranges between 0.003 e 0.006, independently of the Froude number. From the practical point of view, the knowledge of flow frequencies allows verifying whether the applied technique is adequate to the target measurements, because the characteristic frequency of the equipment signals must embrace most of flow frequencies. In the study of Bung (2013), the sample rate of 30 Hz for ultrasonic sensor was

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not able to detect the higher frequencies of the flow in stepped chutes, comparing to the ones identified by a high-speed camera.

According to Liu, *et al.* (2004), the dominant frequency in hydraulic jumps is in the range from 0 to 4 Hz for both horizontal and vertical velocity components. Similar range was found by Chachereau and Chanson (2010), who observed surface fluctuations with characteristics frequencies between 1.4 and 4 Hz, maily below 3 Hz, for all flow conditions and transversal sections. The free surface fluctuation frequencies are constant in the roller region, while they decrase far downstream, being larger for smaller Froude numbers (Murzyn, 2010).

In Fig.5, the data of Simões, *et al.* (2012) were compared to data of Murzyn and Chanson (2009a,b) and Chachereau and Chanson (2009). The mentioned authors used ultrasonic sensors for the free surface measurements. In all the cases the free surface frequency (F_{fs}) were combined with the inflow depth and velocity (d_1 and V_1, respectively).

Considering F_1=3.1, the data of Murzyn and Chanson (2009) present lower values than the other data for $(x-x_1)/d_1>20$. Upstream of this position, the Strouhal number is approximately 0.05, while downstream it becomes about 0.02.

Simões, *et al.* (2012) also presented data of Strouhal numbers for the supercritical region ($(x-x_1)/d_1<0$) which vary from 0.10 to 0.22 aproximately. Just downstream of the jump toe, the data concentrate around St = 0.05 and 0.10. For the mentioned authors, the larger amplitude of St in hydraulic jumps occur around the position $(x-x_1)/d_1$=20 and at the jump toe. This large fluctuation of St close to the toe was pointed only by Simões, *et al.* (2012), while Murzyn and Chanson (2009a, b) and Chachereau and Chanson (2011) found a relatively smooth behaviour along the jump, almost independently of the position.

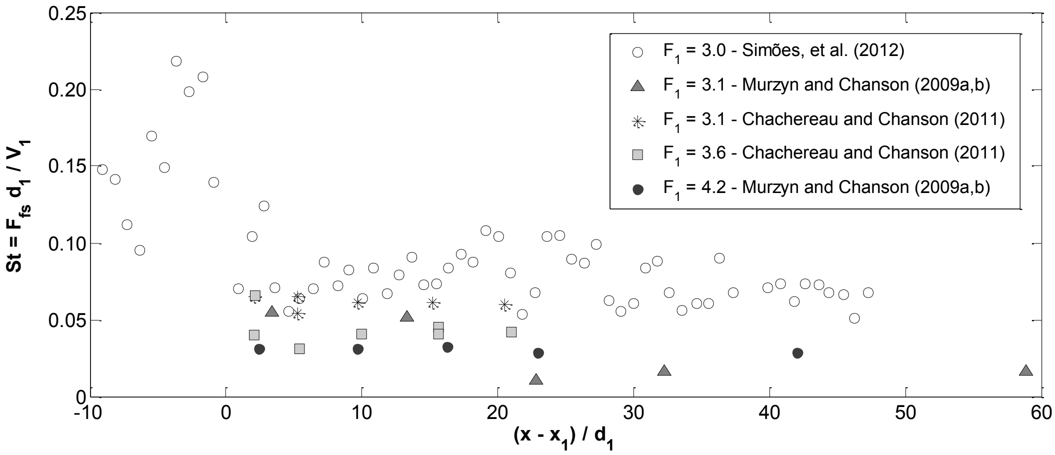

Figure 5. Distribution of Strouhal numbers along the hydraulic jump.

The Strouhal data of Simões, *et al.*(2012) are quite higher than the data of Chachereau and Chanson (2011) and Murzyn and Chanson (2009a, b). However, when comparing the representative frequency of the free surface (F_{fs}), all data present a similar pattern (Fig. 6), excepting the values for F_1 = 3.1 of Murzyn and Chanson (2009a,b) with frequencies around 1 Hz. The data of Simões, *et al.*(2010) and Chachereau and Chanson (2011) suggest that the frequencies have an accentuated reduction downstream of the toe position, around $(x-x_1)/d_1$= 6.

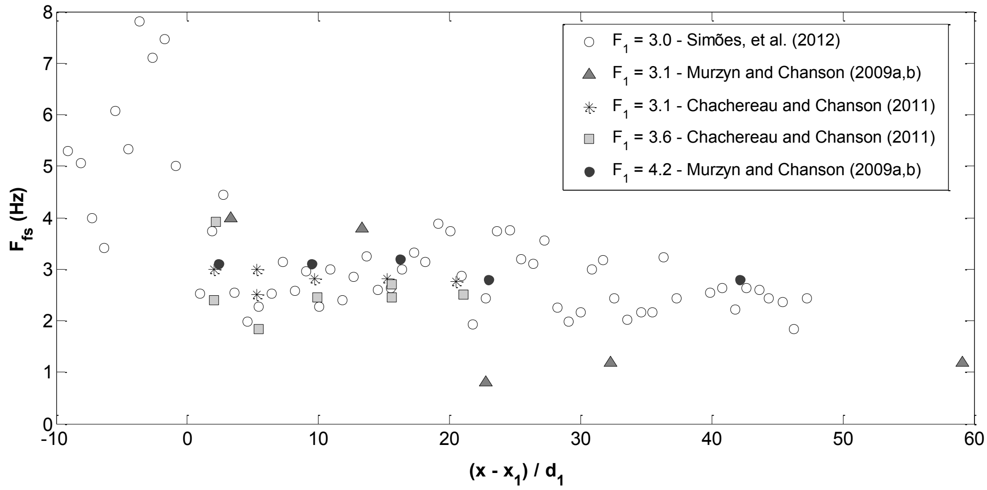

Figure 6. Distribution of dominant frequencies along the hydraulic jump.

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4.3 Roller Length

The flow in the roller region is characterized by strong turbulence production, large recirculation vortices and coherent structures reaching the free surface (Murzyn and Chanson, 2009). This region is responsible for large energy dissipation in hydraulic jumps, so that at the roller end, 95% of the flow energy has been dissipated (Hoyt andSellin, 1989; Marques,*et al.*, 1996 apud Marques, *et al.*, 1997).

The final section of the recirculating flow can be determinated by differents methodologies. Accordingly to Rajaratnam (1965) apud Souza (2011), the final section of the roller is the local where the water reaches 95% of the conjugated depth y_2. Other authors, as Ead and Rajaratnam (2002) and Carollo, *et al.* (2007) defined the end of the roller as the stagnation free surface point, measuring it with a red dye and floats respectively. Another method is based in the visual observation of the flow, analysing the bubbles and water movements.

Even using all these methods, the definition of the roller length is still not definitively established among the different authors, such that in some cases the results do not present convergence. Throught the mean surface profile obtained by Simões, *et al.*(2012), the end of the roller coincides with the position where $x/(d_2\text{-}d_1) = 6.0$ (Fig. 4). Downstream this point, the mean free surface level does not grow substantially. The use of ultrasonic sensors for obtaning the surface profiles was very elucidative because it eliminates the subjective aspect of the visual observations.

The calculated values for roller lengths (Tab. 1 and Tab. 2) show that the value obtained by Simões, *et al.*(2012) is the biggest of the consulted literature, producing L_r=0.86 m. The lengths obtained by authors that also used acoustic sensors (Murzyn and Chanson, 2009b; Murzyn, *et al.* 2007) are larger than the lengths obtained by other methods, suggesting that this may be a trend of this methodology. More data must be obtained to support this conclusion.

Table 1. Experimental conditions of Simões,*et al.*(2010).

Supercritical depth	d_1 (m)	0.055
Subcritical depth	d_2 (m)	0.198
Inflow Froude number	F_1	3.0
Channel width	b (m)	0.41
Aspect ratio (d_1/b)	Ω	0.135

Table 2.Roller length for F_1 = 3.0, considering different methodologies.

Methodology	**Equation**	**L_r/d_1**	**L_r(m)**
Simões,*et al.* (2012b)	$L_r = 6 \cdot (d_2 - d_1)$	15.48	0.857
Hager,*et al.* (1990)	$\frac{L_r}{d_1} = -12 + 8 \cdot F_1$	12.00	0.664
Murzyn and Chanson (2009b)	$\frac{L_r}{d_1} = 15 \quad (\text{for } F_1 = 3.1)$	15.00	0.830
Murzyn, *et al.*(2007)	$\frac{L_r}{d_1} = 7.5 \cdot (F_1 - 1.3)$	12.75	0.706
Carollo, *et al.* (2007)	$\frac{L_r}{d_1} = 4.616 \cdot \left(\frac{d_2}{d_1} - 1\right)$	11.91	0.659
Carollo,*et al.* (2007)	$\frac{L_r}{d_1} = \frac{2.244}{\left(\frac{d_1}{d_2}\right)^{1.272}}$	11.37	0.629

4.4 Hydraulic Jump Length

The hydraulic jump length (L_j) is the distance between the sections with supercritical and subcritical flow depths. This characteristic length is one of the most difficult parameters to be determined in practice, due to the surface wave production and the residual turbulence (Carollo, *et al.,* 2007; Lencastre, 2012). Although there is information in the literature about hydraulic jump lenghts, there is no definitive quantitative definition of this parameter.

Hager (1992) apud Carollo,*et al.*(2007) suggested as hydraulic jump length the distance necessary to "suppress" the free surface turbulence and also for the complete deaeration of large air bubbles. Nóbrega (2013) mentions that some authors define L_j as the section where large fluctuations around the mean surface profile are not more observed.

Therefore, it is convenient to define a hydraulic jump lenght based on the flow turbulence. Moreover, the distance over which the effects of the hydraulic jump are relevant is almost impossible to be determined by visual observations.

Ortiz (1981) was one of the first authors that evaluated the lengths of hydraulic jumps as dependent of the relative turbulence intensity $K_u = u'/\bar{u}$ in the longitudinal direction u ($\bar{u}$ is the mean flow velocity). The end of transition zone was considered as the position where K_u was about 0.1, which is characteristic for the usual turbulence in channels.

Following the turbulence criteria, Simões,*et al.*(2010) suggest the Eq. 3for F_1=3:

$$\frac{L_j}{d_2 - d_1} = 9.52 \tag{3}$$

Simões, *et al.* (2010) defined L_j as the distance from the toe of the hydraulic jump to the region of invariance of the w'/V_c curve. In Fig. 7 it is possible to observe that w'/V_c assumes values of the same order of magnitude presented at the upstream flow (from hydraulic jump). Moreover, the Strouhal numbers show a lower scattering downstream of this position. Visually, the end of the hydraulic jump could not be quantified by means of the mean free surface profile, because no variation is observed at this position (see Fig. 3).According to the equations proposed by Simões, *et al.* (2012), the hydraulic jump length is 1.12 larger than roller length, for F_1=3.0.

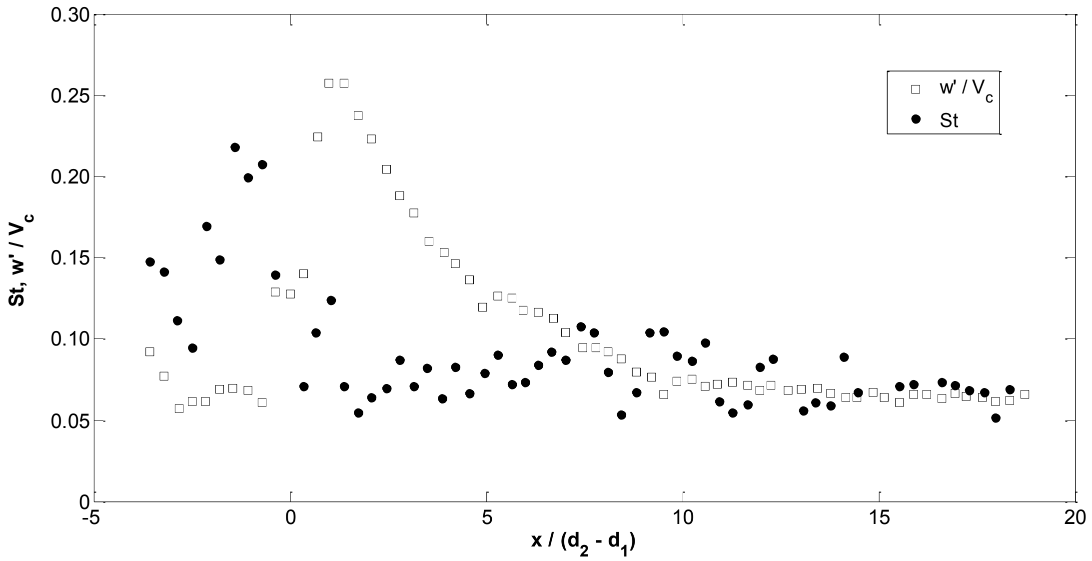

Figure7. Strouhal distribution and relative turbulence intensity.
Adapted of Simões, *et al.* (2010, 2012b).

Table 3.Hydraulic jump length for F_1 = 3.0, considering different methodologies.

Methodology	**Equation**	**L_j/d_1**	**L_j(m)**
Simões,*et al.* (2012)	$\frac{L_j}{(d_2 - d_1)} = 9.52$	24.57	1.36
Hager (1995)	$\frac{L_j}{d_1} = 10 \cdot \alpha_j \cdot tanh\left(\frac{F_1 - 1}{\alpha_j}\right), \alpha_j = 22$	19.95	1.10
Simões (2008)	$\frac{L_j}{d_2} = \frac{F_1^2 - 81.85 \cdot F_1 + 61.13}{-0.62 - 10.71 \cdot F_1}$	19.18	1.06
Marques, *et al.* (1997)	$\frac{L_j}{d_2 - d_1} = 8.5$	21.94	1.21

The equations proposed by Hager (1995) and Simões (2008) were defined from the data of Peterka (1984) – Tab. 3. Peterka (1984) measured the hydraulic jump length as the distance from the toe of the jump until the point where the high velocity jet started to leave the channel bed or until the point at the surface imediately downstream the roller (see Peterka, 1984). Marques, *et al.* (1997) studied the hydraulic jump characteristics as a function of the pressures at the bottom of the channel and its statistical parameters. As occured with the roller length, the L_j value presented by Simões, *et al.*(2010) was the largest value found among the equations applied in the present study.

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Following the criteria of Simões, *et al.* (2012), an analysis of the hydraulic jump length in terms of the decay ratio of the relative turbulence intensity (IR) is proposed here, as represented by Eq. 4. The equation represents how significant is the decreaseness of IR downstream of the hydraulic jump, relatively to the first region of the flow (between the maximum turbulence position and the end of the jump). The data of Simões, *et al.* (2012), when applied to the ratio between turbulence intensities shown in Eq. 4, produces the value 0.026, and a minimum fluctuation intensity w'_{min} (=$IR_{min} \cdot V_c$) around 0.06 m/s These values might be used as a starting point for analyzing hydraulic jump lengths with different F_1, considering the ultrasonic sensor methodology. This proposal is presented here in Eq. 5.

$$\frac{IR_{Lj} - IR_{min}}{IR_{max} - IR_{Lj}} = 0.026 \qquad (4)$$

where:

IR_{Lj} relative turbulence intensity at the position of hydraulic jump length
IR_{min} minimum turbulence intensity
IR_{max} maximum turbulence intensity

$$\frac{IR_{Lj} - 0.06 \cdot V_c}{IR_{max} - IR_{Lj}} = 0.026 \qquad (5)$$

5. CONCLUSION

Because the hydraulic jump is a complex phenomenon, several questions about its characteristics remain unanswered. Among these questions, the possible correlations between macroscopic characteristics and flow turbulence may be pointed out. Due to the entrainment of air bubbles and water ejections, the turbulence in hydraulic jumps is difficult to be measured, even with the different techniques available nowadays. However, it was observed that the ultrasonic sensor presents advantages in relation to other methods due to ease application, low costs, and ease data manipulation for spikes rejection. Besides this, it is a non intrusive technique.

It was verified here the adequacy of the ultrasonic sensor for measuring physical characteristics of hydraulic jumps and its turbulence parameters. The ultrasonic sensor measures specifically free surface instantaneous levels along the longitudinal direction. With the acquired data, mean profile calculations and spectral analyses can be perfomed, showing which frequencies are presented in the output signals. Besides, the characteristics lengths can be evaluated (roller length and jump length) as functions of turbulence parameters.

In the present analysis, results from Simões, *et al.*(2010, 2012) were used as basis for comparisons. The authors made tests for inflow Froude number of 3.0. The analysis covered mean free surface profiles, Strouhal number, roller length and hydraulic jump length.

The main differences between the data of Simões, *et al.*(2010, 2012) and results from others studies were observed in the quantification of the lengths of the roller and of hydraulic jump. In the present study a more detailed analysis of the different deffinitions was made, pointing to the convenience of using the suggestions of Simões, *et al.* (2010, 2012), who choose the roller end as the position where the free surface "stops increasing" (does not grow substantially), while the hydraulic jump length was considered as the section corresponding to the distance from the toe of the hydraulic jump until the first section of the region of invariance of the w'/V_c curve. In particular for hydraulic jump lengths, a new equation was proposed based on the decay ration of the relative turbulence intensity.

Considering the main purpose of this study, that is , the comparison of different measurement methodologies, few data were found in the literature for F_1=3.0 using LDV, PIV, or alternative methodologies. Therefore, most of the comparisons were made for acoustic displacement data.

The literature data used in the present analysis point to the convenience of using acoustic sensors in measurements of the hydraulic jump, and to the necessity of more experimental measurements using ultrasonic sensors in order to clarify the ways to use turbulence as a criterium for quantifying hydraulic jump characteristics.

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