Velocities measurement in highly turbulent and aerated flows

Luis G. Castillo and José M. Carrillo
Civil Engineering Department, R&D Hidr@m Group - www.upct.es/hidrom
Universidad Politécnica de Cartagena, Paseo Alfonso XIII, 52, 30203 Cartagena, Spain
e-mail: luis.castillo@upct.es; jose.carrillo@upct

Measurement of instantaneous velocities with ADV equipment, are very reliable in laminar and turbulent flows without the air presence. However, in two-phase (water-air) flows, such as inside of a hydraulic jump, the register measurements can be wrong. When air bubbles pass through the measurement volume, the sound echo is not correctly transmitted. In this paper some digital filters are analyzed and applied to the registers of instantaneous velocities measurements inside of free and submerged hydraulic jump. The obtained results are compared and contrasted with supported experimental and theoretical results.

Keywords: Acoustic Doppler Velocimeter, digital filtering, turbulent high two-phase flow

1 INTRODUCTION

Acoustic Doppler Velocimeter (ADV) equipments measure the velocity of acoustic targets moving with the fluid, rather than directly the fluid velocity. Since these acoustics targets follow the fluid motion with negligible inertial lag, their velocity is assumed to be identical to the velocity of the fluid. ADVs are able to measure the time-averaged flow field with an accuracy better than 4%. However, the signal suffers parasitical noise contributions with the following characteristics (Blanckaert and Lemmin [1]):

- Its energy content is uniformly distributed over the investigated frequency domain (white noise).
- It is unbiased: $\overline{\sigma_i} = 0$.Therefore, it does not affect the estimation of the time-averaged velocity $\overline{u}$.
- It is statistically independent of the corresponding true Doppler frequency: $\overline{\sigma_i f_{D,i}} = 0$ if $i \neq j$.
- The noise of the different receivers is statistically independent: $\overline{\sigma_i \sigma_j} = 0$. Noise-free estimation of the turbulent shear stress are obtained if $\overline{\sigma_i^2} = \overline{\sigma_j^2} = \overline{\sigma^2}$. However, the estimation of the turbulent normal stress is affected by noise.

The spikes in ADV time series can be caused by many factors, including high turbulent intensities, aerated flows that have undesirable acoustic properties, and phase difference ambiguities that occur when the velocities exceed the upper limits of ADV probe velocity range. Although spikes can be reduced or eliminated in many cases by adjustment of probe operational parameters, there are some situations in which spikes cannot be entirely avoided (Wahl [2]).

A hydraulic jump is characterized by a sudden rise of the free-surface, with strong energy dissipation and mixing, large-scale turbulence, air entrainment, waves and spray. So, in order to eliminate and/or correct the anomalous data but maintaining the continuity of the register, it is necessary a digital filtering of the information.

2 METHODS

Despiking involves two steps: (1) detecting the spike and (2) replacing the spike. There are some spikes detection algorithms. In this paper the following ones have been applied:

- Acceleration Thresholding Method (Goring and Nikora [3]), modified in this paper.
- Progressive cut-off of the lower and upper limits as a function of the statistical 5 and 95% (Castillo [4]).
- Phase-Space Thresholding Method [3], with the modified version [2] and in this paper.

2.1 Acceleration Thresholding Method (ATM+C)

In order to consider a point like spike, the acceleration must exceed a threshold $\lambda_a g$, and the absolute deviation from the mean velocity of the point must exceed $k\sigma$, where λ_a is a relative acceleration threshold, σ the standard deviation and *k* a factor to be determined. The acceleration is calculated from $a_i = (u_i - u_{i-1}) / \Delta t$, where u_i is the discrete velocity time series and Δt the sampling interval. This method is a detection and replacement procedure with two phases: one for negative accelerations and the second for positive accelerations. In each phase, numerous passes through the data are made until all data points conform both, the acceleration criterion $\lambda_a g$ and the magnitude threshold $k\sigma$.

Goring and Nikora [3] indicate that good choices for the parameters are: $\lambda_a = 1\text{-}1.5$ and $k = 1.5$. However, for hydraulic jump cases, the λ_a value should be calculated as a function of the section position (d_j) inside of the hydraulic jump and its corresponding Froude number, Fr_j.Then, the acceleration a_j:

$$a_j = \frac{u_j}{\Delta t} = \frac{Fr_j\sqrt{gy_j}}{\Delta t} = \lambda_{aj}\, g \qquad (1)$$

where $\lambda_{aj} = Fr_j\sqrt{y_j}/(\Delta t\sqrt{g}) \geq 0.5$ and Δt the time interval between data points. y_j takes the depth value y_{dj} when the flow is downstream and y_{uj} when the flow is upstream (see Figure 1). In this way, the parameter λ_{aj} is established by the flow specific characteristics in each section.

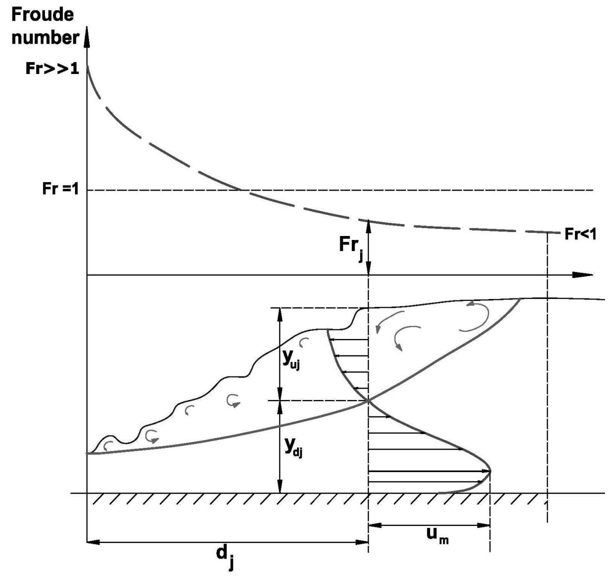

Figure 1: Froude number variation and principal parameters inside of the hydraulic jump.

The *k* threshold arises from a theoretical result from the theory of normal probability distribution, which says that for *n* independent, identically distributed, standard, normal, and random variable ξ_i, the expected absolute maximum is

$$E(|\xi_i|_{max}) = \sqrt{2\ln n} = \lambda_U \qquad (2)$$

where λ_U is denominated as the Universal threshold. For a normal, random variable whose standard deviation is estimated by σ and the mean zero, the expected absolute maximum value is $\lambda_U\sigma = \sqrt{2\ln n}\,\sigma$. However, this threshold can result very wide when the time distribution is not normal, like in the case of the velocities distribution inside of a hydraulic jump.

2.2 Progressive cut-off the lower and upper limits in function of 5% and 95% statistical (PCLU)

This method is based on the above conclusions. Hence, due to that the velocity time distribution does not fit as a normal distribution, it is better to estimate a threshold trends to the upper limit really registered in the signal. The data filtering is based on progressive cut-off of the lower and upper limits, as a function of the 5 % and 95 % statistical [4]. From the mean, $\bar{u}$ and maximum, u_{max} values registered in the data series, the first relative amplitude is determined, $A_1 = u_{max} - \bar{u}$. Next, is found the value $u_{mín} = \bar{u} - A_1$ and the general amplitude $A = u_{max} - u_{mín}$. Finally, the superior cut value, $X_{máx.c}$ and the lower cut value, $X_{mín.c}$ from the initial series are obtained, so that $X_{máx.c} = u_{max} - (0.05A)$ and $X_{mín.c} = u_{mín} + (0.05A)$. This process can be repeated if the data series need it. However, it is recommended not to do more than two filtering data, so that the initial series to be little altered. In the original method, the spike is replaced automatically by the upper or lower value of the corresponding cut. However, in this paper the spike was replaced by the sample median.

2.3 Phase-Space Thresholding Method (PSTM+W)

The method considers the concept of a three-dimensional Poincaré map or phase-space plot in which the variable and its derivatives are plotted against each other. The points are enclosed by an ellipsoid defined by the Universal criterion and the points outside the ellipsoid are designated as spikes. The method iterates until the number of good data becomes constant. Each iteration has the following steps [3]:

1. Calculate surrogates for the first and second derivatives from central differences algorithm: $\Delta u_i = (u_{i+1} - u_{i-1})/2$ and $\Delta^2 u_i = (\Delta u_{i+1} - \Delta u_{i-1})/2$. Note that is not divided by time step Δt to ensure that some equations do not become ill conditioned.
2. Calculate the standard deviations of all three variables σ_u, $\sigma_{\Delta u}$ and $\sigma_{\Delta 2u}$, and thence the expected maxima using the Universal criterion.
3. Calculate the rotation angle of the principal axis of $\Delta^2 u_i$ versus u_i using the cross correlation:

$$\theta = \tan^{-1}\left(\sum u_i \Delta^2 u_i / \sum u_i^2\right) \qquad (3)$$

4. For each pair of variables, calculate the maxima and minima ellipse. Thus, for Δu_i versus u_i the major axis is $\lambda_U\sigma_u$ and the minor axis is $\lambda_U\sigma_{\Delta u}$; for $\Delta^2 u_i$ versus Δu_i the major axis is

$\lambda_U \sigma_{\Delta u}$ and the minor axis is $\lambda_U \sigma_{\Delta 2u}$; and for $\Delta^2 u_i$ versus u_i. The major and minor axes, *a* and *b*, respectively, are the solutions of:

$$(\lambda_U \sigma_U)^2 = a^2 \cos^2 \theta + b^2 \sin^2 \theta \qquad (4)$$

$$(\lambda_U \sigma_{\Delta 2u})^2 = a^2 \sin^2 \theta + b^2 \cos^2 \theta \qquad (5)$$

A most accurate system of equations is:

$$(\lambda_U \sigma_U)^2 = a^2 \cos^2(\theta/2) + b^2 (\lambda_U \sigma_u / \lambda_U \sigma_{\Delta 2u})^2 \sin^2(\theta/2) \qquad (6)$$

$$(\lambda_U \sigma_{\Delta 2u})^2 = a^2 (\lambda_U \sigma_{\Delta 2u} / \lambda_U \sigma_u)^2 \sin^2(\theta/2) + b^2 \cos^2(\theta/2) \qquad (7)$$

5. For each projection in phase space, it has to identify the points that lie outside of the ellipse and replace them. At each iteration, the replacement of the spikes reduces the standard deviation and thus the size of the ellipsoid. This despiking algorithm uses the mean and standard deviation, the classic estimators for locations and scale, respectively. However, a single outlier of extraordinary magnitude can corrupt both parameters and affect significantly the performance. Wahl [2] proposed the sample median as an estimator of location and, the median of the absolute deviations from the sample median, as estimator of scale. He added to the WinADV computer program [5] the modified algorithm. The program incorporates too the Chauvenet´s criterion to define the rejection probability and exclusions thresholds, while the position of the *u*, Δu and Δ_u^2 data points are expressed in spherical coordinates.

3 APPLICATIONS AND CONCLUSIONS

Figures 2 and 3 show two horizontal velocity register obtained inside of a hydraulic jump in identical conditions of position and flow. The flow in the measured point was horizontal, with a very small vertical component. The registers were obtained with a data acquisition of 20 Hz, the unique difference consisted in that the velocity range of the first register was +/-100 cm/s (permitted theoretical horizontal maximum velocity +/-300 cm/s) and, for the second register, +/-250 cm/s (permitted horizontal maximum velocity of +/- 360 cm/s). In the case of the clean register, all the methods give similar results in the sample mean after of filtering and, are a bit higher than the mean value of the original series. However, the standard deviations are reduced over the five percent after of filtering. This circumstance indicates that the turbulence normal stress is not correct and, we would be able to discriminate the real stress from the white noise.

For the case of velocities registered inside of hydraulic jump, the combination ATM+C and PCLU methods constitutes the most robust procedure of filtering.

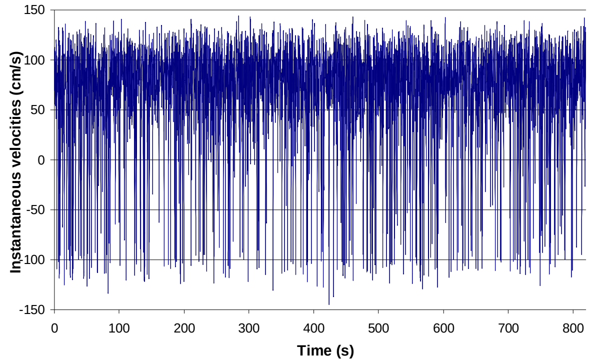

Figure 2: Pathological velocity register. Collected with a velocity range of 100 cm/s.

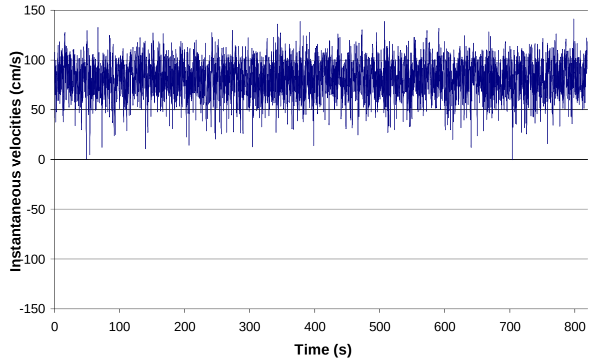

Figure 3: Clean velocity register. Collected with a velocity range of 250 cm/s.

The mean value and the standard deviation are the most similar to the original series values and, it is the only procedure that let us to obtain the mean value from the pathological register, with an error lower that 3% (Table 1). From the systematic application of the ATM+C and PCLU methods to the registers collected with velocities range of 250 cm/s in different sections of free and submerged hydraulic jumps (Figure 4).

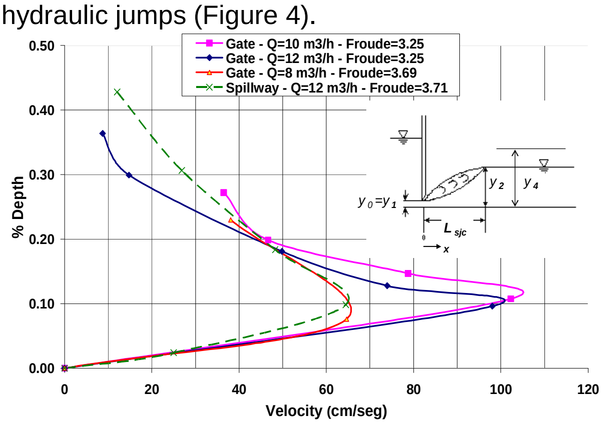

Figure 4: Velocity distributions in hydraulic jumps.

From the analysis of the mean velocity distribution, an universal velocity distribution law [6] was obtained, valid in the range [0.2 ≤ x/L_{sjc} ≤ 0.7] (Figure 5). The scalar length *Y* is the depth where the velocity is equal to the half of the registered maximum velocity, $\bar{u} = u_m/2$, and, y_{max} is the depth where $\bar{u} = u_m$.

Table 1: Comparison of results obtained by the application of different filtering methods.

		Pathological register	Clean register
Length of time series:		4504	4504
Time interval between data point (s):		0.20	0.20
Sample mean (cm/s):		69.56	81.56
Standard deviation (cm/s):		52.73	18.63
ATM+C method	Spikes identified:	1238	98
	Sample mean after of filtering (cm/s):	82.2	82.01
	Standard deviation after of filtering (cm/s):	25.96	17.78
PSTM+W method	Spikes identified:	581	44
	Sample mean after of filtering (cm/s):	80.91	81.81
	Standard deviation after of filtering (cm/s):	18.25	18.28
ATM+C and PSTM+W methods	Spikes identified:	1323	120
	Sample mean after of filtering (cm/s):	83.24	82.08
	Standard deviation after of filtering (cm/s):	24.68	17.70
ATM+C and PCLU methods	Spikes identified:	697	30
	Sample mean after of filtering (cm/s):	79.81	81.66
	Standard deviation after of filtering (cm/s):	27.59	18.56

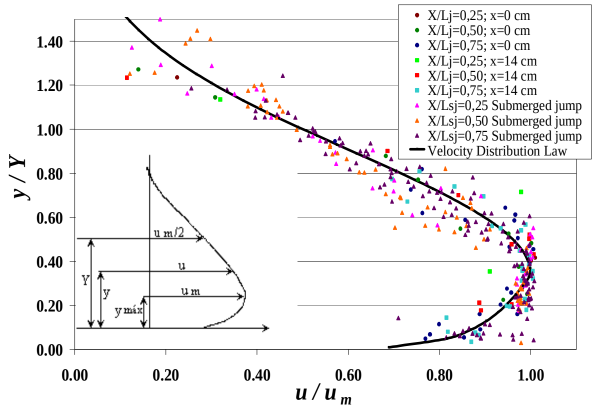

Figure 5: Velocity distribution law inside of free and submerged hydraulic jumps. Ranges of validate: 2.5 ≤ F_{r1} ≤ 5; 0.25 ≤ x/L_{sjc} ≤ 0.75; 4 ≤ y_4/y_0 ≤ 10.

The best fit of the velocity distribution law inside of free and submerged hydraulic jumps are:

$$\frac{\bar{u}}{u_m} = \left(\frac{1}{k}\frac{y}{Y}\right)^{1/n}; \quad 0 \le \frac{y}{Y} \le k \qquad (8)$$

$$\frac{\bar{u}}{u_m} = \exp\left[-\frac{1}{2}\left\{\frac{1.177}{1-k}\left(\frac{y}{Y}-k\right)\right\}^2\right]; \quad k \le \frac{y}{Y} \le 1.5 \qquad (9)$$

For 2.5 ≤ F_{r1} ≤ 5, 0.25 ≤ x/L_{sjc} ≤ 0.75, 4 ≤ y_4/y_0 ≤ 10, the parameters *k* and *n* for free and submerged hydraulic jumps with undeveloped flow are 0.342 and 9.5, respectively [6].

Figure 6 shows the relationship of experimental law obtained with various submerged hydraulic jumps, and parameterized as a function of the Froude number in the flat gate. Experimental data collapse into a single experimental law with a regression coefficient R^2 = 0.984:

$$(y_4 / y_3)/F_0 = 1.173(y_3 / y_0)^{-0.766} \qquad (10)$$

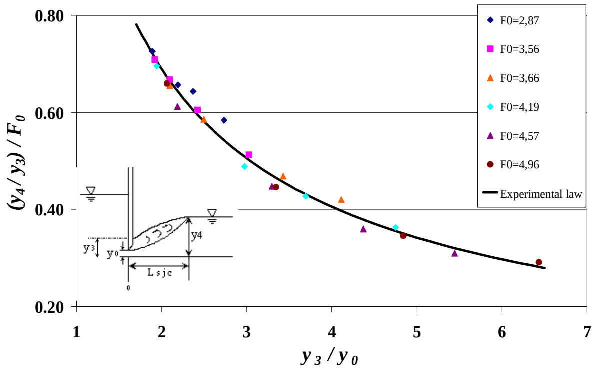

Figure 6: Experimental law for depths relations in submerged hydraulic jumps.

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