FILTERING AND VALIDATION OF VELOCITIES OBTAINED WITH ADV EQUIPMENT INSIDE OF HYDRAULIC JUMPS

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Abstract. *Measurement of instantaneous velocities with ADV equipment, are very reliable in laminar and turbulent flows without the air presence. However, in two-phase flows (water-air), for example inside of a hydraulic jump, the register measurements can be wrong when air bubbles pass through the measurement volume, because in this instant the sound echo is not correctly transmitted. In this paper are analyzed some digital filters and applied to the registers of instantaneous velocities measurements inside of some configurations of free and submerged hydraulic jump.*

1 INTRODUCTION

Acoustic Doppler Velocimeter (ADV) 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 fluid velocity. ADVs are able to measure the time-averaged flow field with an accuracy that is better than 4%. However, the signal suffers parasitical noise contributions and this noise has 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 estimates 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 estimates of the turbulent shear stress are obtained if $\overline{\sigma_i^2} = \overline{\sigma_j^2} = \overline{\sigma^2}$. However, the estimates of the turbulent normal stress, are 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, it is necessary a digital filtering of the information, in order to eliminate and/or correct the anomalous data but maintaining the continuity of the register.

2 METHODS

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

- Acceleration Thresholding Method (Goring and Nikora[3]) and modified in this paper.
- Progressive cut of the lower and upper limits in function of 5 and 95% statistical (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 a point be a 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 is the standard deviation and *k* is a factor to be determined. The acceleration is calculated from $a_i = (u_i - u_{i-1}) / \Delta t$, where u_i is 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 to the acceleration criterion $\lambda_a g$ and the magnitude threshold $k\sigma$. Goring and Nikora[3] indicate that good choices for the parameters are: $\lambda_a = 1-1.5$ and $k = 1.5$. However, we have observed that for hydraulic jump cases the λ_a value must be calculated in function of the *j* section position (d_j) inside of hydraulic jump and its corresponding Froude number, Fr_j .Then the acceleration a_j in function of Froude number is:

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

Where $\lambda_{aj} = Fr_j\sqrt{y_j}\,/(\Delta t\sqrt{g}) \geq 0.5$, Δt is 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 of measurement.

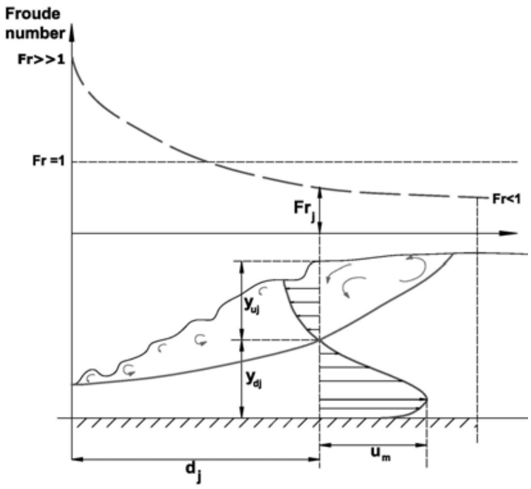

Figure 1. Froude number variation and principal parameters inside of hydraulic jump

The threshold *k* that is usually applied arises from a theoretical result from normal probability distribution theory which says that for *n* independent, identically distributed, standard, normal, random variable ξ_i , the expected absolute maximum is $E(|\xi_i|_{\max}) = \sqrt{2\ln n} = \lambda_U$, where λ_U is denominated the Universal threshold. For a normal, random variable whose standard deviation is estimated by σ and the mean zero, the expected absolute maximum is $\lambda_U \sigma = \sqrt{2\ln n}\sigma$. However, this threshold can result very wide when the time distribution is not normal, as in the case of the velocities distribution inside of a hydraulic jump.

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

The method is based on the above conclusions. So, because the velocity time distribution does not fit a normal distribution, then 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 of the lower and upper limits, in 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 they are obtained the superior cut value, $X_{máx.c}$ and the lower cut value, $X_{mín.c}$ from the initial series, 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 Thersholding Method (PSTM+W)

The method uses 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 $\theta = \tan^{-1}\left(\sum u_i \Delta^2 u_i / \sum u_i^2\right)$.
4. For each pair of variables, calculate the ellipse that has maxima and minima. 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 $(\lambda_U \sigma_U)^2 = a^2 \cos^2\theta + b^2 \sin^2\theta$ and $(\lambda_U \sigma_{\Delta 2u})^2 = a^2 \sin^2\theta + b^2 \cos^2\theta$.

However, it can be demonstrated that an equations system more precise obeys to the following expressions:

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

$$(\lambda_U \sigma_{\Delta 2u})^2 = a^2 (\lambda_U \sigma_{\Delta 2u} / \lambda_U \sigma_u)^2 \sin^2(\theta/2) + b^2 \cos^2(\theta/2). \qquad (3)$$

5. For each projection in phase space, identify the points that lie outside of the ellipse and replace them.

At each iteration, 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 and, the position of the *u*, Δu and Δ_u^2 data point is expressed in spherical coordinates.

3 APPLICATION AND CONCLUSIONS

Figure 2 shows two horizontal velocity register obtained inside of a hydraulic jump in identical conditions of position and flow. The registers were obtained with a rate of data acquisition of 5 points per second and, the unique difference consisted in that the velocity range of the left register was +/-100 cm/s (theoretical horizontal maximum velocity +/-300 cm/s) and, for the right register, +/-250 cm/s (horizontal maximum velocity of +/- 360 cm/s).

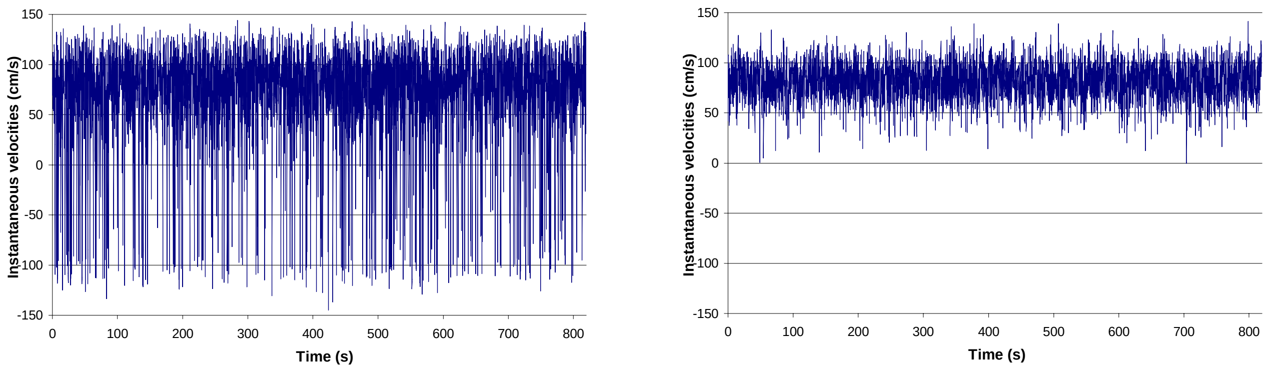

Figure 2. Types of velocity registers. Left: pathological register. Right: clean register

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. It is interesting to note that for the case of velocities registered inside of hydraulic jump, the combination ATM+C and PCLU methods constitute the more robust procedure of filtering. We can observe that the mean value and the standard deviation are the most similar to the original series values and, is the only procedure that let us obtain the mean value from the pathological register, with an error lower that 3% (Table 1). From systematic application of the ATM+C and PCLU methods to the time registers of velocities in different sections inside of free and submerged hydraulic jumps (Figure 3a) and, from analysis of the mean velocity experimental distribution, it was obtained a universal velocity distribution law[4], in the range [$0.2 \leq x/L_{sjc} \leq 0.7$] (see Figure 3b).

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

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

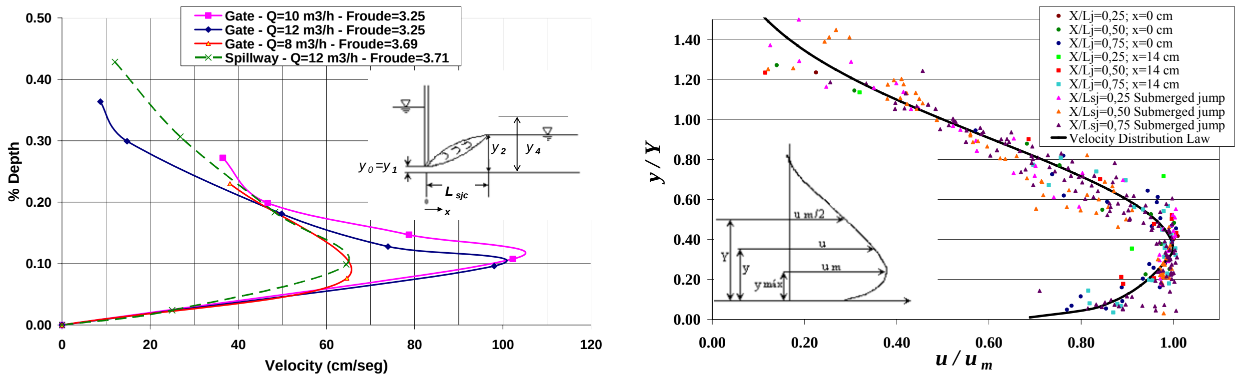

Figure 3. (a) Velocity distributions in the middle of hydraulic jump. (b) Velocity distribution law inside of free and submerged hydraulic jumps. Validities ranges: $2.5 \leq F_{r1} \leq 5$; $0.25 \leq x/L_{sjc} \leq 0.75$; $4 \leq y_4/y_0 \leq 10$

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