Ultrasonic wave interaction with air-water boundary layer

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This paper presents a collaborative study of the Universities of Strasbourg and Hokkaido with the support of Ubertone. Its goal is to analyze and understand the ultrasound wave behavior at the water-air boundary. Measurements with an Ubertone UB-Flow profiler have been done for different water height and discharge configurations on a flume of 16 meter length and 0.6 meter wide. The instrument allows the possibility to work on the raw Doppler data. This facility was used to dissect the phenomena on the air-water interface and to get the interpretations.

Keywords: Acoustic, Doppler method, water height scattering

1 INTRODUCTION

There are several methods for the flow velocity profile evaluation. One of the commonly used is the pulsed ultrasound technique: the estimation of the flow velocity at different depths along a profile can be obtained by Doppler evaluation from the backscattered acoustic signal. The measured ultrasonic signal at each depth is the result of the reflection of the emitted beam by the moving scatterers in a volume defined by the ultrasonic beam geometry and the range-gated echo duration [1].

Getting accurate velocity or amplitude measurements through this technique might become difficult if the observed volume is close to a physical boundary. Indeed the amplitude of the generated parasitic echo might strongly disturb the measurement. This disturbance can be observed in configurations where the Doppler instrument is placed in the bed of an open channel flow, emitting the ultrasonic beam up, with a weak angle to the vertical. Often a significant decrease in the fluid velocity near the surface is observed although it doesn't reflect the flow's physics.

Many studies have been done on the ultrasonic detection of moving interfaces in gas-liquid two-phase flows [2], using variety of information's coming from the scattered intensity, Doppler shift or statistics about Doppler velocity spreading near the interface.

The aim of the present work focuses on analyzing and understanding the ultrasound wave behaviour at the water-air boundary, when the instrument has a weak angle with the vertical for both measurement of the velocity profile on the flow and the water height. In order to understand the different effects on the fluid velocity and amplitude measurements near the surface, the study of the air-liquid moving interface is carried out on the complex raw Doppler data samples accessed for each volume. Arguments for the observed phenomena will be given as well as an interpretation of the possible information on the ultrasound beam after reflection on water height.

2 METHODS

2.1 Pulsed ultrasound principle

The measurements were performed with an UB-Flow profiler [3], which has three functionalities: it allows to record a flow velocity profile, the measurement of the backscattered signal amplitude and the determination of the water height. This instrument works on the pulsed principle and thereby allows precise knowledge of the position in the flow of a given data at a given time stamp [4].

The UB-Flow is a single immersed hydrodynamic device equipped with two transducers placed at the front. Measurements from this study were performed with the transducer centered on 1.5MHz with the first layout of the instrument (figure 1).
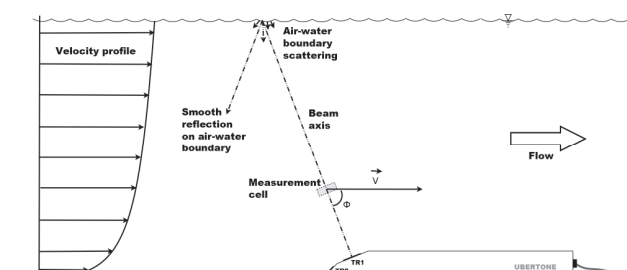

Figure 1: UB-Flow in a flume

A standard set-up for velocity profiling with this instrument is to place it on the bed of a flume. In this

case the 1.5MHz transducer presents an angle of 75° with the flow, and is used for both measurements of velocity profile and water height. Collected data near the air-water boundary can then present following behavior:

      -spreading of backscattered amplitude over several cells

      -substantial velocity decrease near the boundary layer

2.2 Background on air-water boundary layer

Ultrasound wave reflection on the water-air boundary layer exhibits a complex behavior depending on the size, the shape and the motion of the interface.

With a smooth, undisturbed air-water interface, the ultrasound waves reflect symmetrically to the plane perpendicular to the boundary layer. Thus, in our layout, with an angle of 15° with vertical, no signal from the interface returns to the transducer and the interface acts like a mirror for ultrasounds (figure 1).

When the air-water interface is in a disturbed state, motion and shape of the boundary layer as well as the surface wavelets allow the scattering of the ultrasonic waves in a large cone that can be received by the transducer (figure 1).

As our measurements were carried out with an ultrasonic beam showing a weak angle of 15° to the vertical, no detection is possible in the case of a smooth interface, but only in a turbulent situation, which is the case in a standard flow.

The air-water interface information can then be present in several measurement cells depending on the instrument configuration, and is mixed with backscattered signal coming from the suspended particles in motion within the flow. The main criterion is the position of the cells in relation to the ellipsis formed by intersection of ultrasound beam and air-water interface.
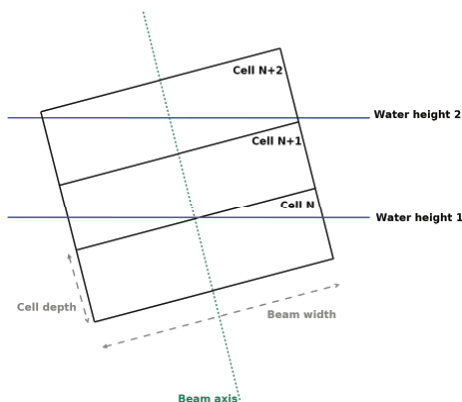

Figure 2: Ultrasound cells placement and different air-water interfaces

An example of measurement cells with different possible water heights is shown figure 2. The number of cells impacted by the air-water interface

depends on the beam width and depth, for a given transducer angle with the vertical.

3 MEASUREMENTS AND OBSERVATIONS

3.1 Open Channel setup

Measurements were done on the flume of the hydrologic platform of University of Strasbourg. This flume has a length of *16 m*, a width of *60 cm* and a maximum water height of *80 cm*. Its slope is adjustable. The flow rate and height of water in the channel were controlled by a pump and were measured by an electromagnetic flow meter and a scale, respectively. The instruments were placed in the flow, in an area where the hydraulic regime is well established. Their measurement beams go from the canal bottom to the water surface (figure 3), therefore with an angle of 75° with the flow.

Figure 3: Two UB-Flow's placed in the flume

A typical configuration for the instrument is given in Tab. 1.

Table 1: Parameters of the instrument.

Variable	Symbol	Value
Carrier frequency	$f_0(MHz)$	1.5
Cycles per pulse	N_{em}	4
Pulse Repetition frequency	$PRF(Hz)$	500
Number of cells	N_{vol}	62
Cell depth	$d_{vol}(mm)$	2.5

Measurements were done for different water heights growing from *~30cm* to *~45cm*.

3.2 Profile scanning

Figure 4 shows a typical velocity and echo intensity record for a configuration with a water height of *44.5 cm*. The main peak in the echo intensity profile corresponds to the air-water interface detected by the ultrasonic beam. However we can observe a second peak on the same curve synchronized with a fall in the velocity profile (around *43cm*). In order to

verify that it is not a multi-reflection of the ultrasonic waves from a previous burst, the PRF was changed, without effect on the shape and the position of this phenomenon.
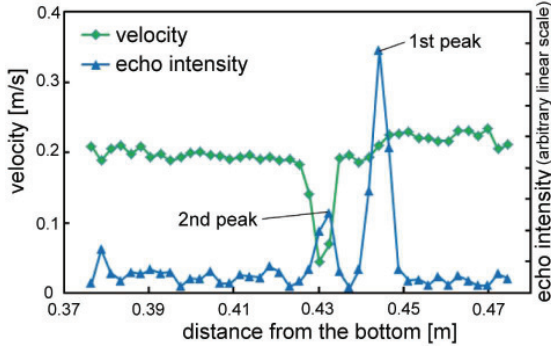

Figure 4: Detailed profiles of the velocity and the echo intensity with a free surface at 44.5cm

The hypothesis investigated is that this behavior is generated by the side lobes of the ultrasonic beam. These lobes send hugely less energy in the medium but if they meet large elements, like the air-water interface, the backscattered signal can be important. In order to understand this phenomenon, the raw data have been investigated. The UB-Flow allows the record of the complex envelope with in-phase and quadrature components of the Doppler signal for a selected cell. The Doppler signal in several cells was analyzed for the same established flow rate.

4 RESULTS AND DISCUSSION

4.1 Transducer radiating aperture

A cylindrical transducer produces an ultrasonic beam which is equivalent to a spherical wave in his farfield region and can be written [5] at range r and time t as follows:

$$P(r,\theta,t) = \Re\left(P_0 r_0 \frac{D(\theta)}{r} e^{-\alpha r} e^{i(kr-\omega t)} \right) \qquad (1)$$

P_0 is the reference pressure, normally defined at $r_0 = 1m$, $D(\theta)$ is the transducer directivity function, θ is the angle between the position r and the axis of the transducer, α is the medium attenuation, k is the wavenumber for the sound in water and ω is the wave pulsation. The directivity function represents the angle reliance of the emitted pressure and is written as:

$$D(\theta) = \frac{2J_1(ka_t \sin\theta)}{ka_t \sin\theta} \qquad (2)$$

J_1 is a Bessel function of the first kind and a_t is the radius of the transducer. Figure 5 represents the modulus of this function and shows clearly that there is a part of the ultrasound intensity that is emitted in a direction near to an angle of 15° with the axis of the transducer. As the transducer in this case has an angle of 75° with the flow, this part is therefore

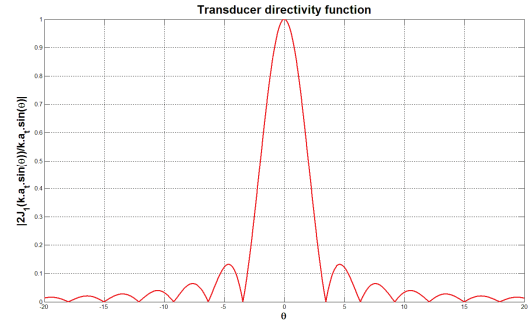emitted perpendicular to the air-water interface.

Figure 5: Modulus of the directivity function $D(\theta)$

4.2 Air-water interface

To analyze and fully understand the behavior of the intensity and the velocity profiles at the interface, measurements were carried out in this area. Figure 6 shows a schematic illustration of the measurement points for the signal investigation. The cell located on point A is fully in the flow. The cell located on C contains the information coming from the flow through the main lobe of the ultrasonic beam, but can also get air-water interface information on C' through the lobes at nearly 15°. The cell located on B contains the information coming directly from the air-water interface area through the main lobe.
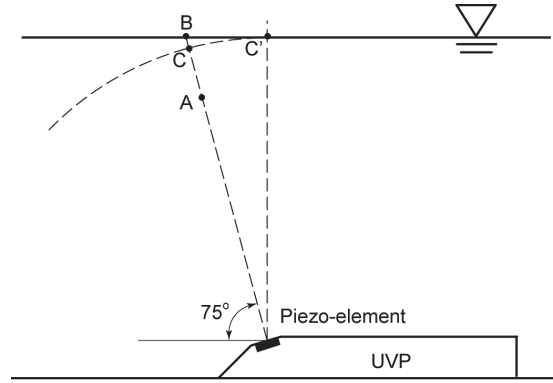

Figure 6: Schematic illustration of the investigated areas

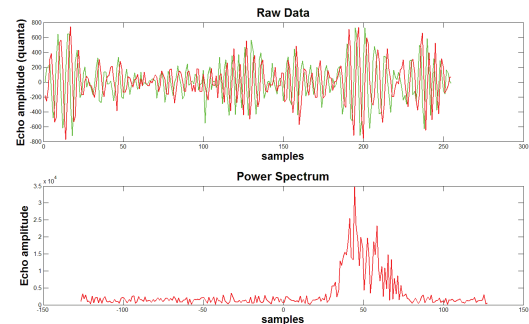Figure 7 shows the complex raw data and their corresponding Fourier spectra on cell A.

Figure 7: a) Complex raw Doppler data b) Associated Power Spectrum

The Doppler signal backscattered by the particles

moving with the flow can easily be observed on the raw data. The Fourier transform's gives a standard spectrum centered on a mean Doppler shift.

Figure 8 shows a typical result on the complex raw data and their corresponding Fourier spectra for the cell located at position C.
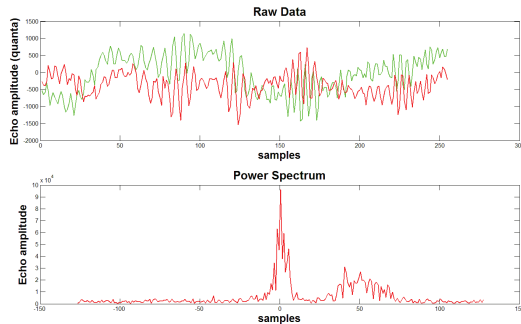

Figure 8: a) Complex raw Doppler data b) Associated Power Spectrum

The raw data show the presence of the signal coming from the moving particles, but superimposed with a kind of moving baseline. According to these fluctuations with different time scales, the power spectrum has two clear peaks: the peak at a higher frequency shows a similar Doppler frequency as that on cell A, and a peak at lower frequency, around zero. These results can be interpreted as the superposition of Doppler signal backscattered by particles in the main lobe of the ultrasonic beam and air-water interface reflecting waves coming from other lobes with a perpendicular incidence. In spite of the poor energy present in these lobes, the energy of the perpendicular reflection is close to the energy backscattered by particles in the main lobe.

Finally, figure 9 shows a typical result on the complex raw data and their corresponding Fourier spectra for the cell located at position B.
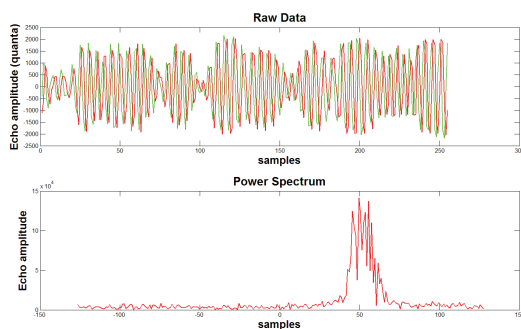

Figure 9: a) Complex raw Doppler data b) Associated Power Spectrum

Here, there is no presence of energy around zero in the power spectrum. Indeed, the symmetrical reflection of the main beam to the plane perpendicular to the boundary layer avoids a strong backscattering from the air-water interface. Nevertheless, the Doppler echo characterizing the particle motion in the flow is several times stronger

than in the cell A. An interpretation can be that the state of the air-water interface is enough turbulent so that the surface wavelets (which move at a velocity near to that of the particles) allow the scattering of the ultrasonic waves back to the transducer's direction.

Figure 10 shows the mean power spectrum for the three cases discussed before. It is clear that, compared to cell A, there is a phenomenon on the cell C/C' which is linked to the reflection of waves from secondary lobes on the air-water interface, but we can see that the Doppler frequency backscattered from particles is not biased, so frequency filtering could be applied here. Another phenomenon, explained before, occurs on cell B where the backscattered echo is stronger than in cell A.
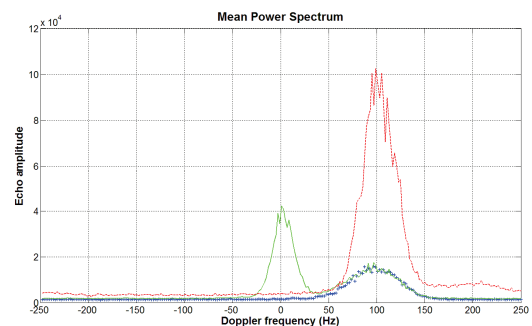

Figure 10: a) Blue cross line for cell A b) Red dashed line for cell B c) Green full line for cells C/C'

5 CONCLUSIONS

The present study focused on the examination of velocity and echo intensity near the air-water interface in an open channel flow. The observed phenomena (figure 4) can be explained by the echos coming from the secondary lobes of the ultrasonic beam and by the surface conditions of the flow.

It could be interesting to make further investigations in order to understand the weak increase of the Doppler shift in cell B, as well as the impact of the motion of the free surface.

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