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Flow velocity profiling using acoustic time of flight flow metering based on wide band signals and adaptive beam-forming techniques

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Abstract. In this paper, we present a novel approach to non-intrusive flow velocity profiling technique using multi-element sensor array and wide-band signal's processing methods. Conventional techniques for the measurements of the flow velocity profiles are usually based on intrusive instruments (current meters, acoustic Doppler profilers, Pitot tubes, etc.) that take punctual velocity readings. Although very efficient, these choices are limited in terms of practical cases of applications especially when non-intrusive measurements techniques are required and/or a spatial accuracy of the velocity profiling is required. This is due to factors related to hydraulic machinery down time, the often long time duration needed to explore the entire section area, the frequent cumbersome number of devices that needs to be handled simultaneously, or the impossibility to perform intrusive tests. In the case of non-intrusive flow profiling methods based on acoustic techniques, previous methods concentrated on using a large number of acoustic transducers placed around the measured section. Although feasible, this approach presents several major drawbacks such as a complicated signal timing, transmission, acquisition and recording system, resulting in a relative high cost of operation. In addition, because of the geometrical constraints, a desired number of sensors may not be installed. Recent results in acoustic flow metering based on wide band signals and adaptive beamforming proved that it is possible to achieve flow velocity profiles using less acoustic transducers. In a normal acoustic time of flight path the transducers are both emitters and receivers, sequentially changing their roles. In the new configuration, proposed in this paper, two new receivers are added on each side. Since the beam angles of each acoustic transducer are wide enough the newly added transducers can receive the transmitted signals and additional time of flight estimation can be done. Thus, several flow velocities are possible to be computed. Analytically defined emitted wide band signals makes possible the identification of signals coming from each transducer. Using the adaptive beam-forming algorithm the receiving transducers can record different signals from the receiver, equivalent to different propagation paths. Therefore, different measurements of time of flight are possible, leading to additional flow velocity measurements. Results carried out in an experiment facility belonging to ICPE-CA, Bucharest - Romania allowed to the validation of the flow velocities computed using this new technique, in symmetric, asymmetric and uneven flow conditions. The acoustic derived values were referenced with those provided from a Pitot tube probe installed in the test channel and the results obtained by the method proposed in this paper are relatively close to this reference.

1. Introduction

In the hydraulic equipment management, the velocity profile represents a fundamental parameter that provides data for flow analysis and its estimation is a topic of interest and great challenge [1]. Flow velocity profile shows not only the velocity magnitude, but also information on transported fluid's behaviour through the domain of interest [2]. Non-intrusive acoustic methods are among the current techniques used in dynamic flow measurements. In contrast to conventional methods, where the



measurement instrument interfere with the flow domain, the flow velocity profiling using acoustic methods allows the estimation of velocity profile as a two variables function: space and time, keeping constants measuring configuration coordinates [3], [4]. Well known methods as ultrasonic pulse Doppler or laser Doppler anemometry are efficient, but limited in terms of measured velocity range imposed by the emitted wave's frequency [5]. The velocities encountered in most hydraulic applications may have high variations. Thus, the method presented in this paper solves this drawback with the use of the emitted wide band signals. In addition, the spatial distribution of the flow profiles is not obtained by adding ultrasonic sensor but by changing the sensing properties, in terms of relative phase delays between receiving sensors, providing also additional acoustic paths that increase the number of velocity points.

In order to prove its applicability, the acoustic time of flight flow metering is used here to find the open channel flow velocity profile, under different flowing regimes.

The paper is organized as follows: the measurement technique principle is presented in section 2, the wide band signals and the beam-forming techniques are detailed in section 3. The results are discussed in section 4 and the conclusions and perspectives are presented in section 5.

2. State of art

The flow profiling approach presented in this paper is based on the acoustic time of flight principle in order to evaluate the velocity profile in a certain flow domain section. A set of several acoustic paths is defined, each one estimating an instantaneous time of flight along the axis which connects the emitter and the receiver. A propagation delay corresponds to a given velocity, so if we measure the delay T (given by the difference between wave's times of flight in the flow direction and in the opposite one), and if we use the known value of the range between emitting sensor and the receiving one, D , we can estimate the particle's velocity along the path defined by the sensor's pairs.

$$v = \frac{c^2 \Delta T}{2 \cdot D \cdot \text{ctg}\left(\frac{f}{2} - \theta\right)} \quad (1)$$

where c is the sound velocity in water and θ is the angle between the flow direction and the ultrasonic beam direction. As shown by this expression the time of flight estimation impacts strongly the flow measurement accuracy. The alternative of using the impulse signals, as transmitted ones, our approach uses wide-band signals whose frequency variation range provides more robustness to the propagation phenomena. The estimation of time of flight (TOF) is then performed using matched filtering between the transmitted signal (the reference) and the received one. The main point of this methodology is the wide band signals (linear modulations, cubic, logarithmic - chirps or discrete frequency modulations, discrete phase, etc.) that have been primarily studied in the radar field, due to their excellent resolution and noise robustness properties. These properties are possible due to the instantaneous signal frequency variation, which provides a wide band duration product being operated by the principle of matched filtering (or pulse compression). As an example of the use of this technique in the context of flow rate estimation, we mention the works we presented in [6].

The property of the matched filter with the emitted signal $s(t)$ and applied to the received one $x(t)$, is that its output is defined by the correlation between these two signals. Thus, given a wide band signal, the temporally matched filter to this signal (i.e. relative to shifted versions of the signal) is constructed with the following expression (the assumption of a stationary configuration is made):

$$h(t) = a \cdot s^*(t_0 - t) \quad (2)$$

where a is a normalization factor, t_0 represents a time reference and the operator $*$ is the Hermitian operator. As this expression indicates, the filter impulse response, $h(t)$, is obtained by time reversal of the original (transmitted) signal. Let's consider the simplest model for the received signal through the measuring system:

$$x(t) = A \cdot s(t - TOF) + n(t) \quad (3)$$

where A and TOF represents, the attenuation, respectively the time of flight of the emitted signal and $n(t)$ represents the signal noise. The application of the matched filter on the signal $x(t)$, expressed as a convolution between x and h , leads to:

$$y(t) = \int_{-\infty}^{\infty} x(\dagger) \cdot s(t - \dagger) dt \tag{4}$$

The estimation of the time of flight is now reduced at the computation of the instant of time for which the matched filter response is maximal:

$$TOF = \operatorname{argmax}[y(t)] - t_0 \tag{5}$$

We also use wide band signals, in this context of flow velocity profiling, in order to ensure a good resolution in terms of wave's time of flight estimation, which leads to accurate differences in transit time computation and, implicitly, good flow velocities measurement accuracy.

3. Adaptive beamforming technique

In the previous section, the use of wide band signals and the associated matched filtering is defined as way to accurately estimate the TOF along one acoustic propagation path. The difference between the TOFs measured in the sense of flow in the counter sense conducts, via the relation (1), to the measurement of the flow velocity related to the acoustic path defined by the transmitter and the receiver. Measuring the velocities in other points requires classically the definition of the corresponding additional paths by many pairs of transmitter/receiver sensors. The alternative proposed by this paper is to use the adaptive beamforming technique is based on the coherent multi-transducer reception measurement principle [7]. According to this principle, the use of multi-element transmitting and/or receiving elements allows to change the directions of wave propagation by modifying the phase delays between the signals transmitted/received by the elements of the sensing array. In order to illustrate this principle in our case, let us consider one acoustic paths defined by one emitting element and two receivers – figure 1 (this is actually the configuration used in our experimental setup presented in the next section).

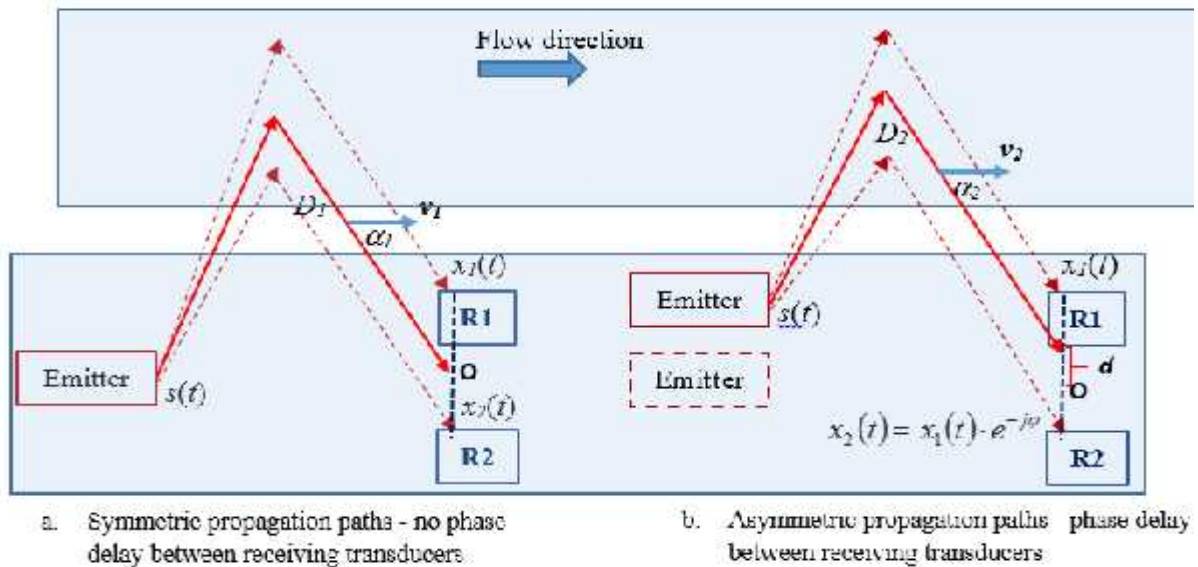


Figure 1. Principle of adaptive beam-forming in the case of two element receiver

The first case (figure 1.a) concerns the symmetric propagation paths where the emitter transducer is located at the same ranges with respect of the receiving transducers. If the transmitted signal is $s(t)$, then the received signal corresponding to the array composed by the two receiving sensors (R1 et R2) is (ignoring the amplitude attenuations):

$$x(t) = s\left(t - \frac{D_1}{c + v_1 \cos \Gamma_1}\right) \tag{6}$$

where c is the sound velocity and Γ_1 is the angle between the axis D_1 between the sensors and the flow velocity. This signal is obtained by combining the signals received by the both receiving sensors

knowing that if these signals are in phase, their combination corresponds to the acoustic path defined by the emitting sensor-bouncing on the opposite wall of the channel and the point **O** that is placed at the half distance between the both sensors. Using the phase summation of the both received signals we obtain the signal x and, by matched filtering processing and considering the same diagram but in the opposite sense of the flow, we obtain the flow velocity along this acoustic path.

In the asymmetric case, if the received signals are delayed in phase with a controlled value, φ , this is equivalent to consider that the emitter has another position (figure 1.b) and that the propagation paths don't have the same range. These new propagation paths are created by electronically modifying the line of sight of the both transducers by a controlled delay, which allow estimating the velocity in these new axes. This is done by processing the signals defined as:

$$x(t) = s \left(t - \frac{D_2}{c + v_2 \cos \Gamma_2} \right) \quad (7)$$

by considering also the signals received when the transmission is in opposite sense of the flow.

This signal corresponds to an acoustic path defined by a virtual position of the emitter that corresponds to a receiving point located at a range d with respect of point **O**.

By setting the phase delays from 0 to +/- maximum admissible value it is possible to define many propagation paths, for each one a flow velocity being estimated. The admissible value is defined as the maximum phase delay for which the two receiving transducers remain in the radiating zone of the emitter. More accuracy may be achieved by using many elements at the emission and/or receiver. This technique is very interesting to measure the velocity profile since it does not require to physically define the acoustic paths. The next section illustrates the interest behind this technique in an experimental facility.

4. Experimental tests and results

The aim of this application is to estimate an open-channel flow velocity profile, using acoustic time of flight flow metering based on matched filtering and adaptive beamforming. The facility test, located at the National R&D Institute in Electrical Engineering from Bucharest - Romania, is a closed loop where the water is circulated through a rectangular Plexiglas channel (see figure 2). We estimate different velocity profiles: symmetric and asymmetric profiles, for multiple flow mean velocities values which do not exceed 1.1 m/s. The obtained results are validated by velocity measurements using a Pitot tube installed downstream the acoustic system.

For all acoustical measurements, 45 degrees acrylic wedge transducers of 1 MHz frequency band were used. The injected waveforms are 800 - 1200 kHz linear increasing sweep frequency signals and they are recorded with a sampling frequency of 200 MHz. Thus, the temporal resolution of 5 ns ensures the estimation of flow velocities down to 0.2 m/s.

Each pair emitter-receiver is placed in "V" configuration which means that both the emitter and the receiver are clamped-on the same channel side. For simplicity, the acoustic measuring system is adapted to each velocity profile [8]. In the case of a fully developed flow with a velocity range between 0.2 and 1.1 m/s and symmetric velocity profile, an acoustic flow metering configuration composed by two emitters and two receivers is proposed. Accordingly, two "V" paths are used for the symmetric velocity profile estimation (see figure 3), which means that there are two flow velocity values available. More values, required to complete the flow velocity profile, will be obtained by phase shifting these two received signals.

In order to create a flow with an asymmetric velocity profile, the open-channel inlet was restrained with about 60% from its complete opening. In these conditions, the flow velocity is increased at the channel bottom and the difference in flow velocity between all the flow layers demand a new acoustic flow metering configuration. The new configuration allows an accurate estimation of the velocity variation in the flow domain section of interest. Two "V" paths (see figure 4) between one emitter and two receivers are created. The third one is established between the two emissions: because the waves in the flow direction and in the opposite direction are generated alternatively, the non-active emitter can record also the wave emitted by the active one. Thus, this transducers configuration allows the flow velocity measurement in three points of the flow domain transversal section. Using the same

principle as for the symmetric velocity profile estimation, also in this case the complete velocity profile can be constructed without changing the transducers position.

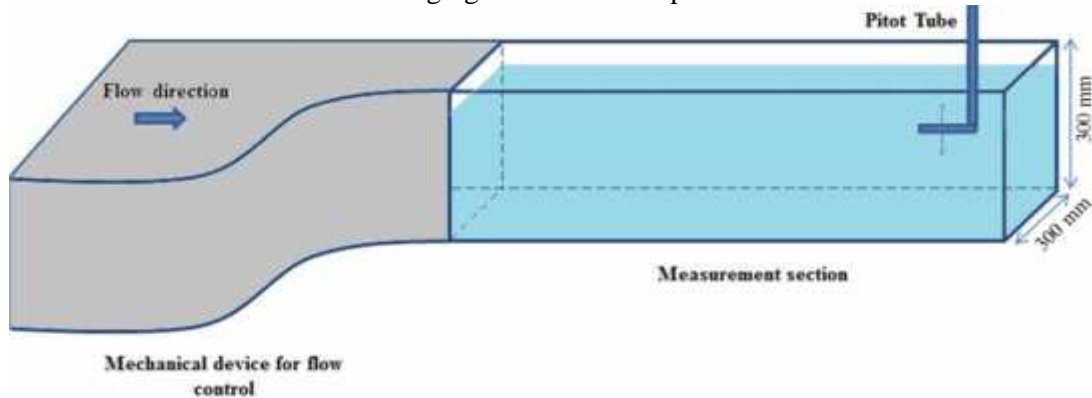


Figure 2. Facility test schema used for velocity profile estimation

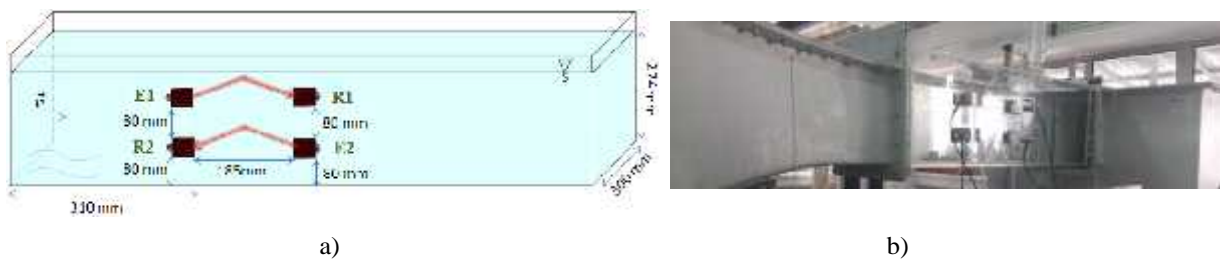


Figure 3. Experimental configuration for the symmetric velocity profile estimation: a) the two “V” paths [E1-R1] and [E2-R2] correspond to emitted signal in the flow direction (the red continuous line), respectively in the opposite direction (the red dotted line); b) The transducers clamp-on open-channel side.

One example of results is presented in figure 5, for the flow velocity profile estimation when the flow rate is equal to $0.0276 \text{ m}^3/\text{s}$, i.e. the instantaneous flow velocity in the case of the symmetric velocity profile estimation lies between 0.29 m/s and 0.30 m/s (see figure 5.a) and in the case of the asymmetric velocity profile between 0.16 m/s and 0.68 m/s (see figure 5.b). Table 1 contains the measured flow velocities using the Pitot tube installed on the experimental facility and the estimated flow velocities using the acoustic method developed in this paper.

The number of points used to construct the velocity profile is chosen by the user taking into account the measurement purpose and conditions. It is necessary to mention that the transducers setup has to ensure no influence (wave attenuation, scattering or deviation) from the free surface or channel bottom.

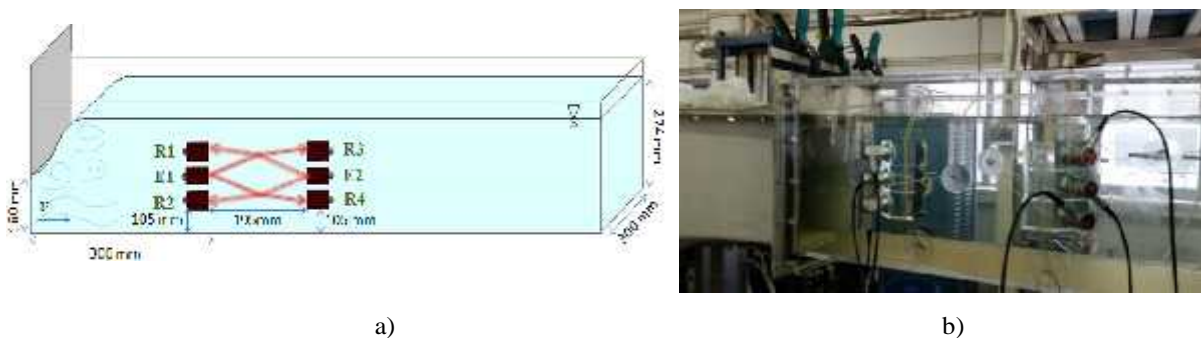


Figure 4. Experimental configuration for the asymmetric velocity profile estimation: a) each three set of “V” paths [E1-R3, E1-E2, E1-R4] and [E2-R1, E2-E1, E2-R2] correspond to emitted signal in the flow direction (the red continuous line), respectively in the opposite direction (the red dotted line); b) The transducers clamp-on open-channel side.

Table 1. Flow velocity values measured with the Pitot tube and estimated with the acoustic time of flight flow meter for the symmetric and asymmetric flow profiling

H (mm)	Symmetric velocity profile		Asymmetric velocity profile	
	V _{measured} (m/s)	V _{estimated} (m/s)	V _{measured} (m/s)	V _{estimated} (m/s)
71	0.2987	0.2964	0.6398	0.625
109	0.2986	0.2986	0.4746	0.4723
149	0.2959	0.2984	0.3468	0.3482
183	0.2965	0.2958	0.2190	0.2631
237	0.2960	0.2968	0.1646	0.1389
277	0.2912	0.2952	0.1650	0.1959

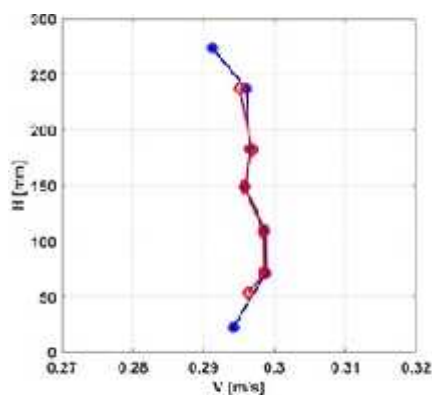


Figure 5.a Symmetric flow velocity profile measured with Pitot tube (the blue curve) and estimated with acoustic time of flight meter (the red curve)

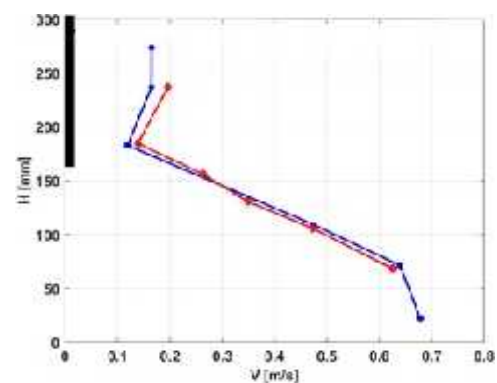


Figure 5.b Asymmetric flow velocity profile measured with Pitot tube (the blue curve) and estimated with acoustic time of flight meter (the red curve)

5. Conclusion

The adaptive beamforming technic implementation allows the signal reception directional adapting electronically. The main difficulties are related the geometric constraints for the multi-transducers configuration installation. Except that, we have shown that the adaptive beamforming algorithm applied for wide band signals represents a robust estimation of flow velocity despite different flow regimes and transducers mechanical misalignments, using multi-paths fusion information which provide an estimate of the flow velocity profile.

In the further works, we will closely investigate the propagation effects between the sensors and the inside parts of the pipe. Namely, it is obvious that the propagation in the solid part of the pipes deforms the transmitting signals but estimating carefully this deformation could be useful to improve the both matched filtering and adaptive beam-forming performances. Also, it will help us defining the ultrasonic wide-band phase interferometry that will lead to the design of agile and high resolution ultrasonic sensing systems.

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