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(A new time of flight) Acoustic flow meter using wide band signals and adaptive beamforming techniques

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Abstract. In this paper we present the result of our research concerning the improvement of acoustic time of flight flow metering for water pipes. Current flow meters are based on the estimation of direct time of flight by matched filtering of the received and emitted signals by acoustic transducers. Currently, narrow band signals are used, as well as a single emitter/receptor transducer configuration. Although simple, this configuration presents a series of limitations such as energy losses due to pipe wall/water interface, pressure/flow transients, sensitivity to flow induced vibrations, acoustic beam deformations and shift due to changes in flow velocity and embedded turbulence in the flow. The errors associated with these limitations reduce the overall robustness of existing flow meters, as well as the measured flow rate range and lower accuracy. In order to overcome these limitations, two major innovations were implemented at the signal processing level. The first one concerns the use of wide band signals that optimise the power transfer throughout the acoustic path and also increase the number of velocity/flow readings per second. Using wide band signals having a high duration-bandwidth product increases the precision in terms of time of flight measurements and, in the same time, improves the system robustness. The second contribution consists in the use of a multiple emitter – multiple receivers configuration (for one path) in order to compensate the emitted acoustic beam shift, compensate the time of flight estimation errors and thus increase the flow meter's robustness in case of undesired effects such as the “flow blow” and transient/rapid flow rate/velocity changes. Using a new signal processing algorithm that take advantage of the controlled wide band content coming from multiple receivers, the new flow meters achieves a higher accuracy in terms of flow velocity over a wider velocity range than existing systems. Tests carried out on real scale experimental facility showed an increase in acoustic time of flight estimation, accuracy of 50% with respect to the existing measurements techniques based only on signal correlation.

1. Introduction

Nowadays, the technological processes monitoring in real time is a requirement for the most of the industrial activities, in particular those processes involving transient and/or turbulent water pipe flows. The fluid flow rate is one of the hydraulic parameters [1] of major interest and the present study is focused on the flow rate estimation improvement, respectively the flow velocity inside the pipes by non-intrusive acoustical methods [2], [3]. A set of tests were carried out, for different flowing regimes, in order to develop an increase efficiency of acoustical flow metering based on time of flight estimation of the received and emitted signals by acoustic transducers.

Techniques to reduce the measurement errors are quite possible and ensure an acceptable accuracy in almost ideal measurement conditions. However, except the cases of idealized measurement conditions (laminar flow, an adequate distance from the elbows, a good propagation of the acoustic signal, etc.), there are several scenarios where current techniques are not effective. One



of them is the measurement section that may not be sufficiently far with respect to a singularity as an elbow, in which case, the rule imposed by the flow standards measurement by time of flight: a distance of 10 diameters downstream and 5 diameters upstream the singularity is not respected [4]. In this context, the flow is not stabilized and time of flight measurement is not correct. Another scenario is the excessive flow rate which leads to the "flow blow" effect (see figure 1). The energy of the received signal is weakened due to the flow velocity and the acoustic beam is shifted in space and widened. In our study, the errors introduced by the "flow blow" effect are compensated with adaptive beamforming technics.

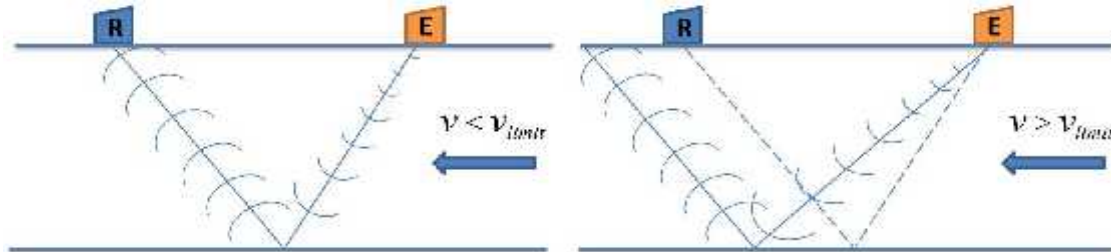


Figure 1. The flow blow appears when the flow velocity exceeds a certain value limit imposed by the flow domain conditions

Too low flow rate will result in too low propagation time differences, which requires an increased sampling frequency. The matched filtering is used for the frequency resolution improvement. Also the two-phase flow and/or the presence of the Doppler Effect can introduce errors in time of flight estimation. Our research is made under the conditions ensuring single phase flow.

This paper is organized as follows: in section 2 it is presented the time of flight estimation methodology, the section 3 contains the adaptive beamforming algorithm description, the experimental tests and results are presented and discussed in section 4. The conclusions and perspectives are highlighted in section 5.

2. State of art

The acoustic flow metering basic principle is to compute the time of flight difference of the ultrasonic emitted waves, in the flow direction and the opposite direction. The principle of average flow velocity measurement (which, together with the physical configuration, allows access to the average flow rate) is shown in figure 2, where we present the significance of the time of flight difference. A propagation delay corresponds to a change in distance, so if we measure the delay T , and use the known value of the sound velocity in water, we can estimate particle's displacement. As we also know the time between the two pulses (the one emitted from point A toward point B, and the one in opposite direction), we can calculate the particle's velocity.

One can see that the time of flight estimation impacts strongly the flow measurement accuracy. In order to increase measurement performances, this study is focused on the use of wide band signals, analyzed using matched filter. At the heart of this methodology we find 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) [5], [6].

The definition of the matched filter with the emitted signal $s(t)$ and applied to the received one $x(t)$, is given 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):

$$h(t) = a \cdot s^*(t_0 - t) \quad (1)$$

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 signal. Let's consider the simplest model for the received signal through the measuring system:

$$x(t) = A \cdot s(t - TOA) + n(t) \quad (2)$$

where A and TOA represents, the attenuation, respectively the time of arrival 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:

$$y(t) = \int_{-\infty}^{\infty} x(\tau) \cdot s(t - \tau) d\tau \quad (3)$$

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

$$TOA = \arg \max[y(t)] - t_0 \quad (4)$$

The diagram of this approach is displayed in figure 3, from which results the formula for the time of arrival of the matched filter.

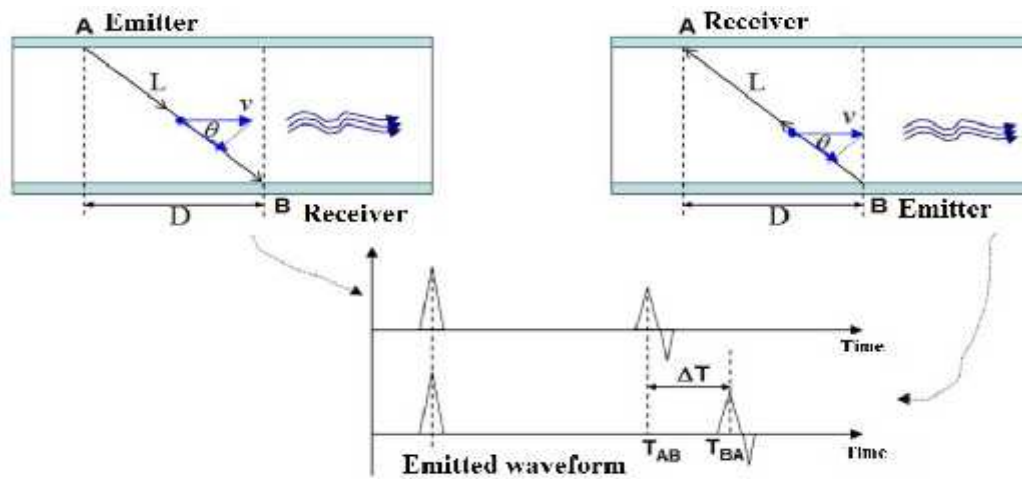


Figure 2. The illustration of the time of flight difference (ΔT) estimation (where L is the traveled ultrasonic wave physical distance, D is the distance between the emitter (point A) and the receiver (point B), θ is the emission angle and T_{AB} and T_{BA} are the time of flight values for the emitted waves in both directions)

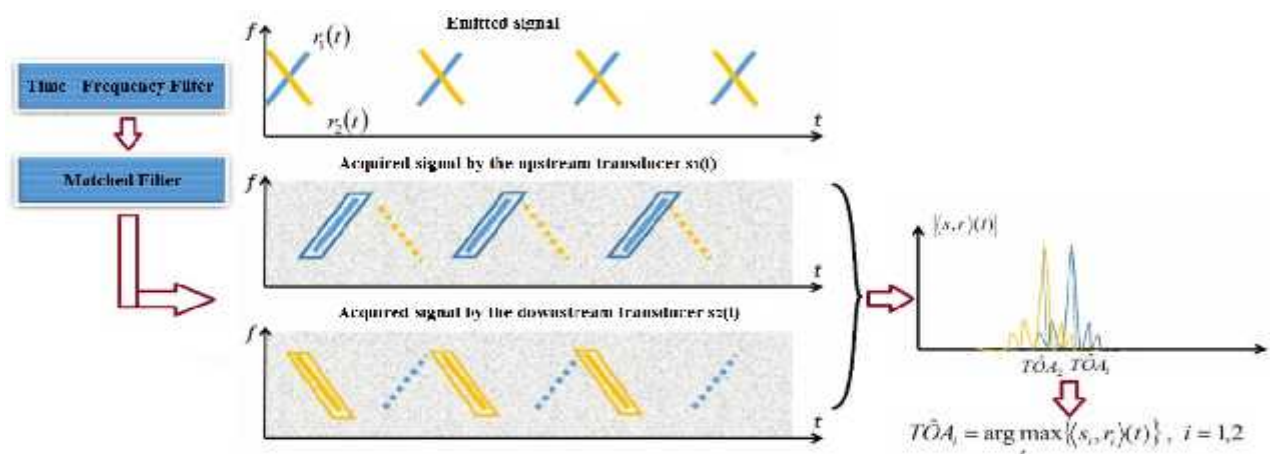


Figure 3. The diagram of the received signal processing using matched filtering technique

The estimated TOA is used to compute first the average flow velocity and then the average flow rate, in the section flow of interest:

$$Q = \underbrace{K_h}_{\text{hydraulic coefficient}} \cdot \underbrace{\frac{c^2 \Delta T}{2 \cdot D \cdot \text{ctg}\left(\frac{f}{2} - \theta\right)}}_{\text{velocity}} \cdot \underbrace{\frac{f \cdot D^2}{4}}_{\text{area}} \quad (5)$$

where θ is the wave refracted angle in water, D is the flow domain internal diameter and K_h is the hydraulic coefficient given by:

$$K_h = \frac{2n+1}{2n},$$

$$\frac{1}{n} = 0.25 - 0.023 \cdot \lg(\text{Re}) \quad (6)$$

$$\text{Re} = \frac{\rho \cdot D \cdot v_{\text{avg}}}{\mu}$$

where μ , ρ , v_{avg} are the fluid dynamic viscosity, density, respectively average flow velocity.

3. Adaptive Beamforming technique

In this section a multi-transducer reception measurement principle is presented (i.e. the adaptive beamforming technique). The reception of the emitted signal is recorded with four transducers, creating multiple recorded series, which allows the use of the beamforming algorithm. The beamforming technique (presented in figure 4) consists in shifting the received signals of each series, and selecting the optimum set of offsets that will maximize the power after the four signals summation.

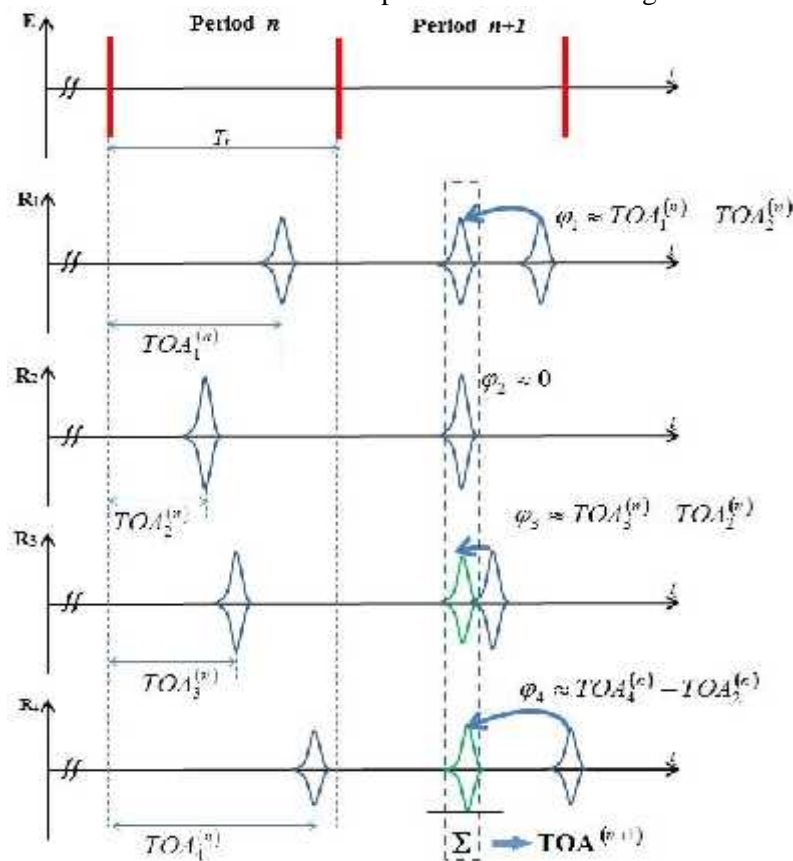


Figure 4. The beamforming algorithm principle

A priori, in this case, it is assumed that the TOAs are quasi-constants from one emission to the next one: during the repetition periods of order of micro-seconds, the hydraulic parameters do not vary so to impact the wave's propagation time and shape. To ensure maximum algorithm accuracy, a local optimization method is used: suppose that $x_i^{q_n}: q_n, i \in \{1, \dots, 4\}$ are the received signals, during the period n and Δ is the shift operator, then:

$$\Delta \{x_i^{(n)}(t)\} \{ \xi_i^{(n)} \} = x_i^{(n)}(t - \xi_i^{(n)}) \quad (7)$$

The shift operator, Δ , in the simplest case, it is identified with a translation operation, for shift values named $\xi_i^{(n)}$ (corresponding to signal i and period n). In this context, the coherent signal sum power, for the period n , is defined by the following expression:

$$P^{(n)}(\xi_i^{(n)}) = \left| \sum_{i=1}^4 \Delta \{x_i^{(n)}(t)\} \{ \xi_i^{(n)} \} \right|^2 \quad (8)$$

which is a function of $\xi_i^{(n)}$. The optimal time shifts set, $\xi_i^{(n)}$, that maximizes the relation (8) is defined by the following expression:

$$\xi_i^{(n)} = \arg \max_{\xi_i^{(n)}} P^{(n)}(\xi_i^{(n)}) \quad (9)$$

with an interval of search of phase differences defined as the neighborhood of the optimum phase shifts obtained during the period $n-1$:

$$\xi_i^{(n)} \in [\xi_i^{(n-1)} - v_i, \xi_i^{(n-1)} + v_i] \quad i = 1, \dots, 4 \quad (10)$$

where $\xi_i^{q_{n>1}}$ represents the optimal shift for the transducer i and v_i is the interval width.

The figure 5 describes the beamforming algorithm diagram in the case of multiple receivers network: $R_i, i = 1, \dots, 4$.

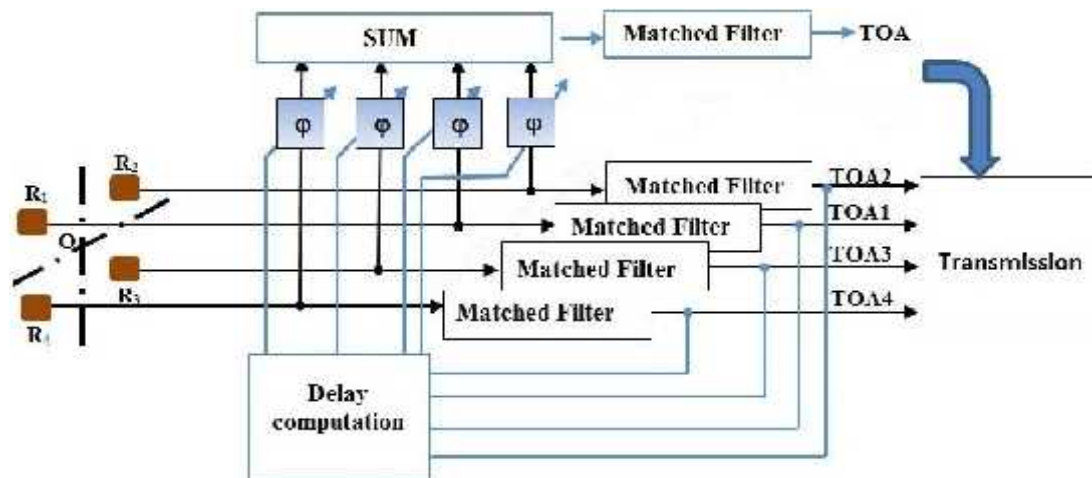


Figure 5. The beamforming algorithm diagram

Each reception is shifted with its corresponding $\xi_i^{(n)}$ computed with matched filtering method. The global TOA that will give the average flow velocity is obtained by matched filtering the shifted receptions sum with the emitted signal.

We can see that this method offers two possible TOAs computing. The first one is to estimate TOAs for the optimal set of phase shifts and to transmit them to the processing center. The second one is to provide a global TOA, after adaptive beamforming optimization.

The flexibility offered by the adapted beamforming algorithm gives greater robustness and accuracy in hydraulic parameters estimation such as flow rate, respectively the acoustical time of flight.

4. Experimental tests and results

The results presented in this section concern the flow velocity measurement through an experimental facility of Centre d'Etudes et de Recherche de Grenoble (see figure 6), which is able to reproduce ultrasonic flowmeter tests on low diameter pipe with large variation of flow rates (between 1 and 11.5 m/s). The experimental test were conducted by the Direction Technique Générale. The tests objectives are: the flow blow effect study under high flow velocity conditions and matched filtering and adaptive beamforming technics performance estimation in the case of wide flow velocity range.

The measurement configuration implementation is composed by two emitter transducers and two receiver transducers, all of them are 1MHz transducers with an emission angle of 45°. The 'V' transducers displacement is illustrated in figure 6. The signals were transmitted to transducers by a dual channel generator and acquired with three oscilloscopes (see figure 6). The received signals are amplified with a variable gain preamplifier between 12dB and 24dB.

For this experimental configuration, the emitted signals parameters are: linear frequency modulation in opposite directions (see figure 7), frequency modulation period of 40 μ s, signal period repetition of 2ms, frequency band between 800kHz – 1200kHz, 5V signal amplitude and the sampling frequency of 100MHz.

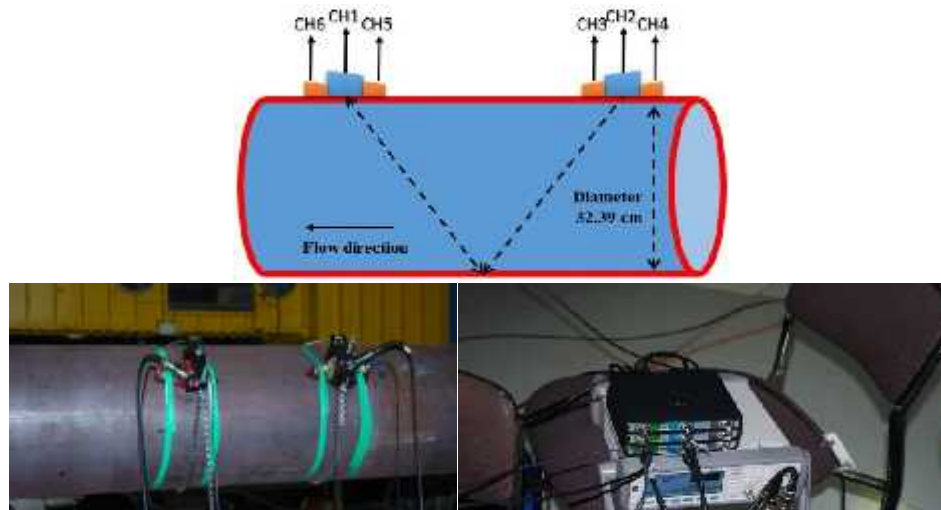


Figure 6. The transducers displacement in 'V' configuration and the equipment used for the experimental tests

In order to illustrate the important contribution of the adapted beamforming algorithm, in figure 8, the signal processing results for two different flow velocities are presented: 5 and 10 m/s. One can see that the matched filters results have different amplitudes, as well as the physical pulses without interest for the present study, but with great chances to skew the time of flight calculations. With the help of the adaptive beamforming algorithm, higher amplitude of the processing system responses is observed, while the artifact pulses are rejected. These clear advantages result in better flow rate performance estimation, shown in figure 9, for the entire flow velocity range: from 1 m/s to 12 m/s.

Another way to visualize the results efficiency is to look at the global errors estimations (see figure 10) for each flow velocity value and each algorithmic configuration: matched filter and matched filter with adaptive beamforming, and for the original recorded signals during few minutes (i.e. approximatively 200 000 signals).

Concerning the results obtained with the matched filter, one can see that the flow velocity error estimation diminishes for low values, between 3 and 9 m/s. This observation is also true for the matched filter with adaptive beamforming results, and this can be explained by the better estimation of the time of flight difference for higher flow velocities values rather than for the small ones.

When the flow velocity is over 9 m/s, the results obtained with matched filter have higher errors. Contrary, in the case of the matched filter with adaptive beamforming, the errors are even lower, meaning that the flow velocity is more precisely estimated. This result shows the motivation for the matched filter with adaptive beamforming method use in order to eliminate the flow blow phenomenon's effects.

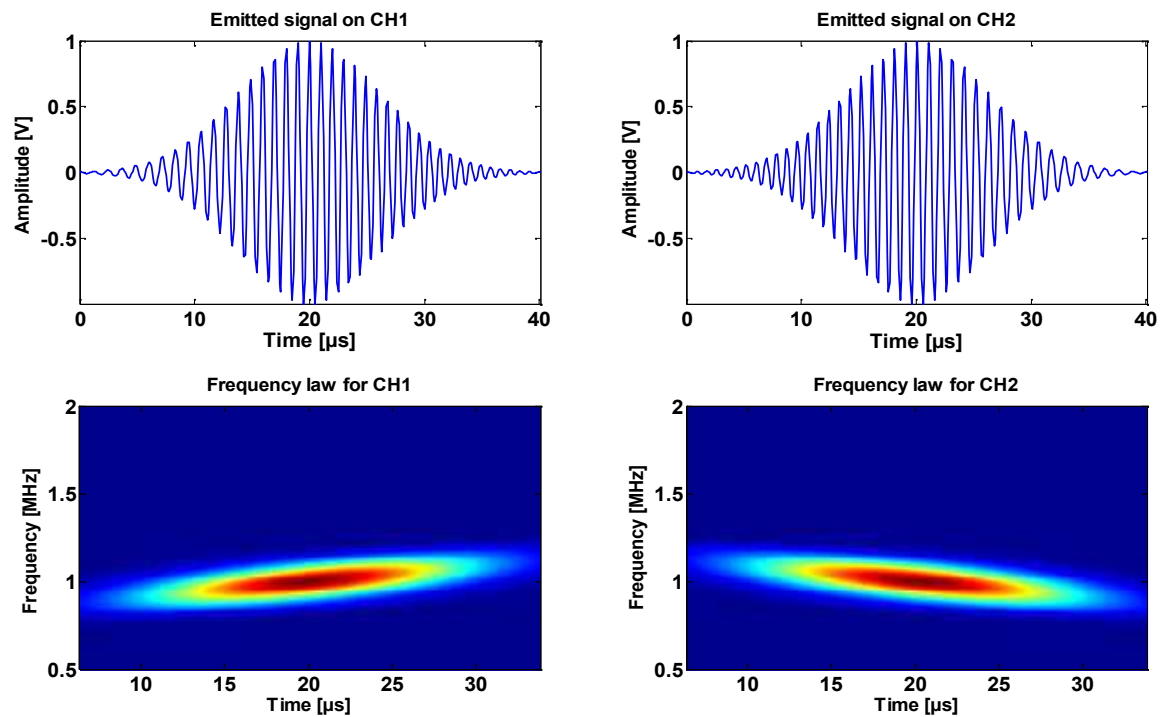
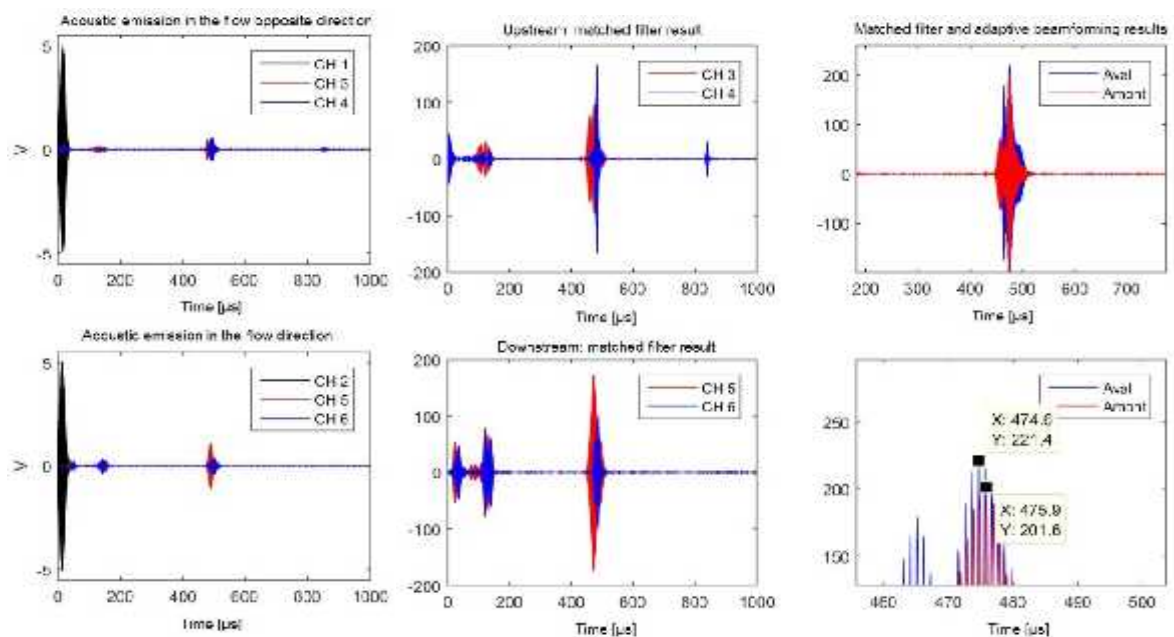
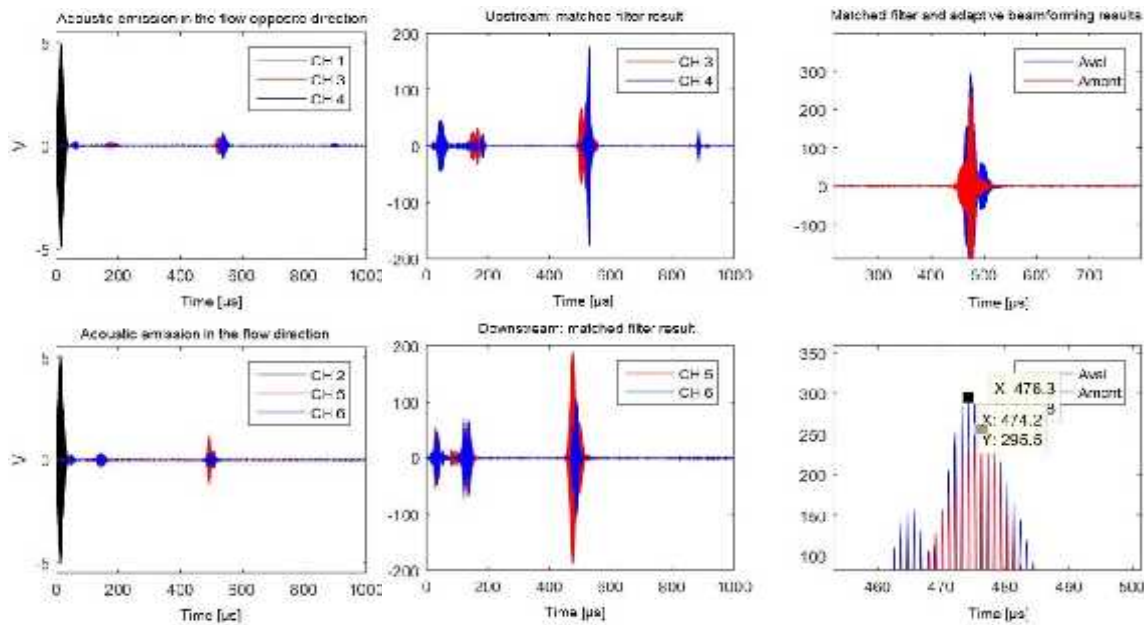


Figure 7. The emitted signals on CH1 and CH2 with their corresponding time-frequency content



a. Signal processing results, for one emission period, at 5 m/s



b. Signal processing results, for one emission period, at 10 m/s

Figure 8. Illustration of results for one emission/reception period and two different velocities

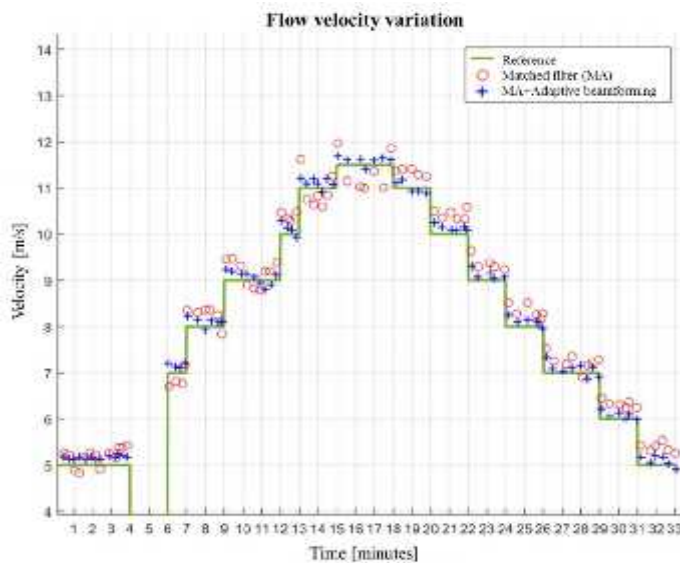


Figure 9. The mean flow velocity estimation using matched filtering and matched filter with adapted beamforming techniques

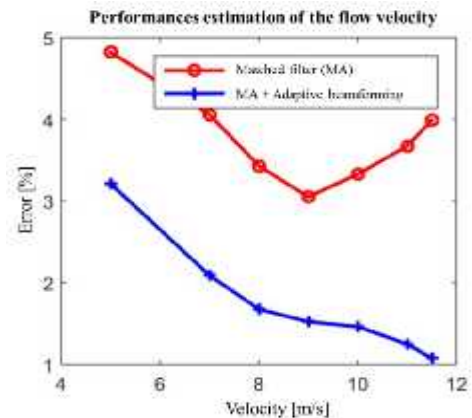


Figure 10. The error variation for flow velocity estimation using the matched filter and the matched filter with adaptive beamforming

5. Conclusions

The principal innovative aspect presented in this paper is the wide-band signal processing. Using wide-band signals, quasi-orthogonal signals can be defined in time-frequency space, in order to create a simultaneous emissions system, upstream and downstream the measurement section of interest. The advantages of this solution are the simpler electronics and the possibility to perform high frequency flow velocity measurements, which allow the transitory pressures detections that may appear in hydraulic circuits.

Acknowledgment

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