Investigation of the Performance of Acoustic Scintillation Flow Meter when Turbulence Levels are Low

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Abstract – Electricité de France (EDF) is funding a 3-year PhD work on acoustic scintillation flow metering, in association with Hydro-Québec and ASL AQFlow. The PhD project aims at improving the discharge estimation when hydraulic conditions are not ideal for acoustic scintillation measurements, as well as providing a better understanding of the effects of sources of interference which can be encountered during the measurement process and can cause inaccuracies in the velocity estimation. In order to achieve these objectives, a fast and portable data acquisition system was set up, which relies on high speed acquisition cards. Each four channel acquisition card can be connected in parallel with up to three others, thus forming a high speed multi channel data acquisition (DAQ) system. A first test of this DAQ system was performed at one of Hydro-Québec's hydroelectric plant. As the ASFM replaced the existing trash rack elements, special equipment was designed and built to create turbulence in the flow necessary for the acoustic scintillation to operate. HPP performance tests by Hydro Quebec were duplicated with the EDF measurement system which recorded the acoustic scintillation raw signals. Using the resources available at the time, the acquired time series have a lower resolution than those provided by the Acoustic Scintillation Flow Meter (ASFM). However, valid velocity estimates are possible even at this lower resolution.

I. Introduction

Water flow estimation in hydro power plant intakes provides important data used to evaluate turbine efficiency and to assure compliance with regulatory release requirements. A flow metering system, which is robust, adaptable and precise, is therefore needed.

As far as low head HPPs, with small converging intakes, are concerned, acoustic scintillation flow metering seems an interesting an innovative solution to the discharge measurement issue.

EDF’s initiative to use the Acoustic Scintillation Flow Meter (ASFM) is part of a continuing process of improving the performances of the hydroelectric plants. Previous measurement sessions performed with the ASFM revealed that flow effects such as transducer support vibrations, grid-induced wakes and low turbulence levels could negatively influence the results. The EDF PhD thesis project was started in February 2011 with the objective to improve flow metering by the ASFM, and to provide solutions for existing problems using advanced signal processing techniques.

This paper deals with the challenges that arose in the first months of the thesis, as well as with the difficulties experienced during the measurements at one of Hydro Quebec’s HPP.

II. The Acoustic Scintillation Flow Meter

The Acoustic Scintillation Flow Meter (ASFM) uses a technique called acoustic scintillation drift to measure the flow velocity perpendicular to a number of acoustic paths established across the intake to the turbine. Short (16 µsec) pulses of high-frequency sound (307 kHz) are sent from transmitting arrays on one side to receiving arrays on the other, at a rate of approximately 250 pings/second [1]. Fluctuations in the amplitude of those acoustic pulses result from turbulence carried along by the flow. The ASFM measures those fluctuations (known as scintillations) and from them computes the lateral average (i.e. along the acoustic path) of the velocity perpendicular to each path. In its simplest form, two transmitters are placed on one side of the measurement section, two receivers at the other (Fig. 1). The signal amplitude at the receivers varies randomly as the turbulence along the propagation paths changes with time and the flow.

If the two paths are sufficiently close (Δx), the turbulence remains embedded in the flow, and the pattern of these amplitude variations at the downstream receiver will be nearly identical to that at the upstream receiver, except for a time delay, Δt. This time delay corresponds to the peak in the time-lagged cross-correlation function calculated for Signal 1 and Signal 2. The mean velocity perpendicular to the acoustic paths is then $\Delta x/\Delta t$.

Using three transmitters and three receivers at each measurement level allows both the magnitude and inclination of the velocity to be measured. The ASFM computes the discharge through each bay of the intake by integrating the horizontal component of the velocity over the cross-sectional area of the intake. In a multi-bay intake, the discharges through each bay are summed to compute the total discharge.

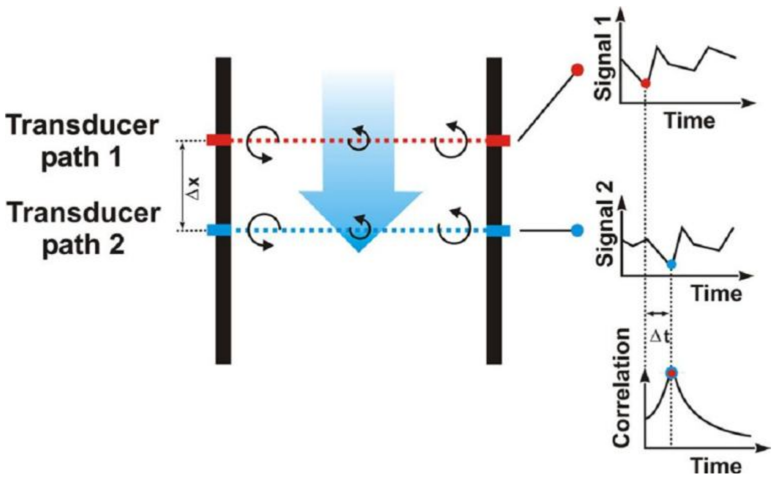

Fig. 1: Schematic representation of acoustic scintillation drift.

The ASFM instrument consists of five major components: transmitting (Tx) and receiving (Rx) transducers and underwater cabling, switching canisters, surface connection cables, a data acquisition Surface Unit, and a PC computer with the user interface for controlling and operating the ASFM (ASFM Link software). The ASFM typically is divided into 3 groups for operation in multi-bay intakes; each group consists of a set of transducers, two switching canisters, and cabling. A single ASFM system can have up to 30 paths with 3 groups (typically 10 paths per bay in a 3-bay intake – Fig. 2). One path from each group may be sampled simultaneously, provided the path lengths are equal.

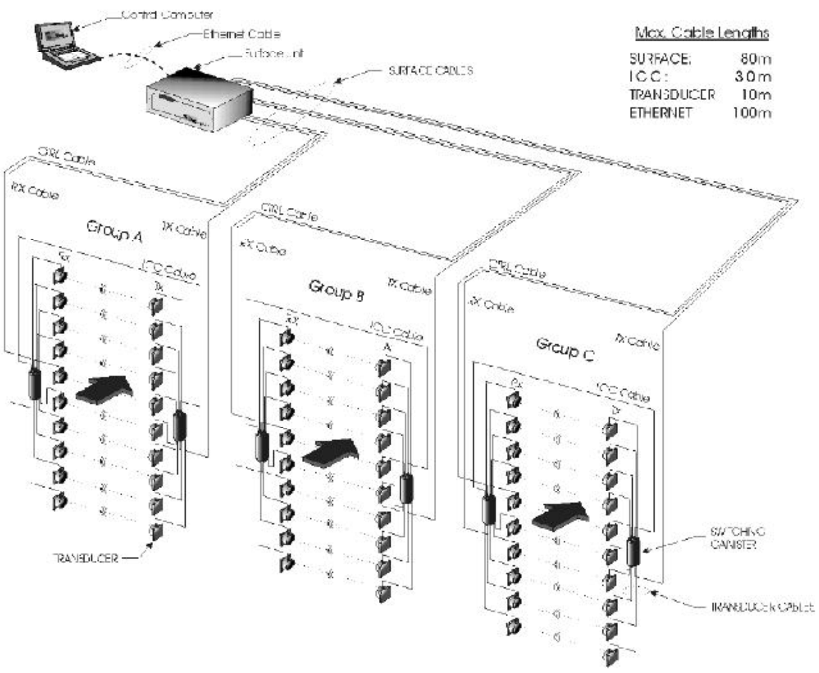

Figure 2: Components of a typical multi-bay ASFM.

III. The multi-channel acquisition system

The scientific investigations done throughout the thesis are based on signals recorded from the ASFM and the first task was to identify the appropriate points of measurement inside the ASFM. In order to study closely the operation mode of the ASFM, as well as to replicate the velocity algorithm inside the ASFM, several signals had to be viewed at the same time, which exceeded the capacities of conventional oscilloscopes. A multi-channel acquisition system had to be designed.

In addition to this problem, a new challenge arose from the fact that the scintillation pulses are being transmitted with a frequency of approximately 250Hz for a period varying from 33 seconds to 120 seconds for each level [6]. Therefore, the acquisition system has to record these pulses for long periods of time and in a format that can be read easily. Furthermore, the acquisition system must be compact as the measurements often take place in zones with too little space to deploy a large and complicated acquisition system.

The solution has been found in the form of a portable computer and as many as four HS4DIFF data acquisition units provided by TiePie Engineering®, as illustrated in Fig. 3.

Each HS4DIFF unit connects to the computer via an USB connection and a synchronizing cable is used to connect two or more units together. A computer application controls the acquisition process by creating a combined instrument from two or more HS4DIFF units.

The combined instrument can support up to five HS4DIFF units. Several options are available for recording the data such as Data Loggers, DiskWriter and AutoDisk. The preferred choice is DiskWriter because it records data easily readable with Matlab® [2].

Figure 3. The HS4DIFF recording unit.

After extensive testing in the laboratory, the system was deployed at one of Hydro Québec's HPP. Two HS4DIFF units were used to record the analog form of the signals, both the transmitted signals and the signal found at the input of the analog to digital converter.

Figure 4. Data is being recorded from the ASFM using two HS4DIFF units (on the right).

The first advantage of such a system is the ability to visualize in the same time the scintillation signals of the ASFM unit and the signals at different stages along the signal path in the electronics, including the envelopes of the received scintillation pulses located at the input of the analog to digital converter (ADC). Most acquisition systems that provide a number of acquisition channels higher than four have low sampling frequencies (up to several hundred kilohertz) or low resolution ADCs.

However, even with such extended capabilities, the system was unable to record all the 250 scintillation pulses which are transmitted in one second. This inconvenient means that the calculated time series have a shorter length compared to the ones provided by the ASFM software and that velocity estimations are more difficult to obtain.

IV. The analysis of the data recorded at Hydro Québec's hydro power plant

The most important part of the data recorded were the received pulses from the three elements of the scintillation transducers (Fig. 5). These pulses are used to construct the time series which characterize the turbulence generated by the water flow and thus calculate the flow velocity.

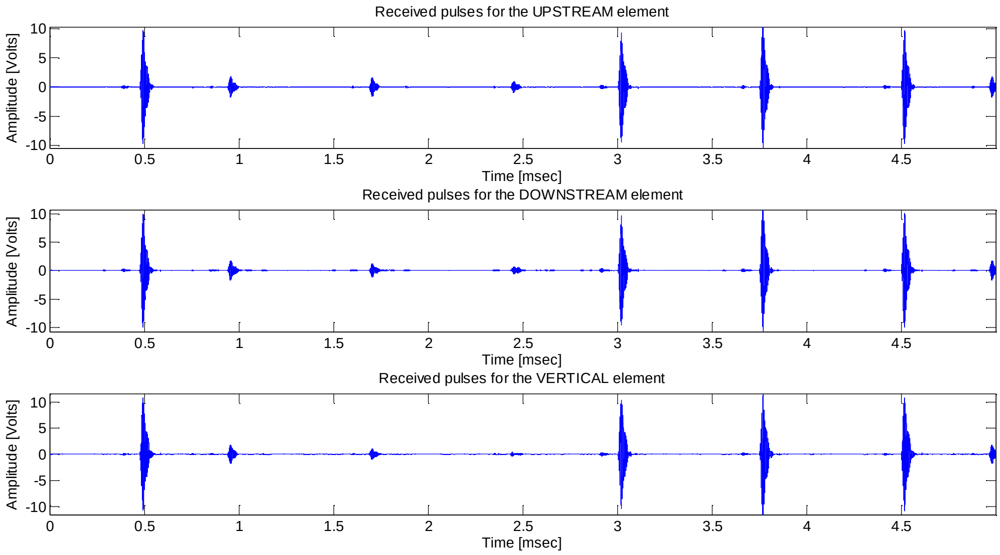

Figure 5. Recorded scintillation pulses.

In Fig. 5, each subplot represents the signal recorded for each element of the acoustic transducer. Each receiving element receives, at the expected moment in time, the corresponding pulse from its counterpart at the transmission level. Since the elements are close, the angles of the beams emitted allow each element to receive the signals transmitted for the other two, hence the succession of the three pulses for each element (the fourth pulse present at the beginning of the signals corresponds to the previous transmission). This phenomenon does not introduce errors in the velocity estimation algorithm because the pulses are separated in time and the necessary identification subroutine is built into the ASFM software.

The signals shown in Fig. 5 display an interesting aspect: on all subplots there are three smaller pulses in the (1 ÷ 2.5) msec. time interval. These pulses (called echoes) are actually reflections from previous pings which are reflected initially at the receiving side (Rx) and then travel to the emission side (Tx) to be once again reflected back to Rx.

These echoes could provide an alternative method to determine the travel time of the signals between the transducers. When the emitted pulse for ping "*n*" reaches Rx, a small fraction of the signal's energy is reflected back at Tx. After reaching Tx, the signal is reflected again and travels to Rx, after ping "*n+1*", as shown in Fig. 6:

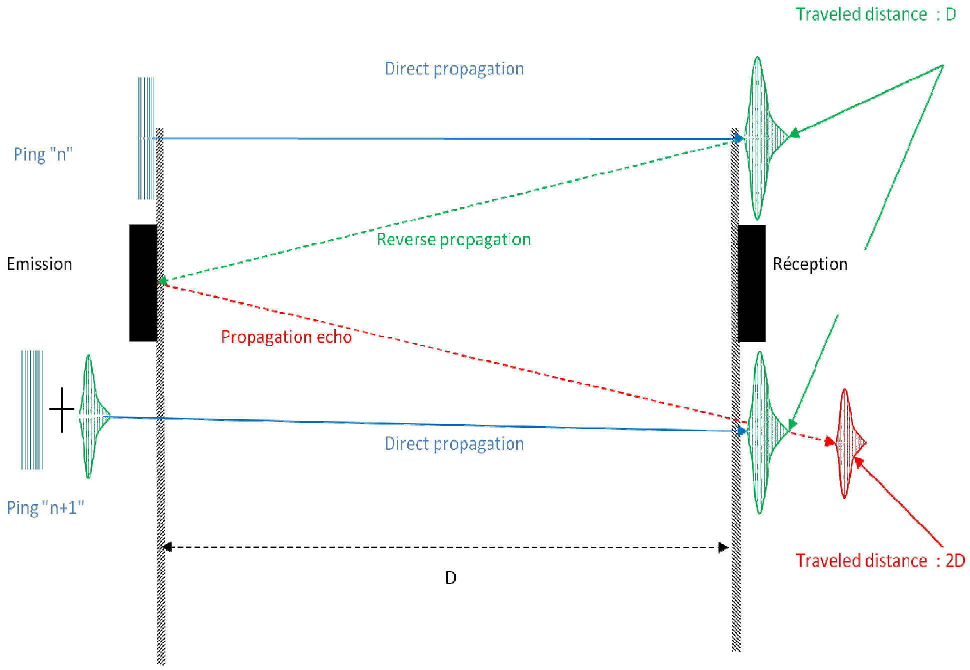

Figure 6. Echo forming between two scintillation pings.

The time of flight between the echoes and the corresponding pings are used to calculate the speed of sound through water and thus water temperature. In the case of the HPP data, we can use the signals illustrated in Fig. 7:

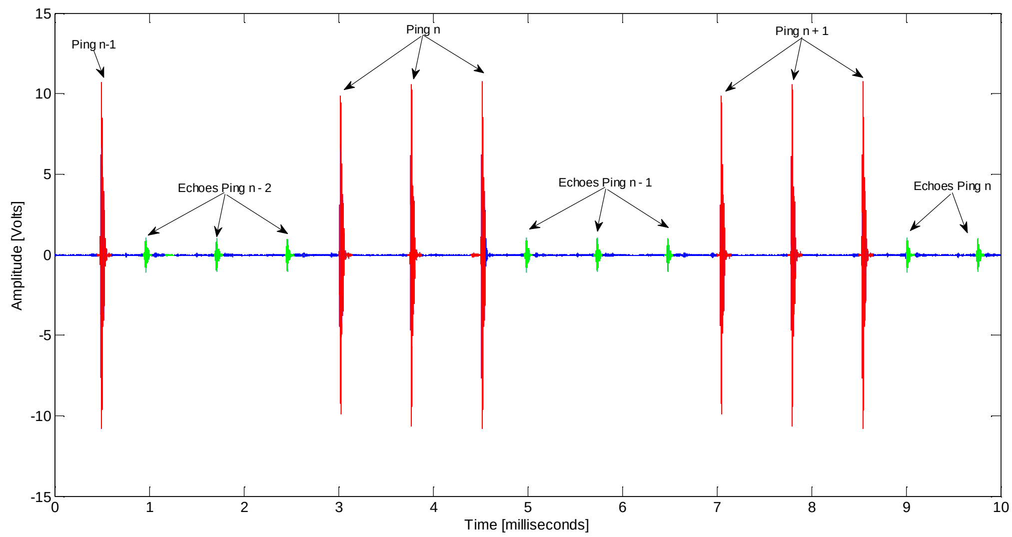

Figure 7. Pings and echoes used for water temperature estimation.

The computation outputs a sound speed of *1491m/s* corresponding to a water temperature of *23°C*, similar to the ASFM values (*22°C* and *1487m/s*). The precision of this technique depends on the sampling frequency of the HS4DIFF unit. The current value for the sampling frequency is 10MHz, but it can be easily increased to 50MHz, which would translate to calculating a time of flight between the transducers with an error of 20 nanoseconds.

Velocity estimation using the recorded data

These on-site measurement sessions were the first in which real data was recorded with the DAQ system and velocity estimations were possible. The ASFM used for data recording had to manage up to 10 levels. Continuous recording of data ensured that for each level an almost equal amount of pings was recorded. Due to the time needed for the data to be written on the disk, a large number of received pings were not recorded, thus making velocity estimations more complicated [3]. This is due to the recording process performed by the oscilloscopes: data blocks are copied into the oscilloscope's buffer memory and then sent to the computer via the USB port. During this time, the acquisition is inactive and the subsequent scintillation pulses are not recorded. The ASFM unit emits 250 pulses / second, therefore, we can say that the turbulence embedded in the flow is digitized 250 times /second, thus a sampling frequency of 250 Hz. For the signals recorded, the actual time series had an average sampling frequency of 15 Hz. The raw time series obtained from these recordings had to be processed using an adaptive interpolation method and a filtering technique in order to correct the spectral modifications introduced by the interpolation.

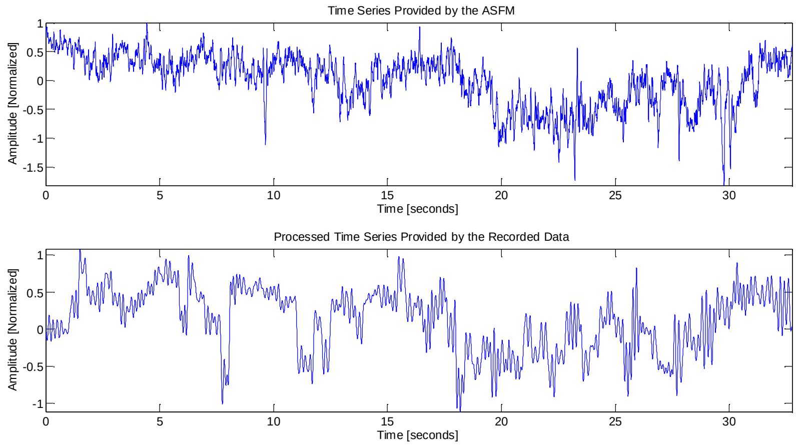

Figure 8. Time series for the UPSTREAM element provided by the ASFM and the recorded data.

The interpolation technique used is a piecewise polynomial form of the cubic "*spline interpolant*" to the data values [4]. This technique has been used successfully to calculate the envelopes of the received pings and gives very good results with interpolating under-sampled data. The recorded signals were digitized with a frequency of 10 MHz, so no interpolation was needed in order to calculate the envelopes of the received pulses. The time series resulted from the envelope detection had to be interpolated in order to be able to estimate the time delays. The interpolation inserts more points between the points of the under-sampled data, thus enhancing the time resolution. However, too much interpolation can have undesirable effects, such as enhancing unwanted spectral components. In order to avoid such drawbacks, the interpolation has been adapted to the spectral content of each time series in such way that the spectral changes are being kept to a minimum.

Reducing the negative effects of the interpolation is done by comparing the resulting spectrum of the time series after interpolation (more precisely the high frequency content) with the spectrum obtained for the time series provided by the ASFM software. The latter have a spectral content which stretches in theory up to 125 Hz (according to the Nyquist – Shannon sampling theorem), so any spectral components found above this value on the interpolated time series spectrums are filtered. Moreover, some spectral components which do not exceed the 125 Hz value can dwarf the other components, rendering the correlation to output a zero delay between the time series. These components were filtered using a Butterworth band-pass filter. Throughout the entire process, the ASFM time series provided a reference for the results.

Velocity estimations were performed both on the interpolated time series and the ASFM time series using an algorithm derived from a diagram provided by AQFlow.

Fig. 9 shows the results of the velocity estimation using the ASFM time series and the interpolated data.

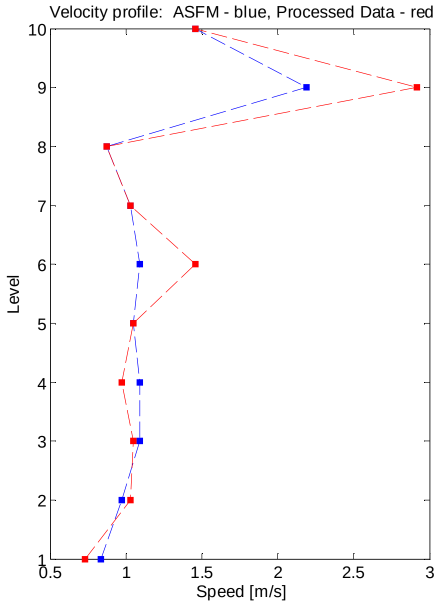

Figure 9. Velocity profiles obtained from the data recorded and ASFM.

The two traces in Fig. 9 show that velocity estimations are possible to extract from the recorded data and the nature of the profile can be the same. However, there are points on the profile (especially for levels 6 and 9) where the interpolation cannot provide an exact value for the velocity. This effect is due to the relatively low number of pings recorded (for these levels the actual sampling rate was lower than 15 Hz), but also due to the turbulence levels not producing enough variation in the amplitudes.

From a signal processing point of view [5], the time series calculated present statistic parameters (mean and variance) which resemble the ones of a Gaussian noise (Fig. 10). Practically, there is no perfect noise waveform and therefore correlations are possible, but the actual correlation peak (which corresponds to the time delay between the two time series) can be comparable to the adjacent peaks, making the delay estimation unsure. Fig. 10 shows an example of two correlations from time series with low and high turbulence levels:

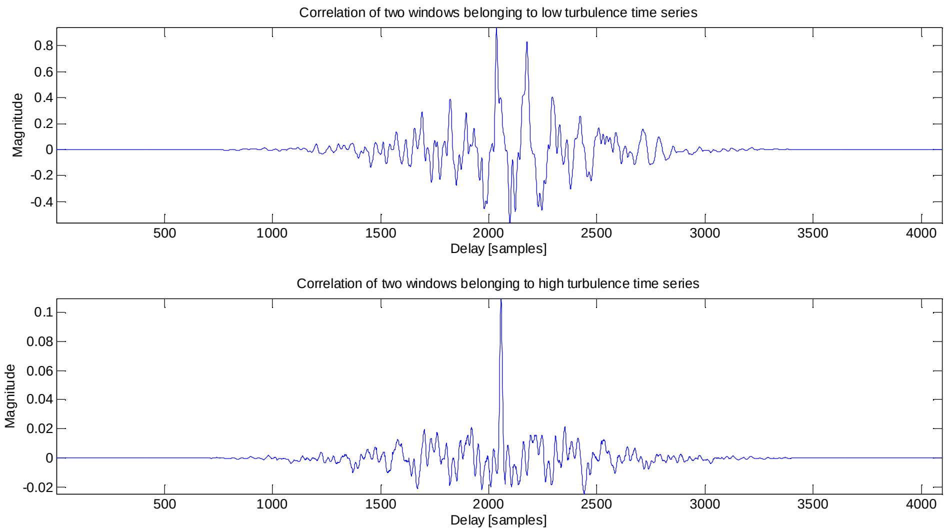

Figure 10. Comparison between correlation of ASFM time series with low and high turbulence levels.

In the first subplot of Fig. 10 the two most predominant peaks correspond to two values of time delay (and therefore velocity) and may create confusion. The ideal situation is to obtain a correlation waveform which resembles the one displayed in the second subplot of Fig. 10.

V. On-site ASFM measurements

A first set of tests were carried out on unit 21 of the HPP under test with the trash racks removed and replaced with the ASFM transducer frame supports. It was evident that the turbulence level was very low. In order to improve the quality of the measurement, it was decided to install a device to generate more turbulence. A series of chains were attached to a barge, forming a chain curtain. The chains were maintained vertically using a heavy weight attached to the lower end. The spacing between the chains was 30 cm for the entire width of the intake bay (Fig. 11).

Fig. 11. Chain curtain used for creating turbulence in the intake bay.

As it can be seen on the ASFM time series in Fig. 12, and the spectral comparison in Fig. 13, the turbulence level has been significantly increased. However, even with the higher turbulence level generated by the chains, the spectral content was yet low compared to a good measurement condition and therefore the system can benefit from further improvements.

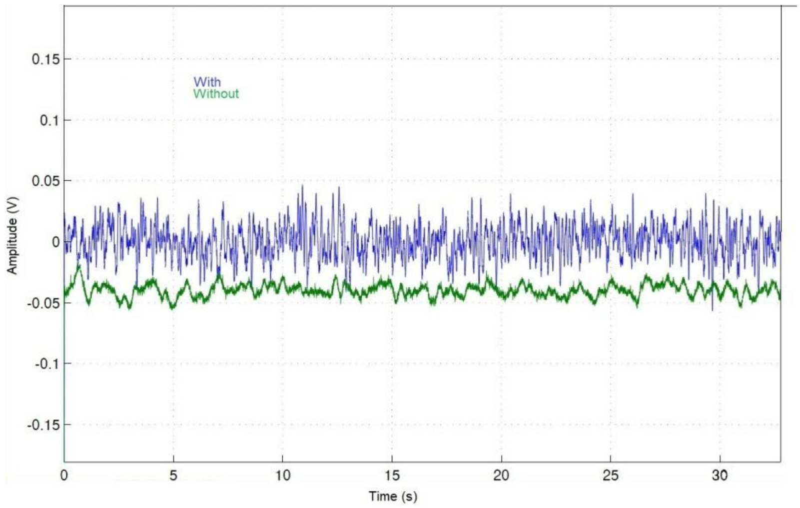

Fig. 12. Turbulence level data of an acoustic path with and without chain curtain

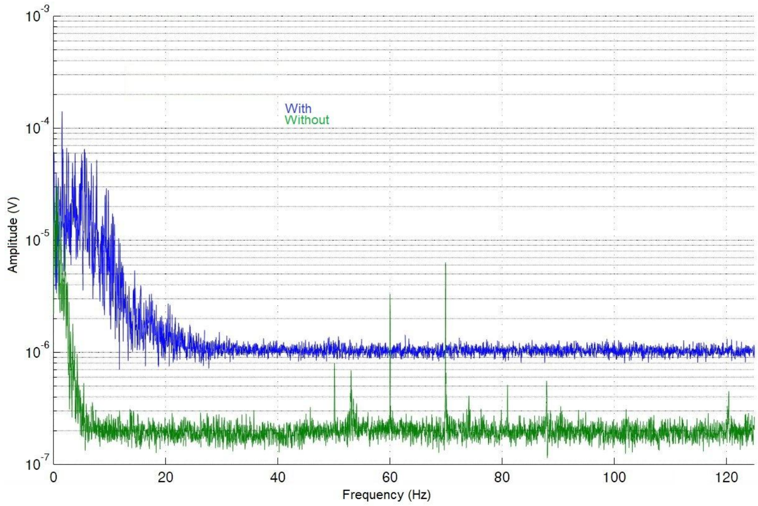

Fig. 13. Comparison of spectral amplitudes of time series with and without chain curtain

Another way to view the effect of the turbulence level is to look at the velocity profile calculated from measurements with and without the chain curtain. Fig. 14 shows that the velocity profile without the chain curtain is inconsistent, especially in the middle of the measurement section. On the other hand, by using the chain curtain, the velocity profile becomes smoother.

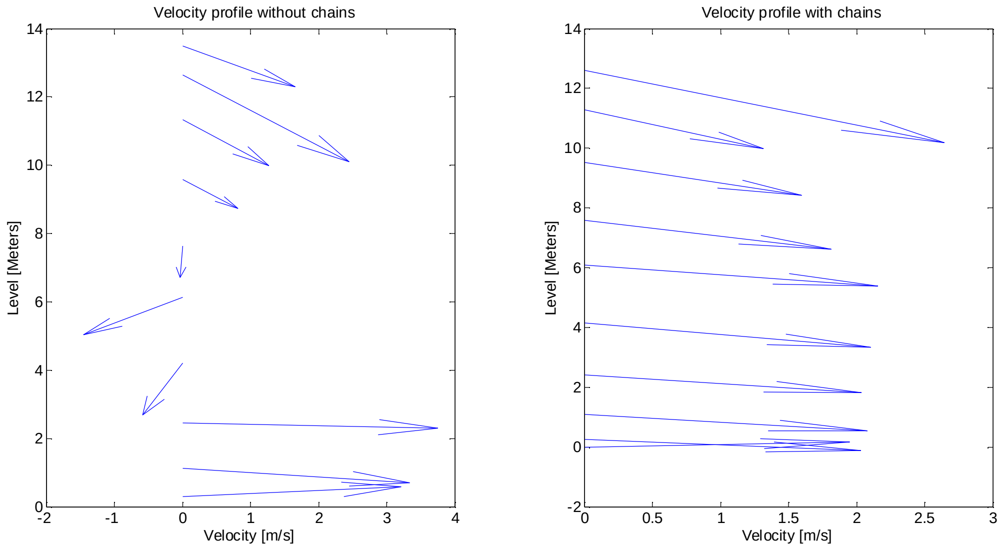

Fig. 14. Velocity profiles calculated with and without chain curtain.

VI. Conclusions

A high speed data acquisition system has been designed and tested in order to acquire raw acoustic scintillation signals used in ASFM flow meter. The data proved useful for direct visualization of the transmitted signals, but velocity estimation proved more difficult to obtain. Signal processing techniques were used to compensate the amount of data that was not collected and in several cases the results matched with the ones provided by the ASFM data series. Concerning the high speed acquisition, the system has been later improved and configured in such a way that has allowed a complete acquisition of the entire scintillation transmission sequence, providing better results of velocity computation.

Future work will concentrate on simulating various causes of ASFM unfavorable situations, such as signal interference, and on applying new signal processing techniques (time-phase-frequency, wavelets decompositions, etc.) to verify if they can improve the actual acoustic scintillation flow metering concept. In the case of low turbulence time series, two possible techniques will be considered: the use of the “Singular Value Decomposition” method to extract relevant correlation data from the time series and the use of the ambiguity function for a more precise localization in time of the correlation peaks.

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