Electricité de France’s study of the acoustic scintillation flow meter results in expanding its range and sensitivity

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Introduction

Electricité de France’s “Direction Technique Générale” (DTG) branch launched a three-year PhD thesis in order to study the Acoustic Scintillation Flow Meter (ASFM) developed by ASL AQFlow. The study was done in a partnership between EDF DTG (owner of one ASFM system since 2006), Hydro Québec (owner of two ASFM systems) and the manufacturer ASL AQFLow. The partnership aimed at sharing information about the mode of operation and components of the ASFM, as well as sharing the results of the research and development and on-site testing, in order to review the concept of the ASFM and, if feasible, to extend its application beyond its present range. Scientific support was provided by Gipsa-lab, a research laboratory within the Polytechnic Institute of Grenoble (INPG), a major player in the international signal processing community, and the R&D division of EDF located in Chatou, Greater Paris area.
In the first two years of the PhD study five major measurement campaigns were performed in France and abroad. In addition, a reduced scale test facility was set up at Gipsa-lab.
The main tasks for the PhD candidate were: to review the operational limits for the ASFM, to investigate the impact of various interferences on the discharge measurement, to get a better understanding of the velocity computation algorithm, to develop a method to filter out the scintillation frame vibrations, and to improve the algorithm, if feasible. It is expected that this study may provide the basis for the next generation of acoustic scintillation flow meters.

1. Background

For EDF’s hydraulic power division, turbine flow metering represents a high stake issue as it involves a significant amount of knowhow, work force and physical resources. It was for this reason that in recent years EDF’s DTG acquired an ASFM in order to exploit its advantages over the current meters (CM) and other flow metering methods, especially at low head hydro power plants (HPPs). Several situations encountered during on-site tests revealed that unusual flow conditions might arise, which are outside of the present ASFM guaranteed specifications and require further research.
Therefore, in 2011, a three-year PhD study was launched, aiming at a better understanding of the ASFM’s mode of operation and, if feasible, finding methods to extend the ASFM’s capabilities beyond its present range of flow velocities between 0.6 and 6 meters/second. The study was to focus mostly on the signals acquired from the ASFM surface unit and their interaction with the turbulent flow environment. Throughout the study, several on-site tests at EDF’s HPPs and under controlled laboratory conditions provided the data set needed for achieving this objective.

2. First steps

One of the first challenges was to develop an in house acquisition system that would be capable of recording the data from the ASFM. Since the ASFM sequence at one measurement level can take up to 33 seconds, it was necessary to find a multi-channel data acquisition system that would have several important characteristics:

- A high sampling frequency: at least three times the maximum frequency of the signals;
- a high transfer rate;
- a sufficient resolution so that the sampling noise would be negligible;

- a readable file format for the recorded data.

For typical acquisition systems, the above mention characteristics tend to contradict each other: most high sampling frequency devices have a low resolution in order to obtain a high transfer rate. It soon became evident that an off-the-shelf solution would not be available.
The quest for a suitable acquisition system found that a joint PC – acquisition board would be more suitable for the study rather than any conventional heavy chassis devices. A four-channel 50 MHz bandwidth acquisition board with a 12 bit resolution was chosen. The acquisition board is controlled by a graphic interface on a PC (Figure 1). The initial software of the board was modified in order to better suit the acquisition process.

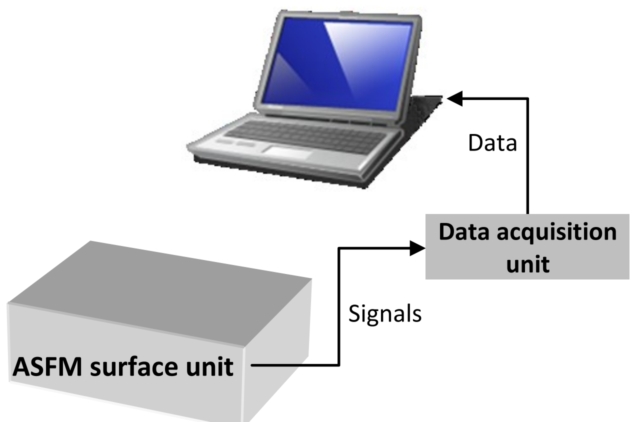

Fig. 1. Data acquisition system schematics

The onsite acquisition process will benefit also from the ultra high portability of the system.

3. Replicating the existing signal processing technique

In parallel with the development of the acquisition system, an important stage was to get a full insight into what the ASFM hardware is made up of (electronic design, main blocks and their mode of operation). Constant dialog with the ASFM's manufacturer, ASL AQFlow, allowed for a rapid development of a software replica of the algorithms embedded in the ASFM.
The replication of the flow velocity estimation algorithm embedded in the ASFM was carried out in several stages. First, the hardware structure of the ASFM was studied in order to identify the system's components: transducer types, transmission and timing blocks, power sources and the ASFM management unit. An in-depth analysis of individual components was made in order to understand the topology and function of each circuit. Based on the documentation provided by ASL AQFLow, tests points for the transmitted signals were identified. The received scintillation pulses and the calculated envelopes were ready to be recorded. Using the layout presented in Figure 1, the emitted and received scintillation pulses were recorded. The bandwidth of the acoustic transducers was calculated.

Second, a special envelope detection was developed in order to compute the time series: having the entire scintillation sequence recorded, each pulse was passed through an envelope detection routine, prior to maxima extraction. A comparison with the original ASFM time series showed that both time series matched.

However, there is a difference between the two algorithms: the ASFM performs all the calculations in real time and the maxima extraction is done digitally, while the rest of the operations take place in the analog form. Recording the scintillation data means that the time series are not computed instantaneously, but after a certain amount of time. This amount of time can be significantly shortened to near-real time by using fast implementation of the algorithms. Saving the data means that very large databases of signals can be gathered and new ideas can be tested on the computer prior to performing on-site tests.

Additional on-site tests have allowed the development of a new signal processing technique based on spectral analysis, using the scintillation pulses from the ASFM. The resulting time series are, within the guaranteed range, similar to the ones from the existing ASFM algorithm. Starting from the raw data recorded, each individual scintillation pulse was isolated and time series were computed via the standard ASFM algorithm. The resulting time series were compared with the ones issued by the ASFM and the signals matched. Obtaining relevant time series is critical for the flow velocity estimation.

However, in cases of unusual or unfavorable conditions, the re-computed time series are more suitable than the existing ASFM ones for velocity calculation. The modified method extracts more turbulence information by "boosting" the information content relative to the turbulent phenomena. The recomputed time series are based on a spectral approach and it is focused on the signal's features where the turbulence has the maximum intensity. A spectral analysis can also provide information about the content of the acoustic signal during propagation through the turbulent flow.

4. Low flow velocities and low turbulence

An initial demand for the PhD study was to investigate ways to improve the ASFM's results for HPPs with no thrash racks installed. As illustrated in [1], [2] and [3], the low levels of turbulence issue had been investigated before and the robustness and stability of the results were clearly affected.

EDF's R&D department has facilitated a scintillation test under controlled conditions. This test was carried in an 80-meter long channel that allowed control of the flow velocity and had a very low level of turbulence. The flow velocity, however, was outside the guaranteed ASFM range.

Additional turbulence was created using a cable and chain curtain. The elements were 8 centimeters apart in order to simulate a real trash rack of a real EDF's HPP. This created an opportunity to see also the effects of a lateral flow on the scintillation signals.

The first task consisted of fabricating a support frame for the scintillation transducers. The support section was constructed from aluminum-profiled beams. These profiled beams allowed rigid and fast construction and the structure could easily be adjusted vertically and horizontally.

Scintillation transducers were mounted on aluminum sheets attached to the profiled aluminum beam frame (Figure 2). In order to avoid unwanted interference caused by the flow around the aluminum sheets, the edges of each sheet had an arched profile with the arc's angle under 30°, obtaining a hydrodynamic shape illustrated in Figure 3.

The profiling of the aluminum sheets also helped the entire structure to adhere to the channel's walls so that no water flow would occur between the walls of the channel and the metal structure. A silicone layer sealed the interface between the aluminum sheets and the channel walls.

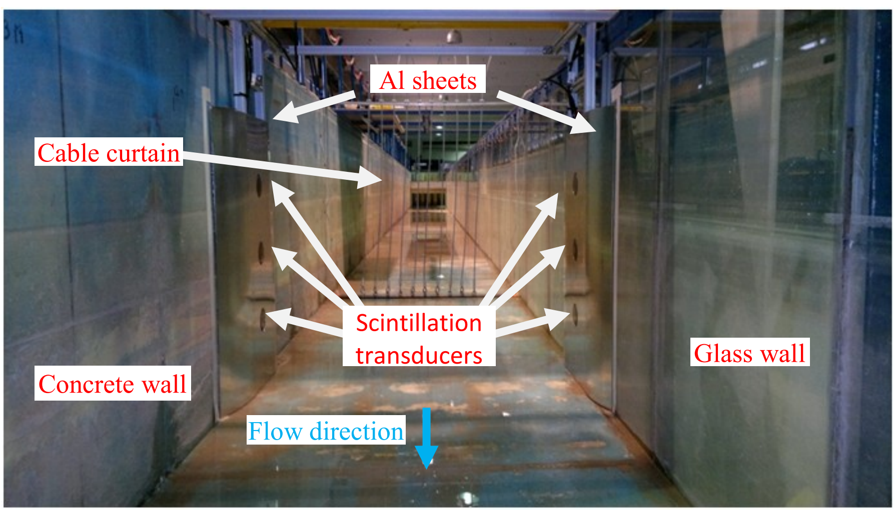

Fig. 2. Scintillation transducers and frame layout inside the test channel.

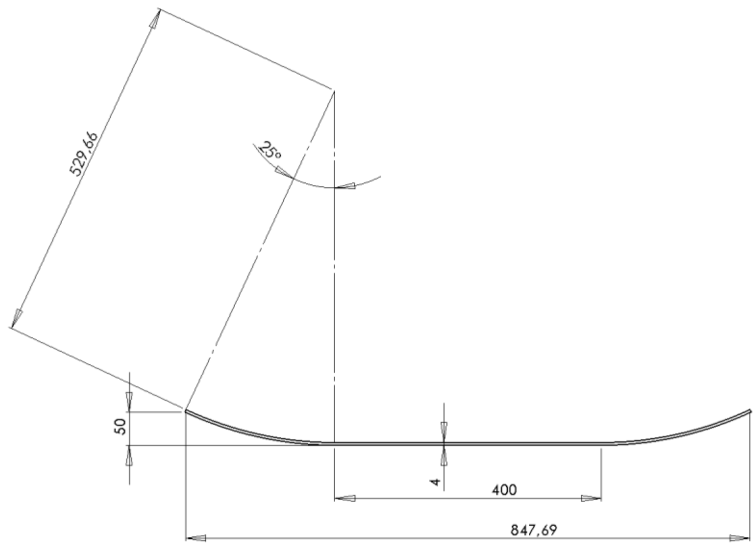

Fig.3. Plan of the hydrodynamic profile of the aluminum sheets – top view.

Three scintillation levels (three pairs of transducers) were installed with a vertical gap of 30 cm between levels, starting from a height of 30 cm from the channel floor. No protuberance that generated interference existed because all fixation devices were hidden within the aluminum sheets. The transducers were aligned in order to ensure close to ideal measurement conditions.

In order to create different types of turbulence, a cable curtain was placed upstream of the scintillation frame: ten steel cables fixed on a horizontal bar and placed on the top side of the channel (Figure 4). The cables were maintained straight using a heavy steel flat bar which rested on the bottom of the channel. The cables coupling allowed their removal in order to create combinations of turbulent flows.

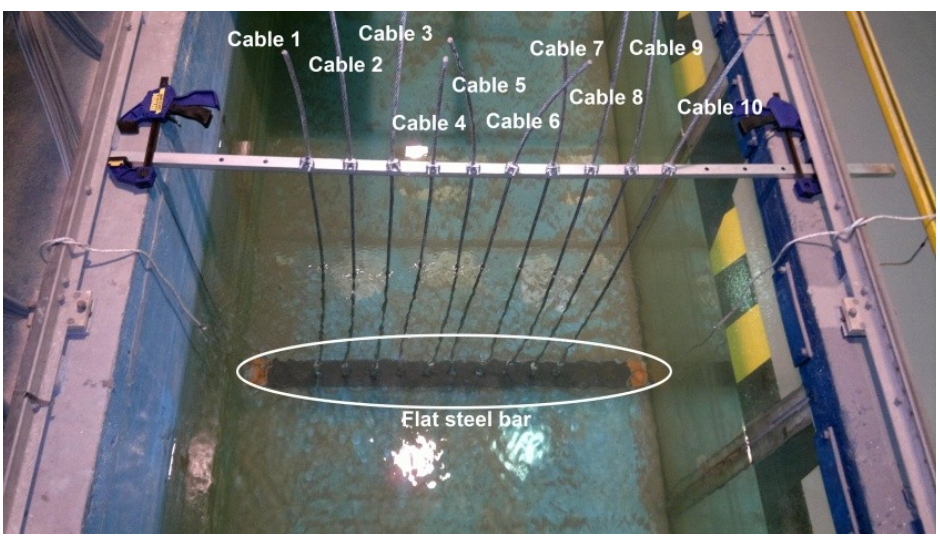

Fig. 4. Cable curtain upstream of the scintillation frame.

In addition to cables, chains also provided extra turbulence. Chains were successfully used for the scintillation tests at one of Hydro Québec's HPP to increase the level of turbulence [2]. A combination between chains and cables completed the range of possible turbulence profiles.

The reference flow measurements were carried out using an acoustic Doppler probe (situated on a moving platform on top of the channel) as illustrated in Figure 5. The Doppler probe was submerged under water to provide the horizontal velocity profile for all scintillation levels.

Fig. 5. Acoustic Doppler probe.

The horizontal flow velocity profiles for the three scintillation levels are illustrated in Figure 6:

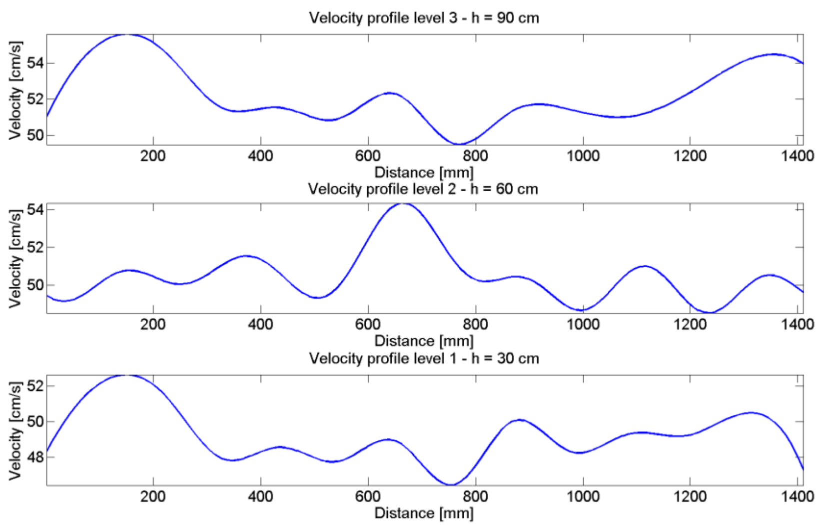

Fig. 6. Horizontal profiles provided from the Doppler probe.

For each level, the mean velocity values were:

- Level 1 (bottom) : 49.2 cm/s;
- Level 2 (middle): 50.4 cm/s;
- Level 3 (top) : 52.3 cm/s

The first tests aimed at studying the behavior of the system without any turbulence caused artificially (with only the low levels of turbulence that was embedded in the flow). Two ASFM runs were made and the results are presented in Figure 7.

It can be seen that the low levels of turbulence, as well as the reduced flow velocity, affected the precision of the ASFM. The Quality Index of the measurements was below 0.5 as anticipated. However, if the same results are processed using the new algorithm, the results improve dramatically, as illustrated in Figure 8. The low levels of turbulence mean that there is a weak footprint on the amplitudes of signals and the velocity information is not visible. However, the velocity information exists and it can be calculated with accuracy by applying the new signal processing algorithm.

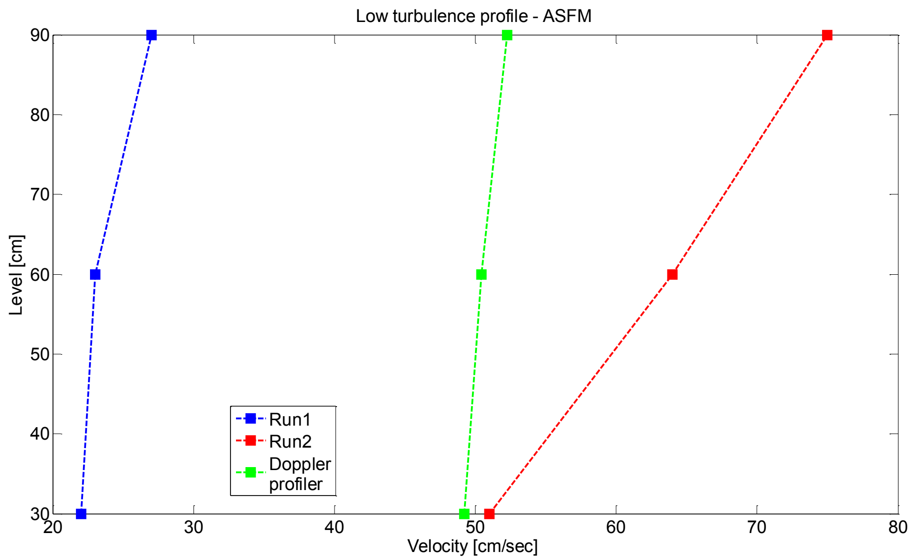

Fig. 7. Flow velocity profiles (blue and red traces) compared with the Doppler reference (green trace).(natural turbulence)

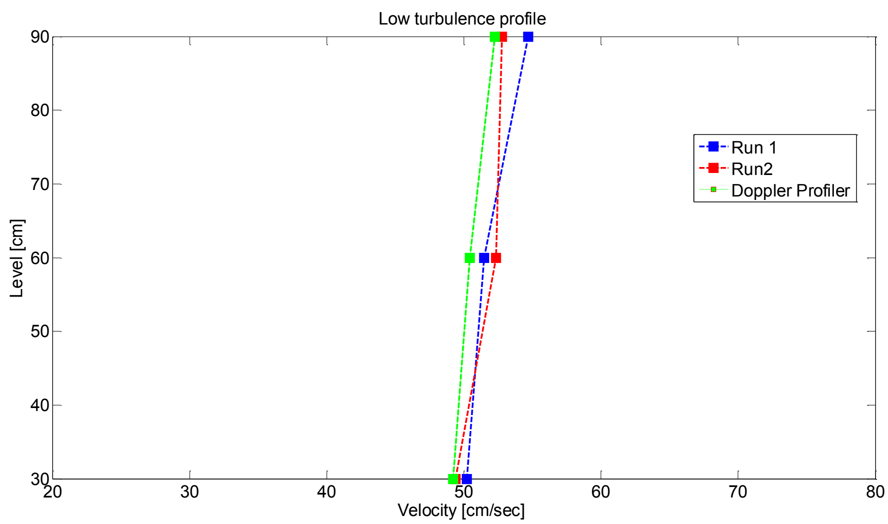

Fig. 8. Flow velocity profiles (blue and red traces) calculated using the new algorithm compared with the Doppler reference (green trace). (natural turbulence)

Given the controlled flow conditions at our disposal, it was necessary to find out how the different types of turbulence created can affect the results of the scintillation measurements (the ASFM and the new technique). Different configurations were considered: placing one cable at a time on the cable curtain in order to quantify the effect of each cable on the results, creating a lateral flow by placing the flat steel bar in diagonal position. A chain + cables curtain was constructed and submerged in water in order to generate a higher level of turbulence.

In the case of turbulence generated by individual chains, the results have shown that the levels of generated turbulence were not enough to produce an improvement in the existing ASFM velocity estimation. However, the results were improved using the algorithm based on the new technique, as illustrated in figures 10, 11, 12 and 13. All the cables were removed in order to study how a single cable and its position can affect the results. Cables no. 1, 6, 7, 8, 9 and 10 were individually placed on the curtain and scintillation signals were recorded. The results (ASFM and new technique) are presented in figures 9 and 10:

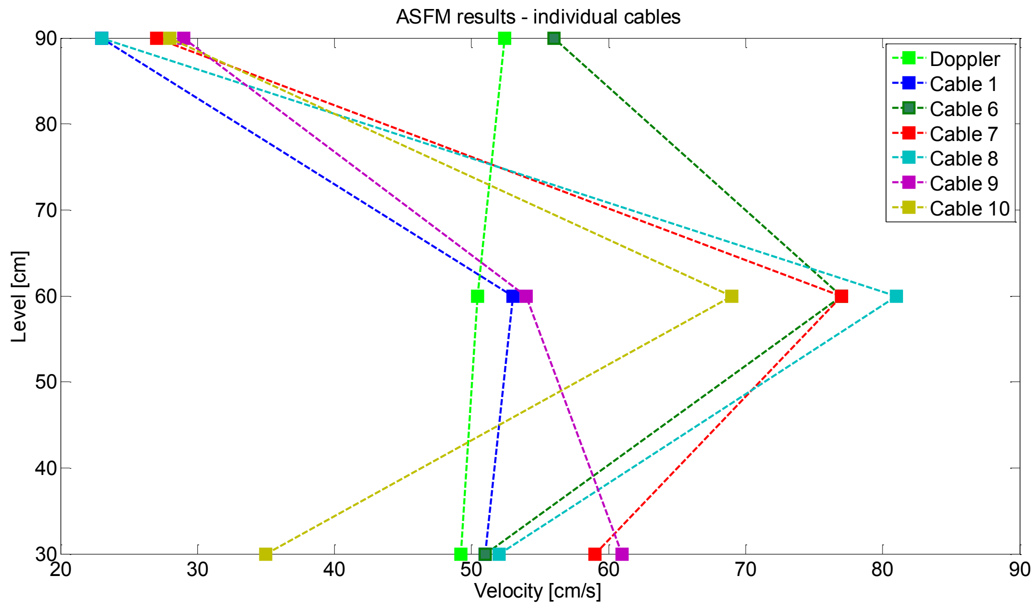

Fig. 9. Velocity profiles calculated by the ASFM compared to the Doppler probe results.

Figure 9 shows that there turbulence introduced by the cables manifests itself differently on the velocities. Turbulence introduced by cables 1 and 9 (placed at the extremities of the curtain) provides less bias than the cables placed in the middle of the curtain. In addition to that, the low flow velocity, outside of the specification range, does not allow for accurate velocity estimation.

However, using the new technique, the results are closer to the Doppler reference, as illustrated in Figure 10.

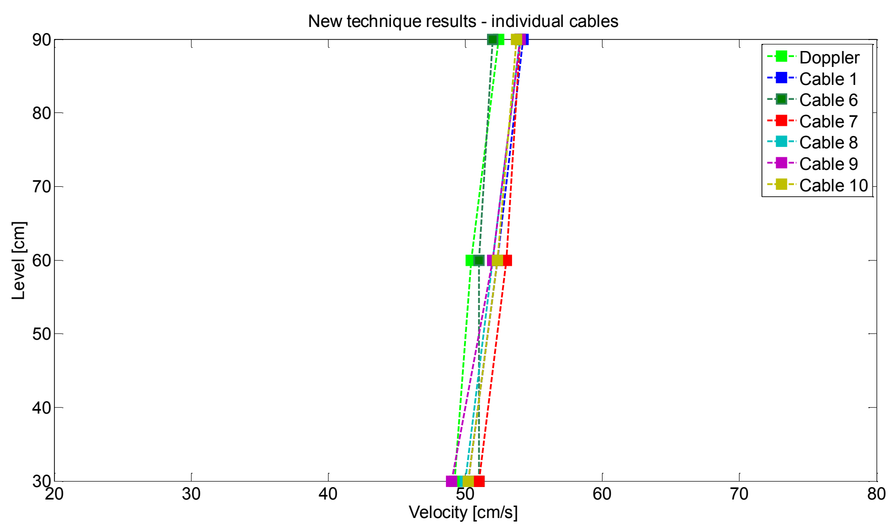

Fig. 10. Velocity profiles calculated using the new technique compared to the Doppler probe results.

The velocity points in figure 10 corresponding to all the 10 cables have a reduced scattering compared to the points in Figure 9. The offset between the reference (light green trace) and the scintillation results is significantly lower than in the previous figure.

In the case of a complete curtain (all the cables attached), several configurations were tested: cable curtain, chain curtain, chain curtain + flat steel bar and chain + cable curtain + flat steel bar. The results are presented in Figures 11 and 12.

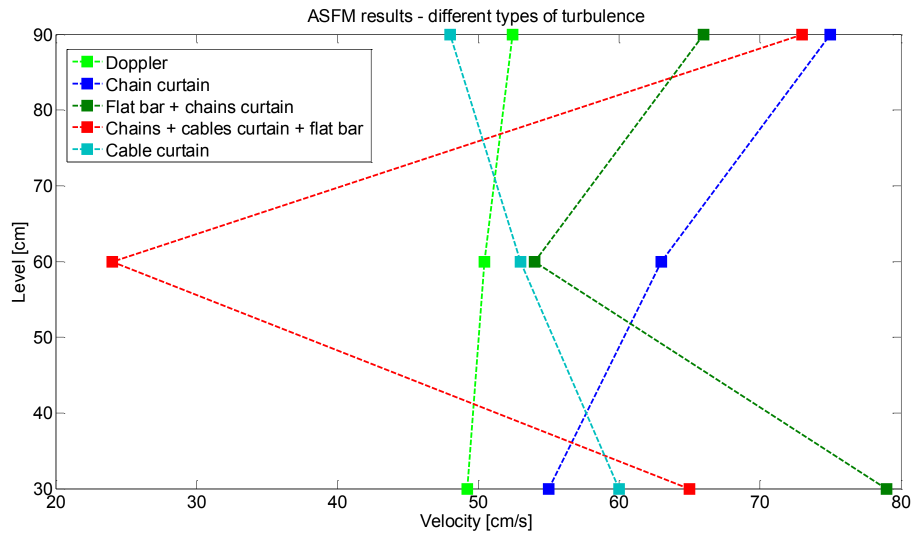

Fig. 11. ASFM velocity profiles for different types of turbulence compared to Doppler results.

Again, Figure 11 shows that the values are scattered around the Doppler reference, with a very high offset between them.

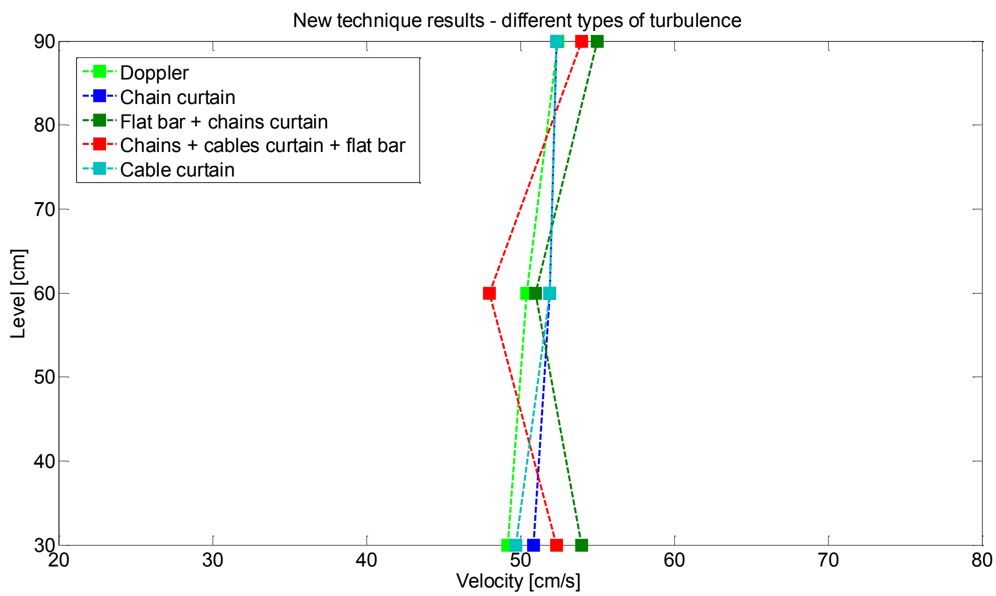

Fig. 12. Velocity profiles calculated using the new technique.

Figure 12 shows that the new technique has managed to reduce the scattering of the velocity values and brought them into the reference velocity range. Thus the new technique “filters” the unwanted effects of turbulence and “amplifies” the signatures of turbulence across each acoustic path.

Plotting the error between the Doppler reference and scintillation results for all tests (Figure 13), it can be seen that the new technique provides more stable values than the ASFM. However, we must keep in mind that such flow velocity was below ASFM specifications.

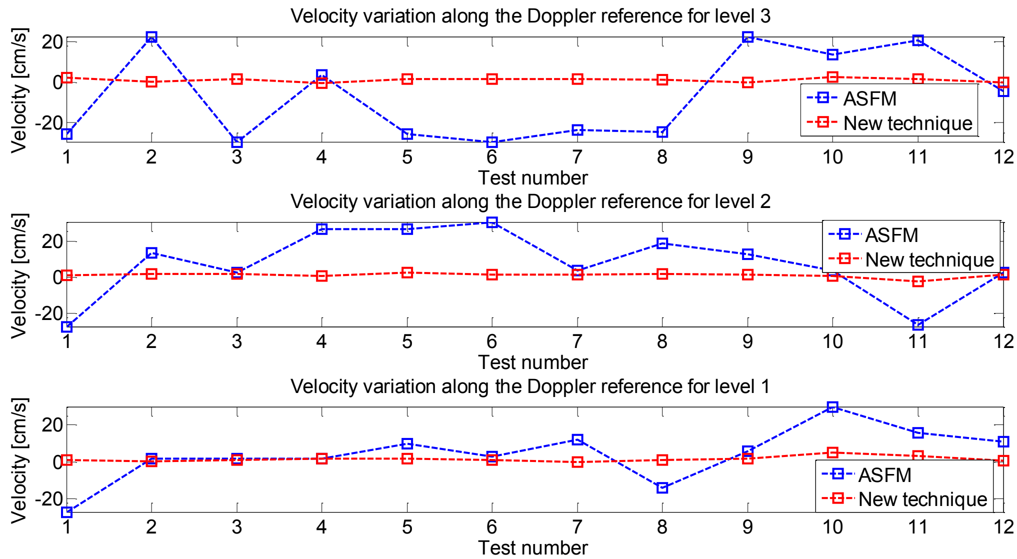

Fig. 13. The difference between the scintillation results and the Doppler reference for each scintillation level – relative to the Doppler reference.

Table 1 presents a comparison between the reference and the flow velocities values calculated:

Cables + low flow velocity				
Doppler [cm/sec]	New technique [cm/sec]	Error [%]	ASFM [cm/sec]	Error [%]
52.2	53.6	2.5	31	43.1
50.4	52.1	3.3	68.5	35.8
49.2	50.2	2.2	51.5	43.1
Different types of turbulence + low flow velocity				
Doppler [cm/sec]	New technique [cm/sec]	Error [%]	ASFM [cm/sec]	Error [%]
52.2	53.4	2	65.5	29.1
50.4	50.7	2.9	48.5	22.3
49.2	51.7	5.1	64.7	31.6
Low turbulence + low flow velocity				
Doppler [cm/sec]	New technique [cm/sec]	Error [%]	ASFM [cm/sec]	Error [%]
52.2	53.7	1.2	51	45.7
50.4	51.9	2.9	43.5	40.6
49.2	49.7	2.47	36.5	29.4

Table 1. Comparison between the Doppler reference and the two algorithms highlighting errors.

5. Conclusions

The PhD study confirmed that within the guaranteed range the existing ASFM provides excellent turbine flow measurement results and thus can successfully compete with older techniques. As shown in this paper, when special situations outside of the ASFM range of flows and velocities arise, for which the existing algorithm was not designed, modified version of the ASFM's signal processing algorithm can allow the ASFM to produce accurate results.

An experiment under laboratory controlled flow conditions was carried out in order to compare the results from the two algorithms. The results show that a low level of turbulence, combined with a low flow velocity, both outside the ASFM guaranteed range, can still provide sufficient information for the new processing technique to compute accurate flow velocities with acceptable systematic error and repeatability. While this new processing method has been tested successfully in several power plants, where the hydraulic conditions were favorable, further testing is planned in plants with unfavorable intake conditions in order to continue the validation of the new technique.

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