THE ACOUSTIC SCINTILLATION METHOD:

TWO CASES STUDY OF COMPARATIVE MEASUREMENTS

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ABSTRACT

The acoustic scintillation (AS) method has been developed to perform discharge measurement for low head power plants with short converging intakes. However, recent experience at Kootenay Canal power plant in British Columbia, Canada has shown that accurate results can be obtained in intakes of higher head power plants.

One of the required conditions for using the AS method is to have trash racks upstream of the measurement section which generate adequate turbulence and insure a satisfactory measurement uncertainty. The first comparative testing was performed in an eight unit, high head power plant. The tests were done to measure the efficiency of each unit in order to optimize power dispatch. The current meter (CM) method was used to measure the discharge with the current meters mounted on a moving frame installed in the intake stop log slots. It was also possible to install another frame in the gate slots, onto which the AS transducers were mounted, so the measurement with the two methods could be performed simultaneously. For this test, there were trash racks upstream of both measurement sections and the results confirmed that the discharge difference between the two methods was within the measurement uncertainty.

In order to study the AS method in detail and to investigate if its usage could be extended beyond the present limitations, Hydro-Québec, Électricité de France and ASL AQFlow have entered in a collaboration project. This project has led to a PhD degree and has yielded several potential developments.

One of these developments was investigated in the second comparative testing, which was done in a control structure that is used to maintain a minimal discharge for environmental purposes. This control structure does not have trash racks because it does not feed turbines. The AS method transducers and the acoustic transit time (ATT) transducers were located in a straight section within few meters of the forebay. The new algorithm developed as part of the collaboration project was used to process the raw data recorded directly from the AS transducers. The results show reduced discharge difference between the two methods.

INTRODUCTION

In the 90's, Hydro-Québec has begun a long-term project, which has the goal of measuring the efficiency of each of its generation units for optimal dispatch [2]. This project has proved to be profitable even if the difference of efficiency between the units is sometimes rather small. This is achieved by carefully choosing the flow measurement method in order the keep the total cost of the test as low as possible. One of the methods used for many power plant tests has been the Current Meter (CM) method [**Erro! Fonte de referência não encontrada.**]. This is often the only code accepted method for guaranty verification for low head power plants. It is then appropriate to have another suitable method for measuring the discharge and so the ASFM was considered for this purpose and also for optimal dispatch. This method has some advantages over the CM method in some situations.

Hydro-Québec has been using the AS method since 2000 and has performed many measurements to compare the Acoustic Scintillation Flow Meter (ASFM) with code accepted methods. Two recent tests was the occasion for performing comparative measurement between the ASFM method and well known methods.

Because the design of the intake was considered favorable, efficiency testing in on eight units of a Hydro-Québec power plant was done with the CM method. For intake measurements, Hydro-Québec is using trolleys that support a single row of current meters [1], which are moved vertically to sample the velocity profile over the entire height of the measurement section. In the present situation, this set up has the advantage of reducing the installation time because it can be used for discharge measurement for four units (during the test, only one of the four unit was operated). Even though discharge measurement is traditionally considered difficult to be performed in intakes, especially in short converging intakes, it is proving to be accurate in many situations and showing many advantages over penstock measurement [1]. As the measurement conditions were also considered good for the ASFM, it was used to measure the discharge in the intake as part of a 3-year partnership between Electricité de France's General Technical Division (EDF DTG), Hydro Québec and the manufacturer of the ASFM ASL AQFLow (the "SMASH" project) [3]. The aim of this partnership is to study the ASFM in detail and to possibly extend its range of usage. This first test serves as a benchmark for normal measurement conditions.

For a second site, provision at the design stage has allowed to install both an acoustic transit time (ATT) as well as an ASFM flowmeter. This site provides water only for environmental purposes, so the level of turbulence was expected to be low since there is no trash racks upstream of both measuring sections so was the conditions considered as difficult for the ASFM. It was a good occasion for testing the new SMASH algorithm.

1 ACOUSTIC SCINTILLATION FLOW METER (ASFM)

1.1 Measurement method

The 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 (in the order of 307 kHz) are sent from transmitting arrays on one side to receiving arrays on the other, at a rate of approximately 250 pings/second [5]. 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 (Figure 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.

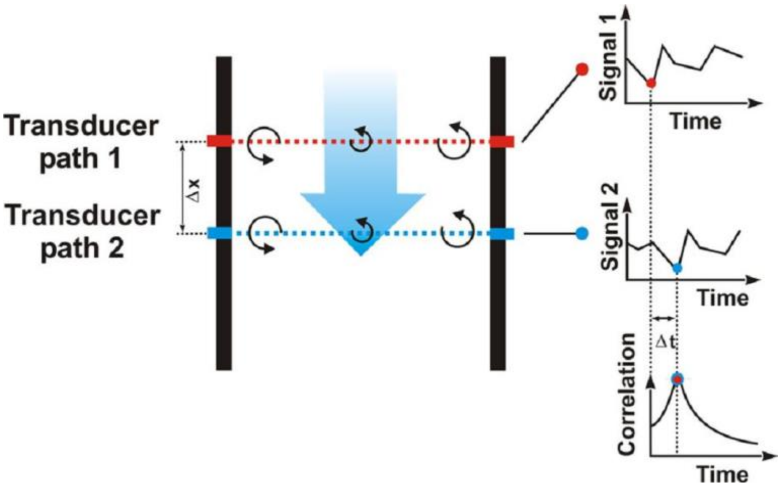


Figure 1: Schematic representation of acoustic scintillation drift.

1.2 Acoustic signal amplitude determination

To determine the acoustic signal amplitude, the ASFM measuring system determines the maximum value of the envelope of each pulse (named ASFM Link algorithm). Some recent works (SMASH project) have shown that another method to characterize the amplitude of the acoustic signal can improve the discharge measurement done in low turbulence conditions, which is the case when no trash racks are present upstream of the measurement section. This method is based on the FFT analysis of each pulse, which was named SMASH algorithm.
This new algorithm requires digitizing the raw signal received by the acoustic transducers with a high speed recording system, typically at 3Ms/s.

2 SITE NUMBER ONE, COMPARISON WITH CURRENT METERS

The first site is a power plant that has eight 190 MW Francis turbines operating under a net head of 141,8 m. Each of the two long conduits provides water to four units. The intake of each conduit has two rectangular bays, which converge into one circular section downstream of the head gates. The measurement sections are 10,97 m by 6,1 m (36 ft by 20 ft). The CM measuring section was located about 10 m from the trash racks in the stop log slots, while the ASFM measuring section was 3,4 m farther downstream in the gate slots (Figure 2). With only one unit in operation, the average velocity was in the range of 1 to 2,5 m/s, which falls within the usual range of both the CM and the ASFM. In effect, the smooth transition (vertically and horizontally) between the trash racks and the measurement sections is likely to produce smooth velocity profiles. The only concern were the trash racks cross members which can generate large wakes. This has been taken into account in the selection of the number of ASFM measurement levels. The flow angle was expected to be near horizontal.

2.1 The ASFM setup

For the measurement, 21 pairs of transducers were installed on a steel frame (Figure 3) which is formed by two main vertical beams that support the ASFM transducers. One bottom plate and a top cross member complete the frame, forming a closed section. The number of transducers was chosen in order to resolve the possible oscillation of the velocity profile due to wakes of the trash racks main cross members. All transducers were set horizontally because the expected flow angle was horizontal, as it was later confirmed by the measurement.

In addition to the normal ASFM measurement system, a high-speed data acquisition system was used to record the raw acoustic signal for each element. In total, 12 signals were simultaneously recorded at a rate of 3,3 Ms/s (3,3 mega samples per second) for a 7 minutes period for each run. Those data were used after the tests for an alternate post-processing analysis.

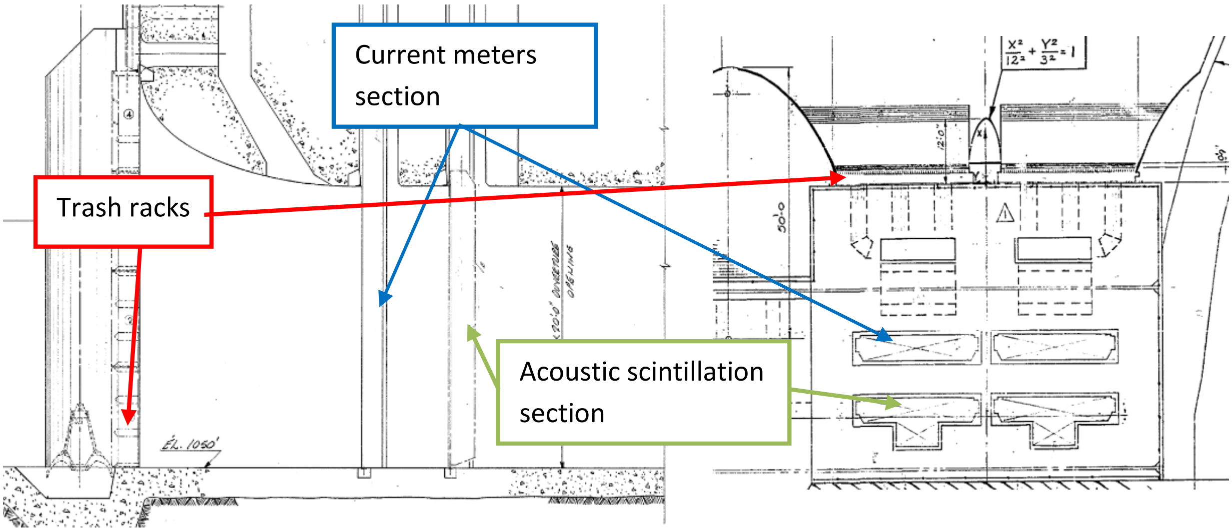


Figure 2: Intake layout lateral view (left) and top view (right)

Figure 3: Frame supporting the ASFM transducers

2.2 The current meters setup

The CM measurement was done with fourteen current meters installed on the bottom of a simple trolley made of two end plates, profiled rods and steel cables (Figure 4). The current meters were equipped with Type A self-compensating propellers that compensate for up to 45˚ flow angle. The profiled rods are the same that are used for the calibration of the current meters. Steel wheels help guiding the trolley in the gate slot both laterally and longitudinally. The frame was moved by means of two hoists controlled by variable frequency power drives, which allowed selection of the travel velocity. The two hoists were synchronized by means of encoders. Two displacement transducers measured the elevation of each end of the trolley. The trolley velocity was set to 50 mm/s except at the top and bottom of the measurement section where it was set to 10 mm/s for better defining the rapidly changing velocity profile. The total measurement time was 8 minutes for each run. The trolley velocity for the profiling method represents about 2% of the average flow velocity at the lowest discharge. The data acquisition software developed by Hydro-Québec allows recording the instantaneous rotational velocity of each current meter, i.e. it records the time stamp of each revolution. Once the rotational velocities are recorded, it is easy to calculate the mean value for different time intervals.

Figure 4: Frame supporting the current meters.

2.3 Results

Due to the presence of trash racks and the presence of a rigid and vibration-free support frame for the ASFM transducers, the conditions for the ASFM testing were very close to ideal, meaning that all flow velocities were used in the computing of the discharge (
Figure 5). The velocity profile measured by the ASFM shows small oscillations which are related to the trash racks cross members.

The CM results show that the velocity profiles produced are similar to the ones from the ASFM, with the ASFM results slightly higher. The small difference (higher velocities in the bottom part of the measurement section) can result from the ASFM measurement section being farther downstream than the CM section, as the velocity profile tends to develop or flatten as the turbulence is mixing the different layers of the flow. A part of the difference can also be due to two other factors: the acquisition times for the CMs and ASFM are not concurrent and the sizes of the measurement sections of the two methods are marginally different.

The 3D velocity profile (also Figure 5) from the CM measurement shows some asymmetry, especially in the bottom part of the section. It is likely due to the asymmetry of the intake upstream of the trash racks or the presence of some debris there. This asymmetry of the velocity profile in the bottom part of the measurement section can be the source of difference between the CM and ASFM methods.

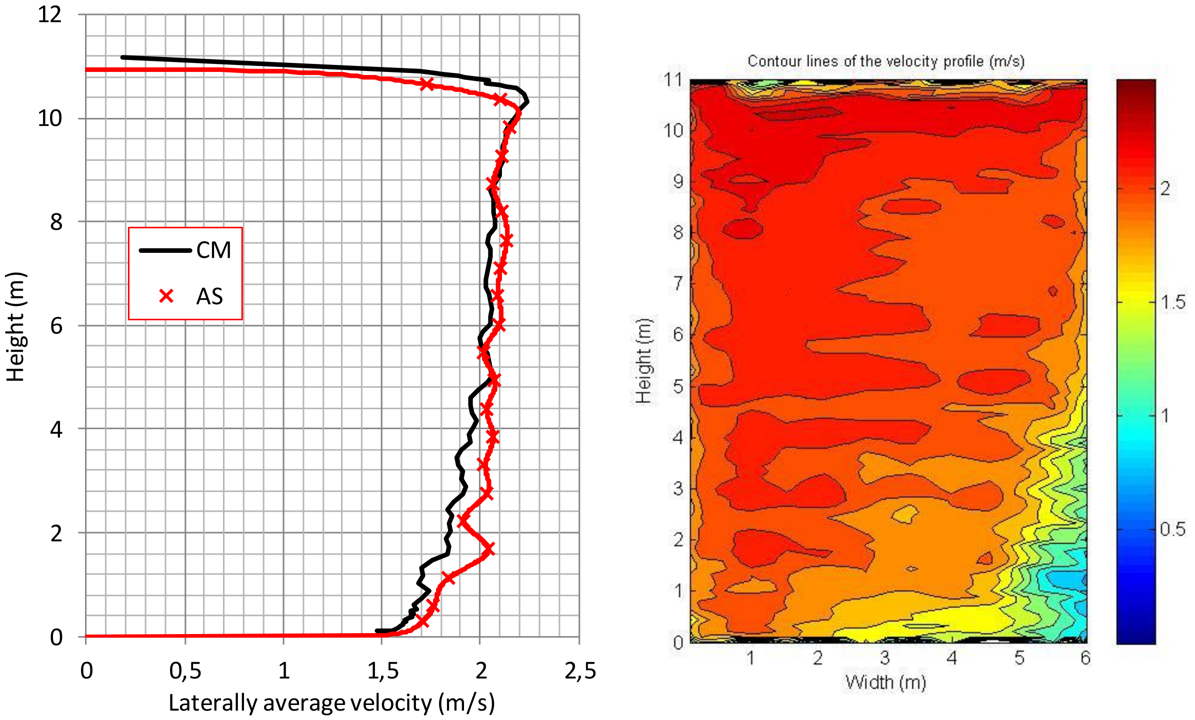


Figure 5: Vertical velocity profile (CM and AS) and 3D velocity profile for CM method.

2.4 Comparison of discharge measurements

The comparison of the discharge measured by the CM and ASFM (ASFM Link algorithm) is shown in Figure 6. It includes the results for four units and 40 runs. Overall, the difference between the two methods is 1,4 %, the ASFM discharge being higher. The standard deviation is ± 0,8 % and includes the deviation of both methods. The random uncertainty of the regression line is ± 0,3 %, which means that there exists a statistical difference of 1,1 % between the two methods. There is no significant variation of the difference between the two methods as a function of the discharge. Both methods have an expected uncertainty of ± 1 % to ± 1,5 %, which means that each uncertainty band falls within the one from the other method. The agreement between the two methods is therefore considered good.

2.5 Reprocessing of the ASFM data

A comparison was made between the standard time series computed by the ASFM (ASFM Link) and the recomputed time series based on the recorded raw signals (SMASH). The new algorithm was used to determine the amplitude of the acoustic pulses. This algorithm has already shown to improve the results of the ASFM in case of very low turbulence [3], which is not within the normal range of usage of the method. This new algorithm will not have a significant effect on the calculated discharge under normal stipulated conditions of usage of the ASFM (adequate turbulence levels downstream of trash racks).

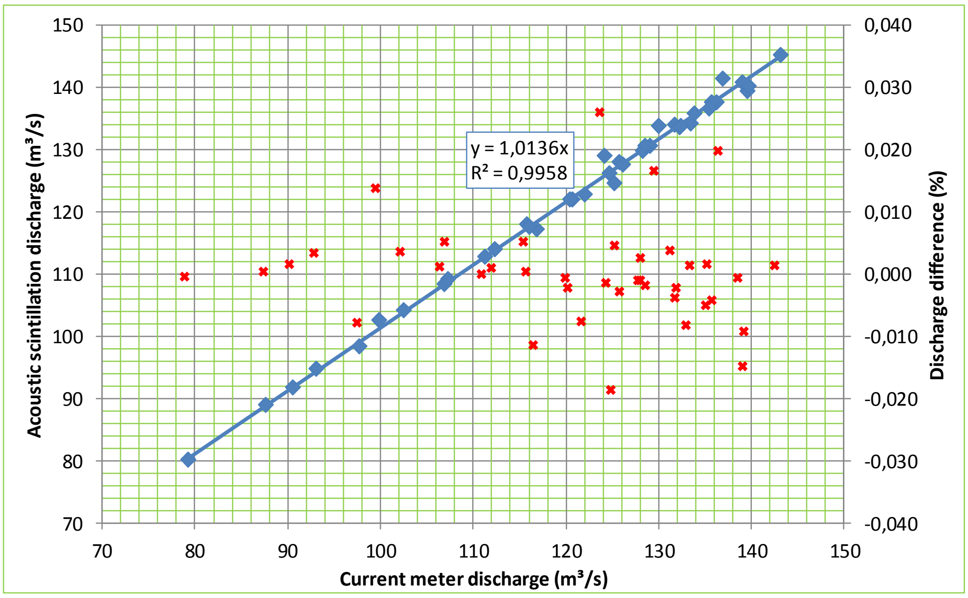


Figure 6: Comparison of discharge measured by CM and AS methods

2.6

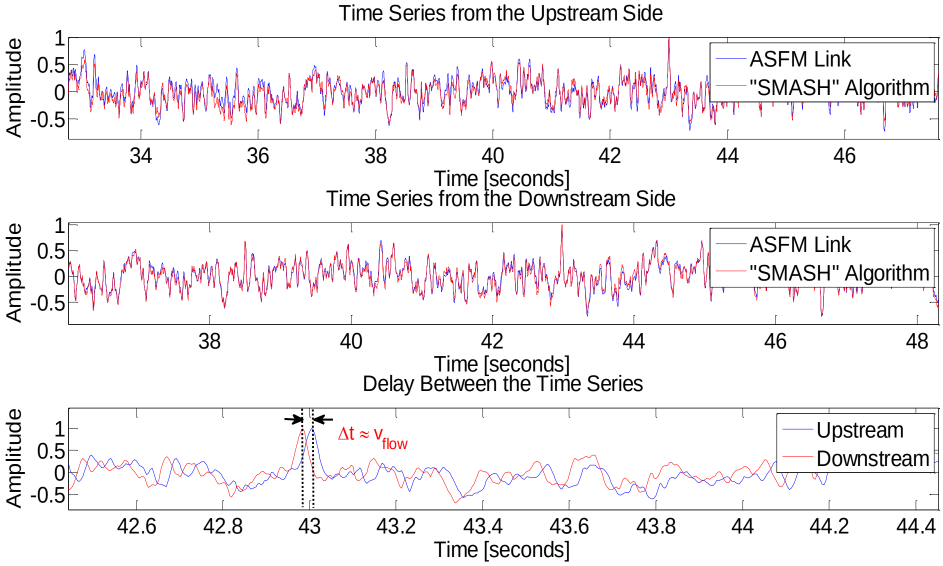


Figure 7: Time series comparison from standard algorithm and recomputed from recorded raw signals.

Figure 7 shows a very high resemblance between the two time series which leads to close values for the total discharge. The quality index of the measurement for each individual level [5] was above 0,9, thus a very high degree of confidence in the ASFM results.

Since there are two conduits at this plant, discharges from the two groups are presented, taken for several runs (Figures 8 and 9).

From the eight runs reprocessed with the new algorithm, the difference from the original calculation (ASFM Link) is 0,35 %, which is low and within the random deviation for those reprocessed values. As expected, this confirms that the difference for the present tests with adequate levels of turbulence is not significant.

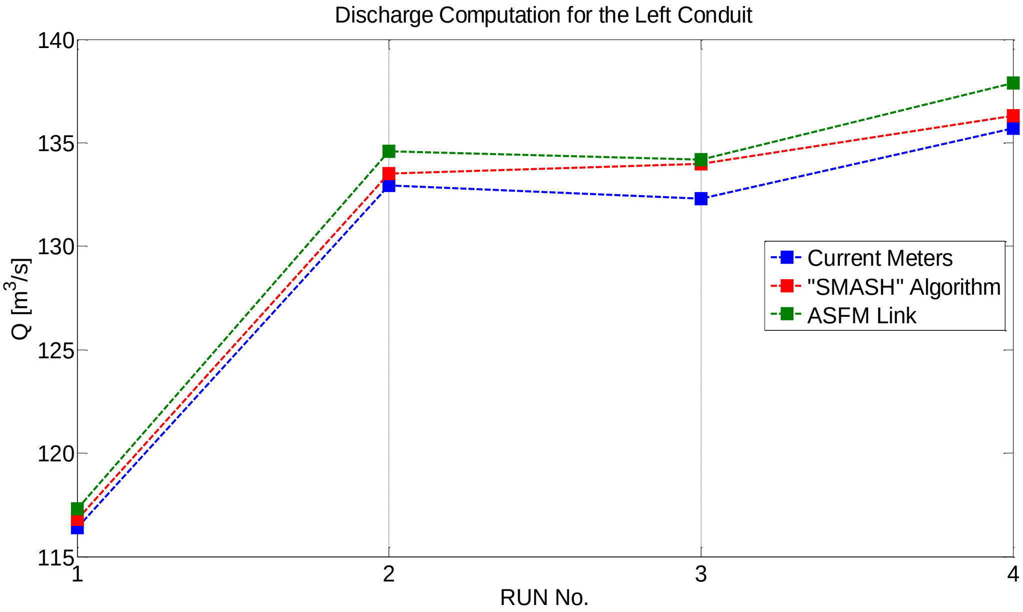


Figure 8: Site number one - Discharge comparison (left conduit).

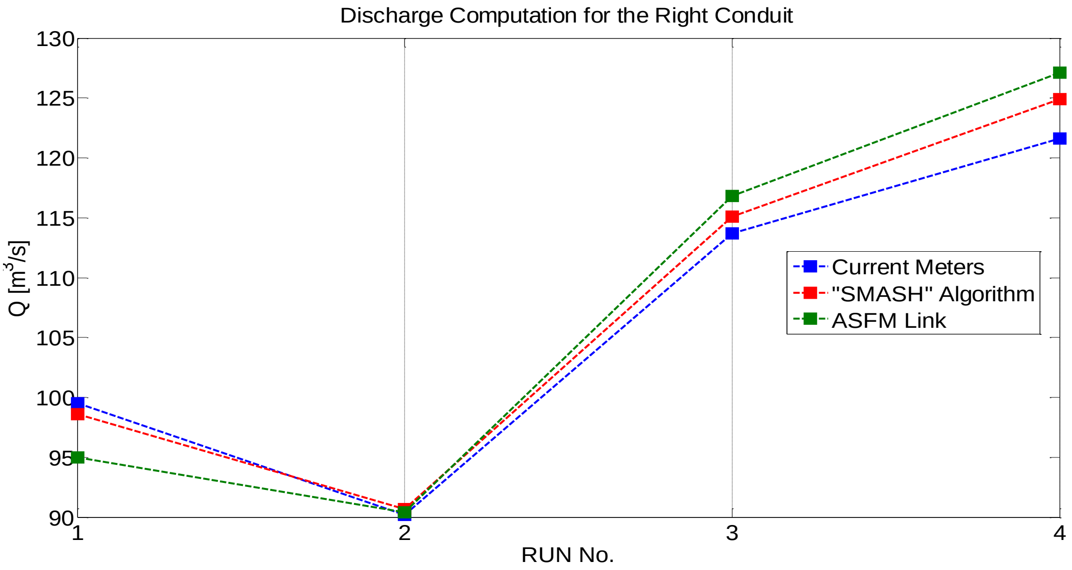


Figure 9: Site number one - Discharge comparison (right conduit).

2.7 Comparison of efficiency

Figure 10 shows the efficiency of the unit #4 (this unit represents an average one from the point of view of discharge comparison between the CM and ASFM). The efficiency measured with the current meters and the ASFM (ASFM Link and new SMASH algorithm) in 2013, the thermodynamic method (unit #8) measured in 1992 and the expected efficiency obtained from the model test step up are plotted as a function of the turbine output. At peak efficiency, all four curves are within 1,4 %. Both the CM and ASFM intake measurement methods, as well as the thermodynamic method, can be considered to have a measurement uncertainty of about ±1 to ± 1.5 %.

3 SITE NUMBER TWO, COMPARISON WITH ACOUSTIC TRANSIT TIME

A comparative test was done in a control structure that is used to maintain a minimal discharge for environmental purposes. To measure the flow on a permanent basis, an acoustic transit time (ATT) flow meter was installed in the channel upstream of the gate. An ASFM was installed downstream of the ATT flowmeter.

The geometry of the channel (Figure 11) is similar to the intake of site number one (Figure 1), with the exception that there are no trash racks upstream of the measurement sections. This measurement sections (ATT and ASFM) are 7,1 m by 5,0 m., while the ASFM measuring section is 5,4 m farther downstream. Both sets of transducers are installed on supports embedded in the concrete.

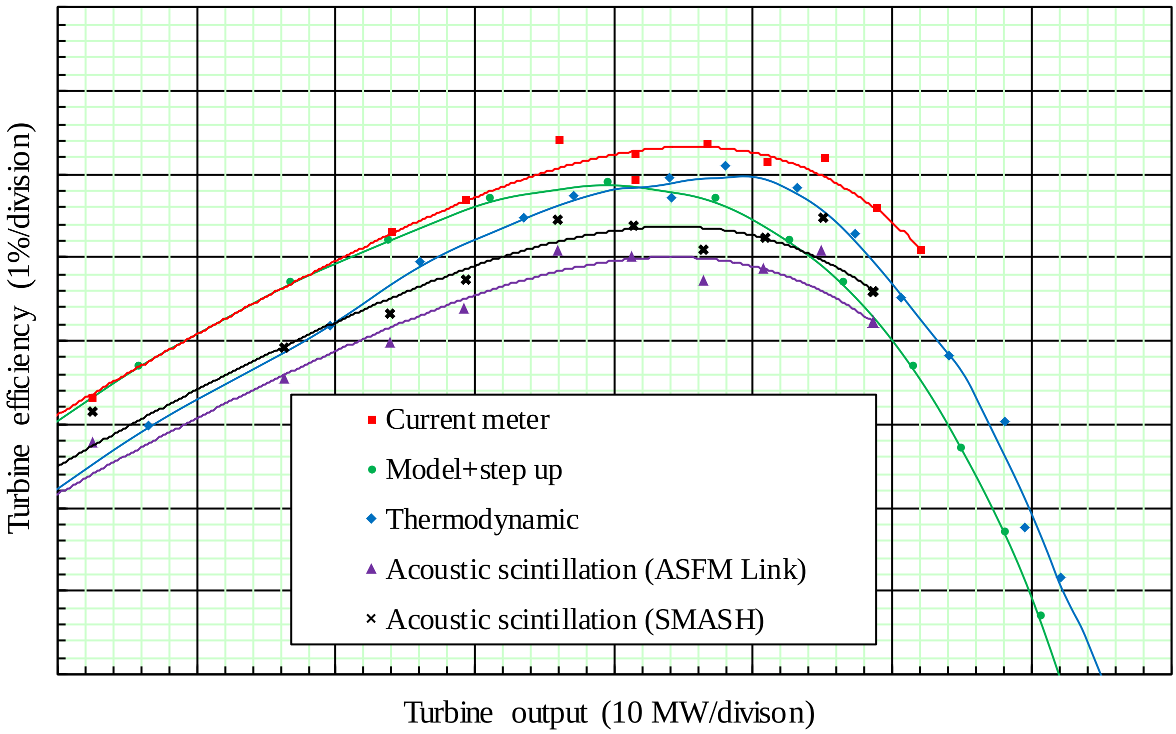


Figure 10: Unit 4 - Turbine efficiency measured with CM, AS and thermodynamic methods and model+step up (prototype) curve.

3.1 ATT setup

The ATT measuring section was located about 10 m from entrance of the channel, which was less than 2 times the hydraulic diameter of the measuring section. The ATT flow meter had eight paths in two cross planes. The Gauss Jacobi integration method was used to integrate the velocity profile. The ATT flowmeter was continuously measuring the discharge and the data was logged onto a computer for analysis. It is worth mentioning that the ATT setup does not comply with the IEC 60041 or ASME PTC 18 for doing discharge measurement for turbine guaranty verification purposes in similar conditions.

3.2 ASFM setup

The ASFM uses eight paths installed 5,4 m downstream of the ATT measuring section. The transducers were set horizontally as CFD and model testing have shown the flow being near horizontal despite the fact that the controlling gate is only nine meters downstream from the measurement section. The average velocity with the normal minimum flow (not the minimum gate opening tested) was in the range of 3,5 m/s, which falls within the usual range of the ASFM. The recording time for each run was 4 minutes or around 30 s for each path. The raw acoustic pulses were also recorded during the tests (see 2.1).

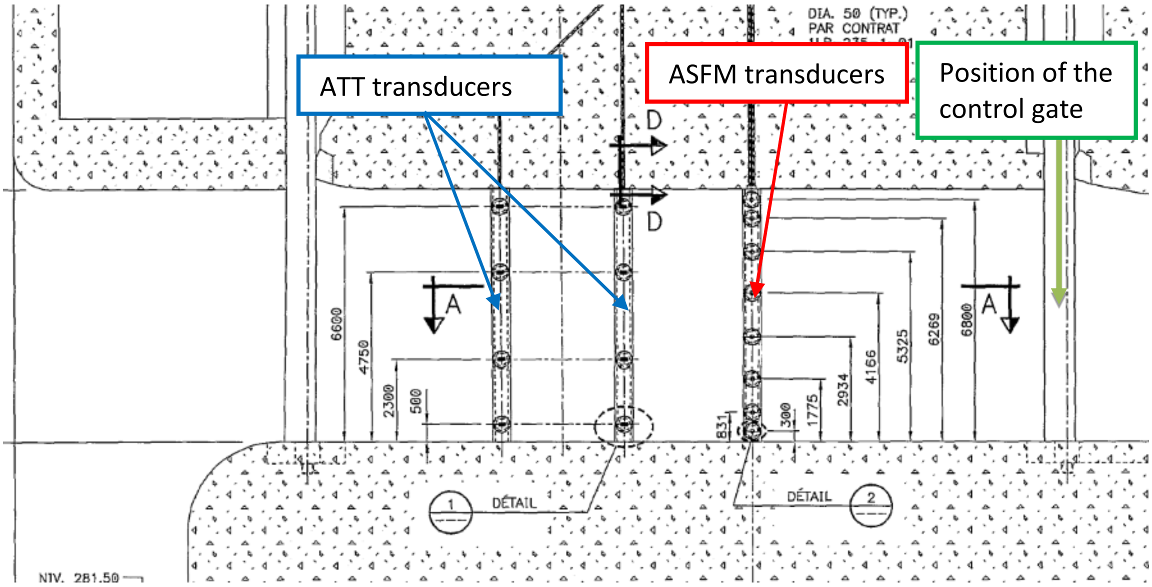


Figure 11: Layout of site number two.

3.3

3.4 Results

Figure 12 shows the discharge for both the ASFM (standard algorithm or Link) and ATT methods for each gate opening tested. The discharge is normalized with the nominal discharge of the gate at the maximum gate opening tested. The same figure shows the discharge difference between the two methods and the quality index (QI, multiplied by 10) for the ASFM method.

Overall, the difference between the ASFM and ATT was 2,3 %, with a standard deviation about the curve of 2,4 %, which is relatively high. The difference varied with the gate opening, from a minimum of around -5 % to plus 10 % at the minimum tested discharge. At this opening, the average velocity was only 0,3 m/s, which falls outside the normal range for the AS method.

As mentioned before, no trash racks were present upstream from the measurement sections, thus the turbulence was virtually inexistent, except for the one generated by the friction on the walls. This may explain the difference between the two methods. The quality index (QI) is another result that indicates the low levels of turbulence.

The asymmetry (vertically) may be another source of possible error for the ASFM. As noted on the cross section of the channel (Figure 11), it is likely that recirculation may be produced at the top and bottom due to none ideal shape. The new SMASH algorithm was then used to reprocess the data and the results are shown in Figure 13. The velocity profiles for two discharges (near 50% and 100 % of nominal discharge) are shown for the original algorithm (ASFM Link), for the SMASH algorithm and for the ATT flow meter. The discharge with the new algorithm is within 1 % of the ATT measured discharge. This is of the same order of magnitude as the measurement uncertainty of the ATT method.

The velocity profiles are also closer to the flatter ATT velocity profiles. There are still some differences there, because the measurement sections and the number of paths and positions are different for the two methods.

It is not yet known what the physical reasons are for this difference between the two algorithms. We may suppose that a number of noise sources (electric, hydraulic, mechanical, etc.) not related to the propagation of the acoustic pulses along the path are superimposed over the normal 307 kHz acoustic signal. Being higher in proportion to the acoustic noise in low turbulence conditions, those noise sources will likely dominate the cross correlation calculation and cause a systematic error. This new algorithm will continue to be verified in future ASFM comparison tests.

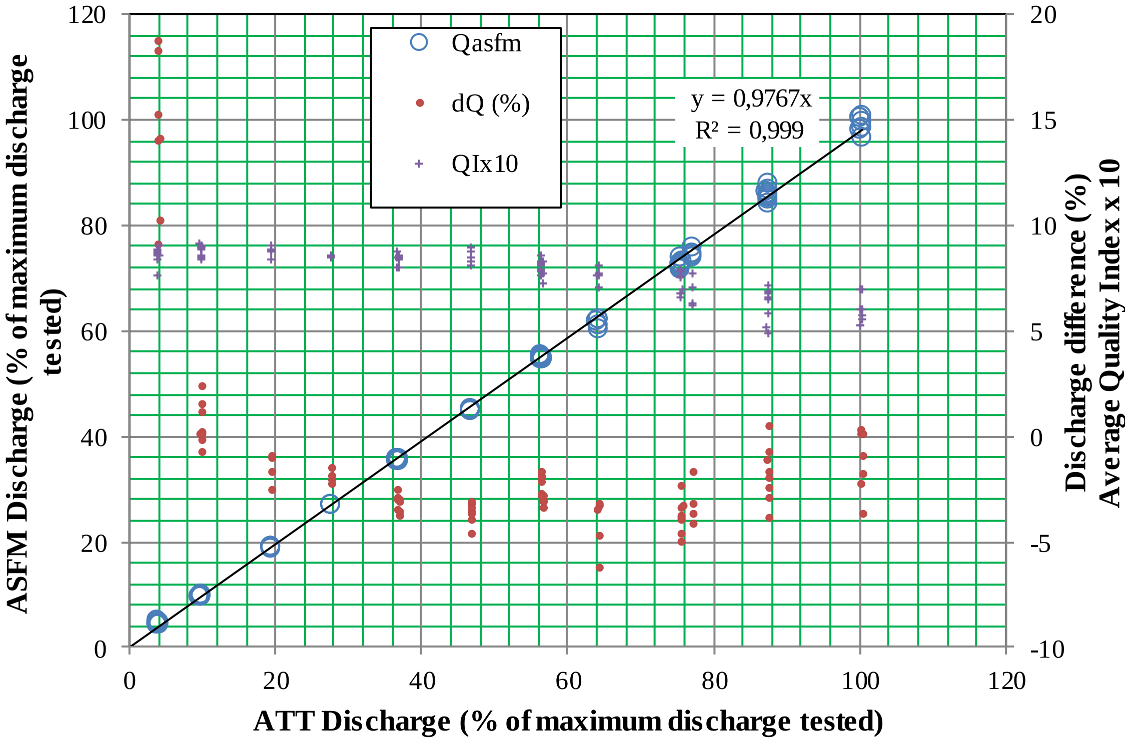
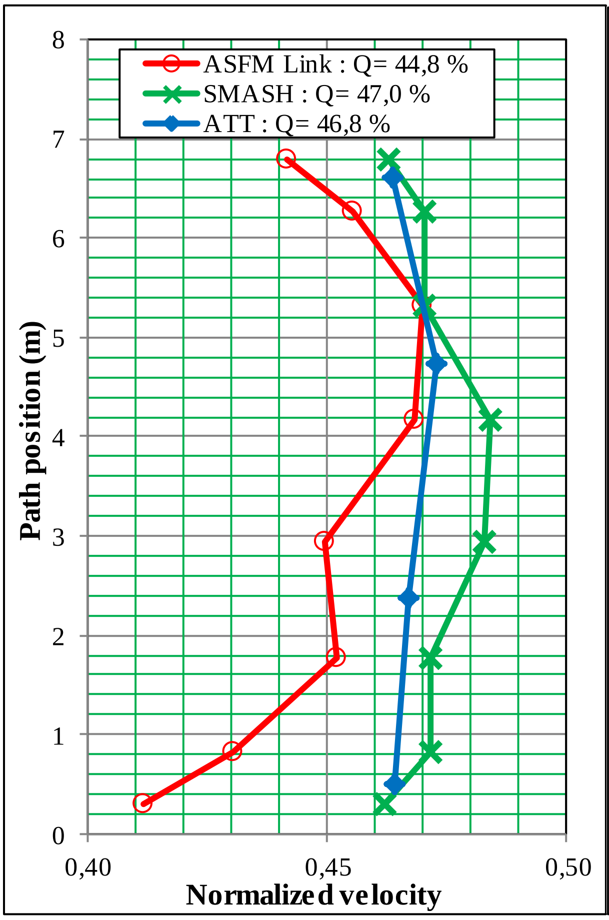


Figure 12: Site number two, comparison of discharge



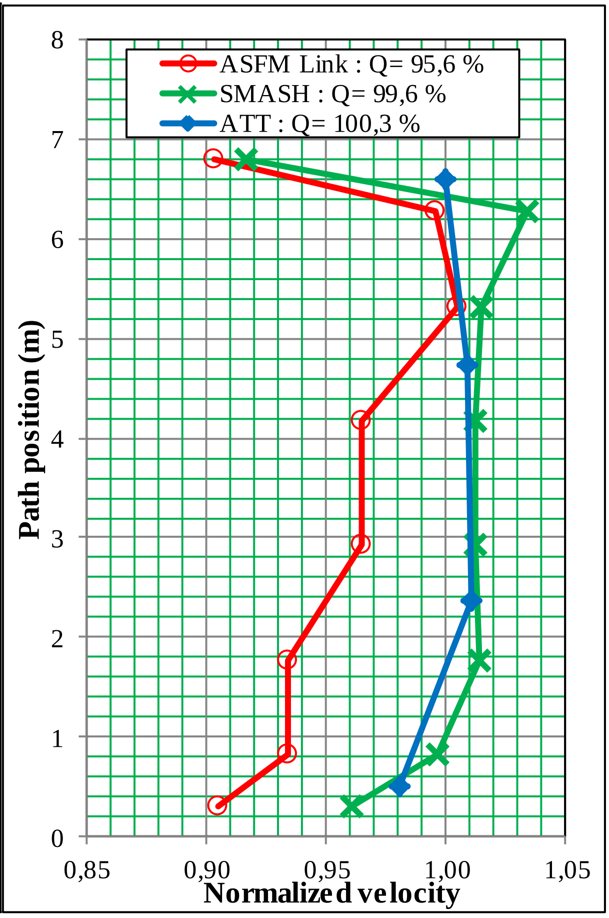


Figure 13: Site number two, comparison of velocity profile between the ASFM Link, SMASH algorithm and ATT, for 50% (left) and 100 % (right) of maximum discharge

4 CONCLUSIONS

Hydro-Québec tested the AS method at two very different sites.

The first site was considered good for the AS method from the point of view of turbulence levels, because of the presence of the trashracks upstream of the measurement section.. As found at other sites where the turbulence conditions were good, at this site the discharge results of the ASFM compared well with the results of other code approved methods.

The second site was a not ideal for the ASFM because of the absence of trashracks. As found previously at sites with similarly low turbulence levels, the difference between the results of the two methods was bigger here.

The new algorithm was used to reprocess the data of the ASFM from both sites. As expected, the ASFM results did not change significantly for the good conditions at the site one, but they did improve under the very low turbulence conditions at the site two.

Although the reason for this improvement is not yet fully understood, the measurement and reprocessing of the data with the new algorithm will be tested more thoroughly in future ASFM comparison tests, as Hydro-Québec, EDF and ASL AQFlow continue to collaborate on this matter.

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