Turbine flow measurement in low-head plants - Acoustic Scintillation Flow Meter: Why? How? Where?

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Introduction

Why: One of the key objectives of every owner of a hydro plant is to maximize its output, either by operating the units at their optimum efficiency or, if conditions dictate, by rehabilitating the old inefficient units or even replacing them with new ones. In order to evaluate the results of these activities, both before and after performance of each unit must be known. Performance testing requires absolute flow measurement, and for low-head units with short intakes this has until recently been sufficiently impractical and expensive that it could rarely be justified. Calls for new, simplified yet accurate absolute flow measurement methods for low-head plants with short intakes have over the last 40 years been numerous (*1 - 3).*

How: The Acoustic Scintillation Flow Meter (ASFM) – an innovative, cost-effective tool specifically developed for the flow measurement in short intakes appears to address these calls. The ASFM

- reduces unit downtime (when frame mounted, it is portable between intakes without dewatering)
- is unobtrusive (no instruments in the flow, making it suitable for long-term monitoring)
- has no moving parts (requires virtually no maintenance and calibration)
- can deliver accurate and repeatable absolute or relative measurements

Where: During the last 15 years, the ASFM has been used in intakes of varied characteristics and with varied results. Lessons learned from these measurements have been evaluated and used in developing guidelines for successful applications. More recent of these are presented briefly below as an introduction to the more detailed description of successful applications in France, Spain, Canada and USA covered in the three companion papers.

1. Why is a better flow measurement method needed for low-head plants?

Traditionally, propeller-type current meters placed on fixed supports attached to the walls of the intake were used for flow measurement in low-head plants *(4, 5).* Large numbers of current meters were used to achieve the desired accuracy, and the unit had to be taken out of service for significant amount of time for the erection of scaffolds and support frames, and for mounting of the current-meters. Another down time of the unit was required for the retrieval of the instruments and dismantling of the support structure. Any instrument malfunction, such as that caused by debris impact, required further unit down time. Even though good results were reported for this method from comparative tests, the accompanying costs were so high that the method never became popular, particularly outside Europe.

In an effort to reduce the unit down time, much smaller numbers of current meters were mounted in one or two rows on light weight moving frames. These were inserted into existing intake slots and traveled the full height of the intake, either stopping at each measurement level for each measurement, or measuring continuously while slowly sweeping the height of the intake (*6, 7).* The measurements could be completed much faster than with the fixed supports, and without the need for unit stoppage and intake dewatering during instrument installation, removal and replacement. In plants with multiple units, fully instrumented frames could be moved between intakes, saving additional time. In plants with two, three or even four intake bays, complex set of lifting mechanisms would be required to synchronize the movement of the individual frames.

For both methods, the current meters require mechanical maintenance and periodic calibration. Their exposure to debris impact makes them unsuitable for long-term flow monitoring. Neither method has yet been accepted by the industry codes *(8, 9)* for flow measurement in short intakes.

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2. How does the Acoustic Scintillation Flow Meter address that need?

The acoustic scintillation flow meter (ASFM) utilizes the effects of natural turbulence embedded in the flow on acoustic signals (Fig. 1). In its simplest form, two transmitters are placed on one side of the intake, two receivers on the other. The acoustic signal amplitude at the receivers varies randomly as the turbulence along the path 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 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 position of the peak in the time-lagged cross-correlation function calculated for Signal 1 and Signal 2. The mean velocity perpendicular to the acoustic path is then Δx/Δt. Because three transmitters and three receivers are used, the average inclination of the velocity is also obtained. The flow is calculated by integrating the average horizontal component of the velocity at pre-selected levels over the total cross-sectional area of the intake.

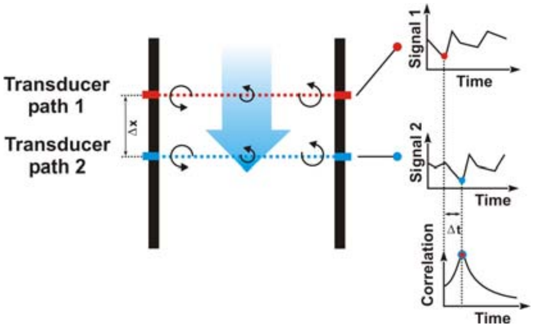

Fig. 1 Representation of the acoustic scintillation principle

The ASFM has no moving parts and requires virtually no mechanical maintenance and calibration, and its acoustic paths are oriented perpendicular to the axis of the intake, making it suitable for very short intakes often associated with low-head turbines, such as Kaplan or bulb.

For the intakes with stoplog or other slots available, the ASFM transducers can be mounted on a frame which is then inserted into the slots fully instrumented (Fig. 2). And because the transducers are mounted on the frame with their faces flush with the intake walls and the cabling is inside the frame, the ASFM does not obstruct the flow, is not vulnerable to debris impact and can be used for long term monitoring. Ref. (*10*) covers long term monitoring with the ASFM in detail, both at Hydro Quebec and at US Army Corps of Engineers.

Once in the slot, the ASFM mounting frame can remain stationary (if it spans the full height of the intake and is equipped with a set of acoustic paths), or it can travel the height of the intake (if it is smaller, with only one or two rows of acoustic paths – Fig. 3). This is somewhat similar to the measurement described above for the current meters, except that unlike the stationary frame housing current meter arrays, the stationary ASFM frame

Fig. 2 – Stationary ASFM frame (courtesy USACE) *Fig. 3 – Moving ASFM frame (courtesy EDF)*

is in fact portable, can be instrumented in the dry and inserted into the intake stop-log slots without dewatering. Consequently, unit downtime and generation losses are minimized to such a degree that the revenue gains from increased efficiency exceed the cost of the testing (*11)*. The ASFM portability is even more beneficial at plants with multiple units, as instrumented stationary frames can be moved from unit to unit relatively quickly and easily. At a North American plant in 2007, flow measurements in 74 small units were completed in 4 weeks (*12).* At another plant, a testing program costing US$150,000 resulted in an annual revenue gain of US$490,000 (*11).* When comparing profiling frame applications, there is virtually no difference in unit downtime and generation losses between current meters and acoustic scintillation. Ref. (*13*) describes in detail the ASFM measurements at Electricite de France at plants with available slots.

Interestingly, even at plants with no slots available for the ASFM frame to be inserted into, where the advantage of the ASFM's portability is largely lost, the ASFM can outperform other measurement methods if appropriate measures are taken. Ref. (*14*) describes in detail ASFM measurements at Union Fenosa Generación, Spain, at plants without available slots.

The ASFM has been used in flow measurements at more than 40 plants and over a hundred units, initially in North America, more recently in Europe as well. In many cases, it produced accurate and repeatable results. For example, performance testing of all 10 units at the Wells project on the Columbia River revealed peak efficiency differences between units larger than 1%, thus allowing the owner to optimize the operation of individual units and the entire plant (*15).* In some cases, however, the discharge values appeared to be biased, as the computed turbine efficiencies were higher than expected (with these expectations usually based on model tests). As this bias varied from plant to plant, but appeared constant for any one unit or for identical units at a plant, the ASFM could be used for index testing, where repeatability of the results is the key requirement. As long as the flow conditions remain reasonably unchanged throughout the testing (head, adjoining units/spillway operation), the ASFM has consistently delivered results with random uncertainties better than ±0.5 %. For example, at the two plants on the River Mino in northwestern Spain with stable operation of adjoining units and stable head conditions, values between ±0.1 and ±0.3% were achieved by Union Fenosa (*16).*

For absolute flow measurements, however, improved understanding of the causes of the bias which would lead to its elimination remained to be resolved.

3. Where will the ASFM produce accurate flow measurements?

An intensive review of correlations between plant characteristics and the occurrence of systematic errors (or bias) at each plant where the ASFM was used indicated that the primary cause was coincident and strong inhomogeneity in the intensity of small-scale turbulence and the mean velocity in the measurement plane. Such nonuniformities are present in the wakes behind large supporting members in the trashracks oriented perpendicularly to the ASFM acoustic paths (*17).*

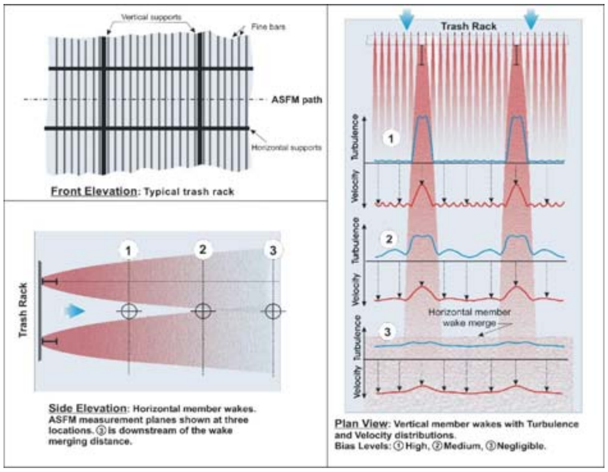

Fig. 4 – Schematic representation of bias errors produced by large vertical trashrack supports

The algorithms incorporated in the ASFM to calculate the path-averaged velocity implicitly assume relative uniformity along the acoustic path for either the local turbulence intensity or the flow velocity. A negative bias in the path-averaged velocity occurs if the path crosses the wake behind a vertical trashrack support, because the lower velocities in the wake are accompanied by elevated levels of turbulence (Fig. 4). The effect increases if the flow enters the intake at an angle, as that increases the projected width of the support members. Zones where elevated turbulence levels coincide with elevated velocities produce positive bias. High background levels of turbulence, such as those produced when the wakes from horizontal members merge, suppress the effect.

The wake effects will not degrade the accuracy of the ASFM if the instrument is installed in classical shape low-head short intakes where

a) the trashrack vertical structural supports are not wider than 100 mm and not closer than 6 m from the measurement plane, and the trashrack has been cleaned prior to the testing,

b) the angle in the horizontal between the inflow velocity vector and the axis of the intake does not exceed 5 degrees, and the operation of the neighbouring units and the spillway, if applicable, is controlled to the degree necessary to stay within this limitation, and

c) there are no unusual shape or convergence irregularities.

When these conditions are not fulfilled, but the wakes from the horizontal trashrack supports have merged before they reach the measurement plane, then the bias due to the wakes from the vertical support members will be reduced to a negligible amount. The distance downstream of the trashrack, X_{merge} required for the wakes from the horizontal members to merge may be estimated as

$$\frac{X_{merge}}{D} = 1.44\left(\frac{H}{D}\right)^{2.2}$$

where H is the vertical separation between the major horizontal trashrack supports, D is their width in the vertical and X is the distance between the trashrack and the measurement plane (all quantities in the same units).

There will be instances where there are significant wakes from vertical members, and the wakes from the horizontal members have not merged to produce a sufficiently uniform turbulence background, or other aspects of the intake conditions have resulted in non-uniform distributions of turbulence and velocity. If the forms of the distributions are sufficiently well known, for example from measurement with vertical orientation of the acoustic paths (*14*), the bias produced by this mechanism may be corrected.

Other effects can produce biases in the ASFM data, even in intakes without large vertical members in the trashracks and that are otherwise favourably configured. Anisotropy (variation with direction) in the turbulence which frequently occurs near boundaries and immediately downstream of trashracks can also produce bias errors. Investigation of the effects of turbulence anisotropy has led to a revision of the algorithm used in the ASFM to compute the flow velocity. The revision improves ASFM performance in regions of strong acoustic fluctuations and unsteady flows, such as those found in Columbia River plants near the boundaries and behind fish diversion screens. The revision to the algorithm takes into account the magnitude of the cross-correlation between the acoustic signals for each of the three pairs of signal paths in the array in addition to the peak timing.

Using the additional information results in a more accurate measurement of the flow inclination angle. Figure 5 shows an example of the velocity vectors from a measurement at Lower Monumental Dam, with fish screens in place, computed using both the original and revised algorithm. The disagreement between the two algorithms is rather extreme, mainly because of the distortion of the flow field by the screens, but also near the floor and the roof. The discharge computed by the revised algorithm is 7% greater than that calculated by the original algorithm, producing efficiency values very close to expected values. Recalculations with the original and revised algorithm for other Columbia River plants where the ASFM has been used for flow measurement have shown consistent bias reductions (*17).* The revised algorithm was subsequently used at Lower Granite dam in December 2004 and when the measurement results were compared with the expected turbine performance from model tests, the bias was found to be less than 1% (*18).*

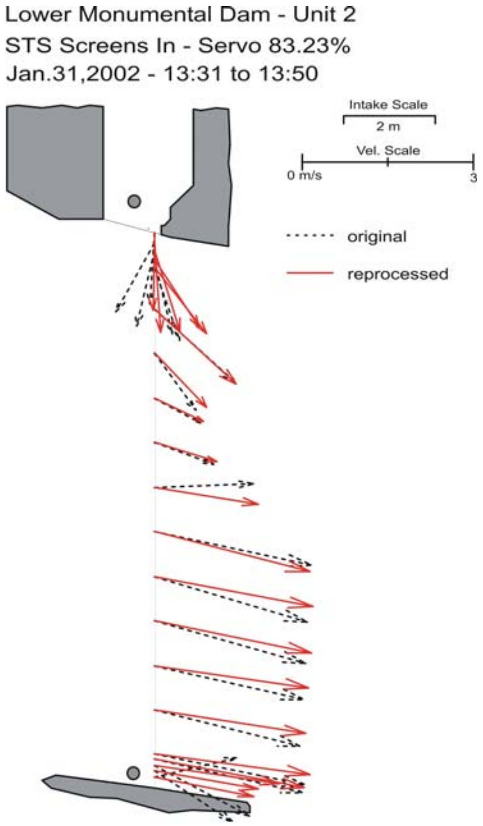

Figure 5 – Example of flow profiles changes for the revised algorithm

It should be noted that for the large plants on the Columbia River system, the revised algorithm had virtually no effect on the repeatability of the discharge values, as they remained roughly the same at about 0.4% standard deviation. At several smaller plants with more irregular intake flow conditions, however, the revised algorithm reduced the variability of repeat discharge measurements significantly.

4. Future Tests

In spite of, or perhaps because of, the better understanding of the measurement bias and better understanding of the characteristics of short intakes in which the ASFM will produce accurate and repeatable measurement results reported in previous paragraphs, and in addition to the successful measurements which will be reported on in the following three papers, many more successful applications of the ASFM for turbine flow measurement in short intakes will be required before the method is fully accepted by the relevant industry codes.

Particularly valuable are the tests in which the performance of the ASFM can be directly compared with other measurement techniques, ideally those already accepted by the codes. Several comparison tests have been documented previously (*15, 18 - 23*), although none of these involved code-approved reference measurements. Two more comparison tests will take place this summer/fall and in both cases code-approved reference measurements will be included.

First, building on the encouraging preliminary comparison between the acoustic time-of-flight method and the ASFM at their Chief Joseph plant on the Columbia River in October 2008, US Army Corps of Engineers will be conducting further comparison testing there in September 2009. This 2160MW plant has two units equipped with the acoustic time-of-flight instrumentation in the penstocks, and both of these units will be used for the comparison tests. Interestingly, this plant has a large vertical pier in the intake, located upstream of the ASFM measurement plane, which produces a significant wake. For that reason, in 2008 the ASFM was equipped with 10 vertical paths in addition to the conventional 20 horizontal paths. The results from the vertical paths allowed a bias correction to be applied to the discharge calculated from the horizontal paths.

In October 2009, ASME PTC-18 committee and CEATI Hydraulic Plant Life Interest Group are conducting a major comparative test at British Columbia Hydro's Kootenay Canal plant on the Kootenay River. This plant was used in 1983 for EPRI sponsored comparative testing of a number of code-approved flow measurement methods under code-approved conditions (meaning a suitably long straight penstock). The time-of-flight method was also included, even though it was not code-approved at the time, and its results were sufficiently impressive (*24)* to lead to code acceptance (full acceptance by the ASME, partial acceptance by the IEC). For the 2009 tests, the time-of-flight instrument installed in a code-approved position within the Kootenay Canal penstock will be the one against which three intake flow measurement methods will be compared: a fixed frame mounted ASFM, moving frame mounted current-meters (both installed in the intake stoplog slot) and an acoustic time-of-flight instrument (installed in the intake downstream of the stoplog slot).

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