Estimating uncertainties in turbine discharge measurements with the Acoustic Scintillation Flow Meter in low-head short-intake plants

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Introduction

Turbine discharges at low-head plants, with short converging intakes and uneven/unstable velocity distributions, are notoriously difficult to measure accurately. This is reflected in the fact that no existing standard or code deals with such measurements and also in the scarcity of published literature on rigorous evaluation of uncertainties associated with these measurements.

In this paper, we describe potential sources of measurement uncertainties, based on our recent discharge measurements with Acoustic Scintillation Flow Meter (ASFM) at several low-head plants on the Columbia River in Washington State, USA. The ASFM was selected by the plant owners as the most suitable tool available today for flow measurements in the challenging hydraulic conditions of their short intakes.

Estimates of the uncertainty due to different interpolation and numerical integration methods for computing the discharge from a finite number of readings at pre-selected elevations are described. Flow in the boundary zones at the roof and the floor of the intake, where the zones are too narrow to allow direct measurement, must be approximated, and the uncertainty associated with these estimates is calculated. Also included are the effects of trash rack support members. The contributions to the uncertainty from temporal variations in the vertical distribution of the velocities in the intake are also estimated. Uncertainties due to angular, linear and time delay measurement, electronic digitizing, transducer mounting, flow bypass and frame vibration are also considered. These elemental uncertainties are classified as bias or precision, and combined individually by the root-sum-square method to give the estimated total bias and total precision uncertainties, estimated with 95% confidence.

The standard installation and operation of an ASFM in the gate or stoplog slot of a short, low-head intake are also described.

1. Background

Turbine discharges at low-head hydroelectric plants with short, converging intakes and uneven or unstable velocity distributions have always been difficult to measure accurately. For many years, current meters were the only suitable technology and even their use, under these difficult flow conditions, was not sanctioned in any existing standard or code.

The need ‘to simplify measurements of large quantities of water in the short conduits of low-head plants’ was recognized as far back as 1970, when J. Guthrie Brown (*1*) described several early experiments with the ultrasonic method. It took many years of experimentation and field applications (including the 1983 EPRI comprehensive comparative testing at Kootenay Canal, B.C., Canada (*2*)), before the acoustic Time-of-Flight (TOF) method was accepted by the 1991 IEC 41 International Standard (*3*) and the 1992 ASME PTC 18 Test Code (*4*). And even then, the IEC 41 acceptance was only as an optional, not primary, measurement method.

And because these experiments did not address the problems specific to short intakes of low-head plants, no specific conditions could be stipulated in either the IEC 41 or PTC 18 for such use. As a result, even today – 2001 – ‘no existing standard deals with discharge measurements in short penstocks or intakes, especially for low-head plants' (*3*). Even the 2001 draft PTC 18 does not give specific provisions for flow measurements in short intakes with current meters, and very few (beyond stipulating that more than 4 paths on two planes will be needed) with the TOF method. It is interesting to note that at Douglas PUD's Wells Hydroelectric Project on the Columbia River in Washington State, USA, up to 18 paths were used recently, together with a steep 78 degree angle, in an attempt to make the TOF method work in a short intake (*5*).

In an attempt to fill this void in suitable technology, over the last 10 years, ASL Environmental Sciences, and more recently a subsidiary company, ASL AQFlow Inc., both of Sidney, B.C., Canada, have developed a tool for accurate measurement of turbine discharge in short converging intakes of low-head plants: the Acoustic Scintillation Flow Meter (ASFM).

2. ASFM operation

The Acoustic Scintillation Flow Meter (ASFM) uses a technique called acoustic scintillation drift to measure the velocity of the water flowing through an intake to a hydroelectric turbine by utilizing the natural turbulence embedded in the flow.

Fig. 1 shows a schematic representation of an ASFM in use. Two transmitters are placed at one side of the intake, two receivers at the other. The signal amplitude at the receivers varies randomly in time as the distribution of turbulence along the propagation paths changes with time and the flow. If the paths are sufficiently closely-spaced, the turbulence may be regarded as being embedded in the mean flow, and then the pattern of these variations (known as scintillations) at the downstream receiver will be nearly identical to that at the upstream receiver, except for a time delay, *Dt*. If these scintillations are examined over a suitable time period, this time delay, *Dt*, can be determined. The mean flow velocity perpendicular to the acoustic paths is *Dx/Dt*, where *Dx* is the separation between the paths.

With the use of three transmitters and three receivers at each end, the average magnitude and the average inclination of the velocity are measured at several preselected measurement levels. Total discharge is calculated by integrating the average horizontal component of the velocity at each level over the total cross-sectional area of the intake.

The transducer arrays can be attached to a frame deployed into stoplog or gate slots, a great advantage for low-head plants where the intakes are typically short with no straight segments and no constant cross-section for other measurement methods to work. The lateral averaging of the velocities results in large-scale eddies not biasing the measurement. And as no instruments are required in the measurement zone, flow interference is minimized, or eliminated altogether. Furthermore, there are no moving parts and thus no ongoing mechanical calibration is required.

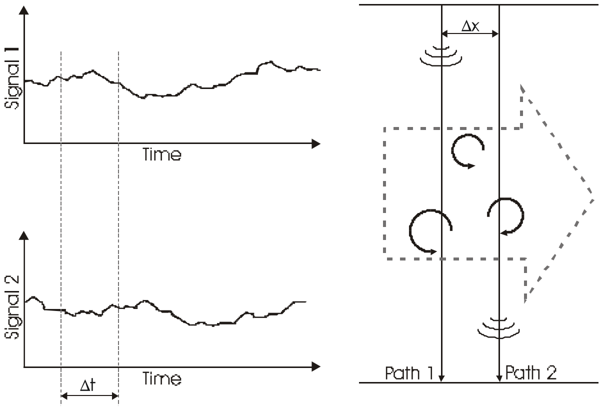

Fig. 1: Schematic representation of ASFM operation

3. Discharge measurements with ASFM

Since 1992, the ASFM has been used for discharge measurement and/or comparison testing as follows:

US Army of Engineers have used it repeatedly at their plants at The Dalles, Bonneville, McNary and Lower Granite; Chelan County PUD at the Rocky Reach and Rock Island plants; Manitoba Hydro at Seven Sisters; Tennessee Valley Authority at Wheeler and Fort Patrick Henry plants; BC Hydro at Revelstoke and Stave Falls; and Hydro Quebec at Laforge-2 and several of their other plants.

4. Sources of uncertainty

In this paper we are concerned with the uncertainties that are associated with measuring turbine discharge with the ASFM in low-head, short-intake plants. Some of the elemental sources of uncertainty discussed below are specific to the ASFM, while others are more general and apply to any velocity-area measurement method.

4.1 Bias uncertainties

4.1.1 Uncertainties due to angular and linear measurement

With the transducer arrays mounted on a frame (Fig. 2), the acoustic path length L and the elevation z are routinely measured to within ±0.1% (e.g. to within ±5mm over 5m).

The transducer array deviation f from the horizontal alignment is measured with digital levels (resolution ± 0.2°) to within ±0.001%. The deviation of the frame from the vertical when the frame is in place in the slot is limited by the amount of clearance between the frame and the sides of the slot, and for typical situations can be stated as ±0.003% (the top could shift by ±5cm over the 15m height).

The transducer path separation Dx is determined by the acoustic separation of the transducer array elements. Extensive measurements on existing ASFM transducers indicate ±0.2% uncertainty in Dx (e.g. to within ±0.07mm over 35mm design separation).

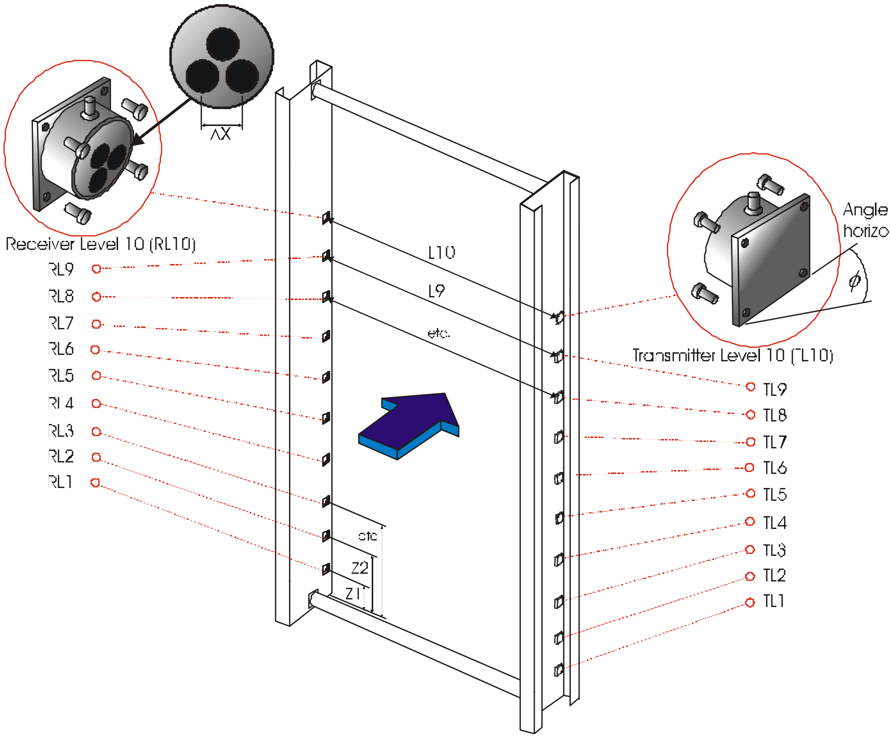

Fig. 2 – Fixed-frame installation and definition of parameters

4.1.2 Uncertainty due to electronic digitizing

The uncertainty for the 12-bit digitizer is specified by the manufacturer as ±0.02% (1 over 4096).

4.1.3 Uncertainty due to transducer mounting

The ASFM transducers are mounted in the frame such that their faces are flush with the surrounding intake wall surface. The uncertainty due to instruments protruding into the flow is therefore judged to be negligible.

4.1.4 Uncertainty due to integration

There are 3 components to this uncertainty source:

- uncertainty due to the integration technique used to integrate the path velocities to obtain the flow rate normal to the measurement section,

- uncertainty caused by the deviations from the assumed velocity profile in the roof boundary layer (area above the measurement section), and

- as above in the floor boundary layer (below the measurement section).

Since the ASFM measures the lateral average velocity, the discharge is computed by

$$Q = \int_0^H v(z) \cos[q\,(z)] L\, dz$$

Normal procedure with the ASFM is to use an adaptive Romberg integration with interpolation in the integrand between the measured points. Various interpolation methods have been used (linear, spline, quadratic), and indicated that the variation in the computed curve area among the interpolation methods is less than ±0.4%. More important is the number of measurement levels used, particularly when the velocity profile is exceedingly non-uniform. Numerous tests which have been reviewed for this paper demonstrate that satisfactory results are obtained with the number of measurement levels ranging from 5 for smaller, uncomplicated intakes, to 10 for larger, difficult geometry intakes, frequently with fish screens and/or deflectors.

Recent measurements in the intake of a bulb turbine at Rock Island plant on the Columbia River in Washington State, USA (Fig. 3) confirmed that even for such difficult flow condition intakes (note how the massive horizontal trashrack support beams introduce significant velocity variations with elevation) increasing the number of measurement levels from 10 to 20 resulted in discharge differences of no more than ±0.3% over the full range of flows (*7*). Thus it has been indicated that for most intakes, vertical sampling resolution of 10% of the intake height will limit the uncertainty due to vertical variation in velocity to less than ±0.5%.

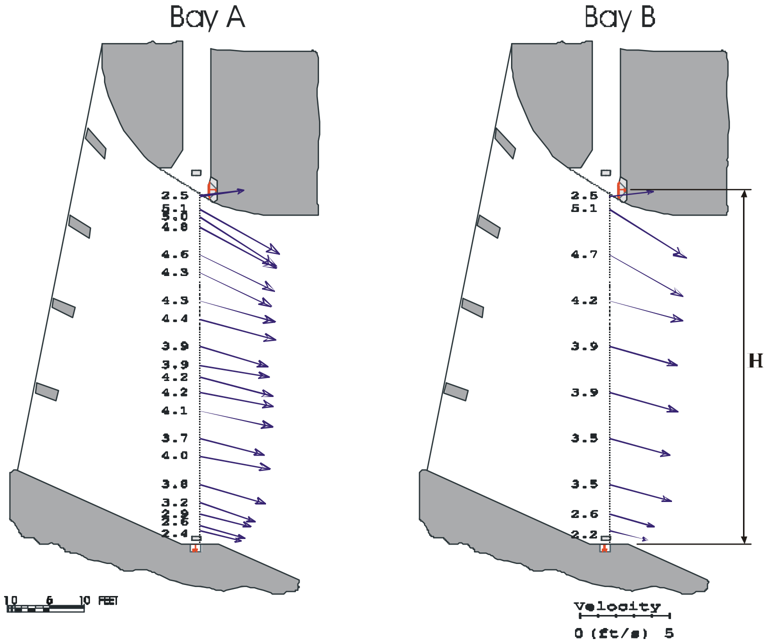

Fig. 3 – Velocity vectors measured in Unit 6 intake, Rock Island Powerhouse Two

With the ASFM, the distance of the closest approach to the floor and the roof is about 25cm, depending on the geometry (width) of the intake, because of interference caused by signal reflections from the boundaries. In the absence of direct measurements, assumptions must be made about the shape of the lower and upper velocity profile between the nearest measurement point and the floor/roof of the intake. With the ASFM, a $1/m$ power law has been assumed for the integration at the roof and at the floor, with the value of m depending on the geometry of the roof. At the floor, the velocity profile is further distorted by the presence of the lower frame support member. The form of the boundary has been estimated from comparisons made between the physical model measurements, computational fluid dynamics simulations and direct ASFM measurements.

However, as this experimentation is still proceeding, a conservative approach has been taken in assuming the uncertainty in these zones to be ±10%. As they typically represent only 3% of the total discharge or less, their contribution to the uncertainty is limited to ±0.3%. This agrees with the well-documented finding that the relative importance of the boundary zones decreases as the size of the intake increases, and all intakes reviewed for this paper have been rather large.

4.1.5 Uncertainty due to flow bypassing the measurement section

In a fixed frame installation, clearance around the sides of the frame for flow to bypass the measurement section limits the magnitude of the uncertainty (which will always be a negative one) to about -0.2%. This would be typical for an intake 6m wide and 15m high, with a clearance of ±2 cm on each side, resulting in roughly 15m x 4cm/15m x 6m = 0.7% of the measurement section. Because of the restrictions and changes of directions, the flow velocity will be less than 25% of the average velocity in the measurement section, so that the maximum uncertainty from this source will conservatively be smaller than -0.2%.

4.1.6 Summary of bias uncertainties

The uncertainties in sections 4.1.1 to 4.1.5 are as follows:

- linear measurement of L ±0.1%,
- linear measurement of z ±0.1%,
- angular uncertainties combined ±0.004%,
- path separation ±0.2%,
- digitizing ±0.02%,
- transducer mounting – negligible,
- integration ±0.5%,
- boundary layers ±0.3%,
- flow bypass –0.2%.

Since these uncertainties are uncorrelated, they can be combined by the root-sum-square method to
$(0.1^2+0.1^2+0.0004^2+0.2^2+0.02^2+0.5^2+0.3^2+0.2^2)^{1/2} = \pm 0.66\%$

4.2 Precision uncertainties

4.2.1 Uncertainty due to time delay measurement

Uncertainty due to time delay Dt measurement is associated with the determination of the precise location of the cross-correlation peaks between two series of acoustic amplitudes. This has been demonstrated in a simulation to be within ±0.25%, and because each velocity estimate is computed from a set of four-second samples, typically 20 or more, the uncertainty is reduced to $\pm 0.25/20^{1/2}$ or approximately ±0.05%.

4.2.2 Uncertainty due to frame vibration

The mounting frames to which the ASFM transducers are mounted are designed and fabricated such that vibration is eliminated. This has been confirmed in the field trials. The uncertainty due to frame vibration is judged to be negligible.

4.2.3 Uncertainty due to velocity fluctuation in time

There are two components to this uncertainty. The first is related to discharge variations assuming all velocities are measured simultaneously.

Since discharge is rarely steady, averaging over some time interval will remove most of the uncertainty but likely not all. Analysis of TOF data taken during tests at Revelstoke (*6*) has shown this uncertainty can be approximated by 3 times the standard error. For the tests under consideration in this paper, this component of uncertainty ranges from ±0.1% to ±0.2%.

The second component is related to changes in velocity distribution during measurement. With the ASFM, the normal sampling period is 90 to 120 seconds, and thus this component can be obtained by splitting the acoustic time series into N shorter blocks and computing the velocity for each individual block. The sample standard deviation of the mean is then given by dividing the standard deviation of the N velocity values by the square root of N. For a typical intake this uncertainty component ranges from ±0.5% at all mid sections (representing about 90% of the total flow) to about ±5% near the roof and the floor (representing about 10% of the total flow). However, since those ten velocities will be combined in the discharge determination, an error on one path may be compensated by an error on another path. Thus the uncertainty associated with the velocity measurement is approximately $\pm 0.55/10^{1/2} = \pm\ 0.18\%$.

4.2.4 Summary of precision uncertainties

The summary of uncertainties in sections 4.2.1 to 4.2.3 is as follows:
- time delay ±0.05%,
- frame vibration - negligible,
- velocity fluctuation in time ±0.2% and ±0.18%.

Therefore, the total precision uncertainty can be approximated by the root-sum-square method as $(0.05^2+0.2^2+0.18^2)^{1/2} = \pm 0.27\%$

5. Conclusions

Based on the measurements undertaken with the ASFM at various sites over the last several years, it is believed that for turbine discharge measurements the ASFM is capable of providing a total precision uncertainty of about ±0.25%.

As for bias uncertainties, a conservative limit to the uncertainties considered in this paper appears to be ±0.66%. More work is being carried out on improving our understanding of these bias uncertainties, and this may lead to a reduction in several of the components listed. There is, however, some evidence that ASFM velocity measurements may be consistently biased low. A theoretical study and field measurement investigative program is currently under way to evaluate and correct for any such bias. Results will be reported in a future publication.

6. Acknowledgements

The authors wish to thank the personnel of the respective utilities for their cooperation and assistance during the installation and operation of the ASFM, and during the preparation of the technical papers listed above. Without their contribution the testing program would not have been possible.

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