Hydro 2002, Kiris, Turkey

Recent advances in estimating uncertainties in discharge measurements with the ASFM

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Introduction

Turbine discharges at low-head plants are extremely difficult to measure accurately, because of their short, rapidly converging intakes and uneven or even unstable velocity distributions. By overcoming most of the practical difficulties associated with traditional measurement methods, the **Acoustic Scintillation Flow Meter (ASFM)** offers an innovative means of discharge measurement in short intakes of low-head plants.

During the last 8 years, the ASFM has been successfully used by seven North-American hydroelectric utilities at 15 different low-head plants. More than 25 complete sets of discharge measurements have been obtained and in each of these, the unparalleled ease of use and labour and cost effectiveness of the ASFM have been successfully demonstrated. As a result, these advantages are now generally accepted.

This paper concentrates on the present understanding of the accuracy of the ASFM, both in terms of the systematic and random uncertainties. The described progress achieved since the initial paper on the ASFM uncertainties was published at Hydro 2001 is based on the results of direct field measurements of turbulent intensities and temperatures in the boundary zones, precise measurements of transducer spacings, and repeat discharge measurements. Further work required to achieve and confirm the accuracies demanded by the hydroelectric industry is also outlined.

1. ASFM operation

Traditional discharge measurement methods such as current meters or the more recently introduced time-of-flight acoustic flow meters, have been and continue to be used for measuring turbine discharges at short intakes of low-head plants. Their continued use, in spite of significant practical difficulties (introduction of obstructions into the flow, intensive labour requirements, including even the necessity of dewatering the intake, and major interference with power generation), clearly demonstrates that a more efficient discharge measurement tool is needed. This tool should be at least as accurate as those available today, but faster, easier and cheaper to use.

In addressing this need, over the last 10 years ASL Environmental Sciences, and more recently a subsidiary company, ASL AQFlow Inc., both of Sidney, British Columbia, Canada, have developed the Acoustic Scintillation Flow Meter (ASFM).

The ASFM utilizes the natural turbulence embedded in the flow, as shown in Fig. 1. Two transmitters are placed on one side of the intake, two receivers at the other. 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 (known as scintillations) at the downstream receiver will be nearly identical to that at the upstream receiver, except for a time delay, Δt.

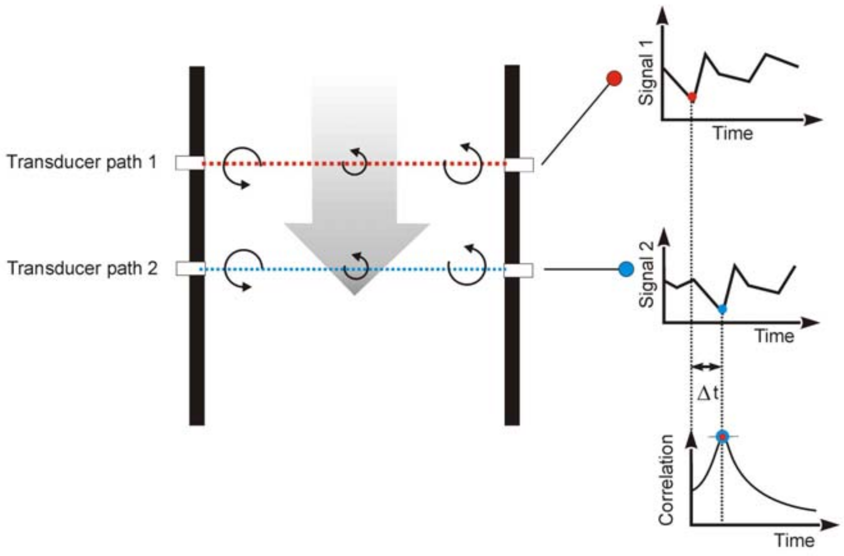

Fig. 1: Schematic representation of ASFM operation

The mean velocity perpendicular to the acoustic paths is then *Δx/Δt*, and because three transmitters and three receivers are used at each measurement level, the average inclination of the velocity is also obtained. The total discharge is then calculated by integrating the average horizontal component of the velocity at several pre-selected levels over the total cross-sectional area of the intake.

2. Measurement history

Acoustic scintillation is a well-proven technology, having been successfully used to measure solar winds, atmospheric winds and ocean currents for over 50 years. In the last 8 years, in addition to comparative turbine flow measurements against current meters, the ASFM has been used to verify efficiencies of aging or refurbished units, to optimize their operation, to confirm compliance with prescribed water release limits, to calibrate Winter-Kennedy readings, and to evaluate the effects of fish screens and fish deflectors on turbine efficiency at the following plants (Fig.2):

2002 – Lower Monumental, USACE, USA
2001 – John Day, USACE
    The Dalles, USACE
    Deep Brook, Nova Scotia Power, Canada
2000 – The Dalles, USACE
    Bonneville, USACE
    Rocky Reach, Chelan County PUD, USA
    Stave Falls, BC Hydro, Canada
    Rock Island, Chelan County PUD
1999 – Seven Sisters, Manitoba Hydro, Canada
    Wheeler, Tennessee Valley Authority, USA
    Bonneville, USACE
    McNary, USACE
1998 – Bonneville, USACE
    McNary, USACE
1997 – Laforge-2, Hydro Quebec, Canada
    Fort Patrick Henry, TVA
1996 – Revelstoke, BC Hydro
1995 – Lower Granite, USACE

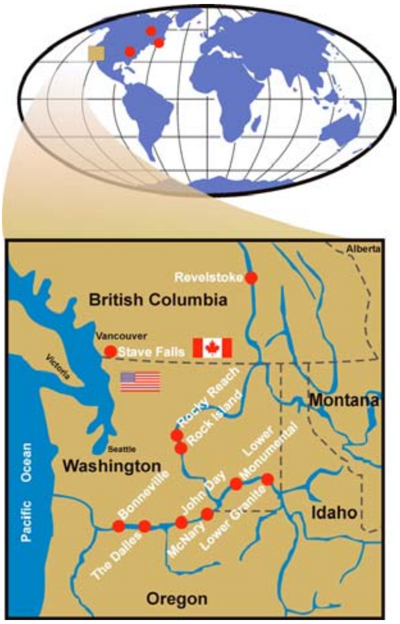

Fig. 2: ASFM site locations

3. Typical application

The ASFM mounts pairs of arrays of acoustic transducers on opposite sides of fixed or movable support frames, which are lowered into the intake stoplog or gate slots (Fig. 3). This permits its use in even the shortest intakes. It also minimizes the required plant downtime during installation and removal, does not require intake dewatering and, in multiple unit plants, permits repeated use of the same frame without removal/reinstallation of the equipment from/to the frame. No instruments are required in the measurement zone, which minimizes interference with the flow, and there are no moving parts requiring maintenance and calibration.

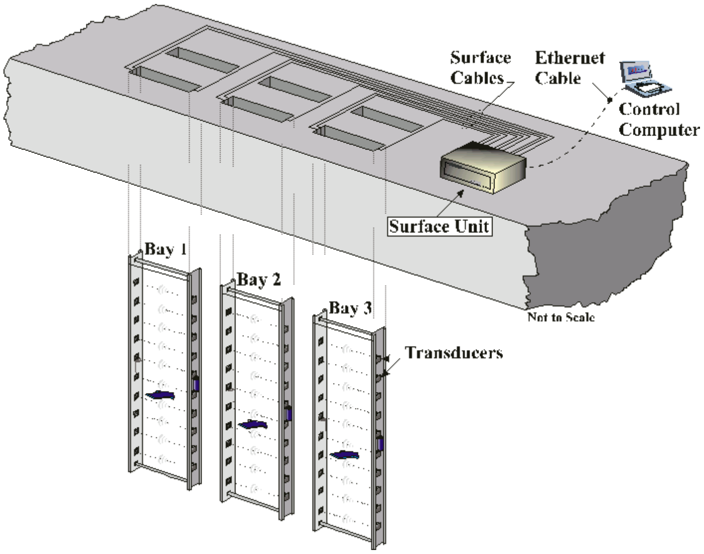

Fig. 3: ASFM Typical Arrangement

The ASFM is so easy to use that it permits alternative scenarios to be explored in the field. Recently, one client used the ASFM to investigate not only what would happen to the unit efficiency when fish screens/fish deflectors were installed, but also whether several of the difficult-to-remove components could be left in place through the winter without too much of a penalty in reduced efficiency.

4. Current understanding of the ASFM accuracy

At Hydro 2001 in Riva del Garda, Italy, preliminary estimates of uncertainties in measurements with the ASFM in low-head short-intakes plants were presented (*1*). Although the numbers quoted at the time looked promising for both the systematic and random uncertainties, it was noted that not all uncertainties were included, and a specific caution was raised regarding an apparent low bias in the ASFM results. Since that time, much work has gone into gaining a better understanding of the ASFM accuracy issues. The progress made to date is described in the following paragraphs.

4.1 Systematic uncertainties

Evidence accumulated from recent use of the ASFM in hydroelectric intakes strongly suggests circumstances exist which can cause significant systematic errors in discharges computed from the ASFM flow measurements. When present, the errors manifest themselves as anomalously high turbine efficiencies, indicative of a negative systematic error in the flow data. The magnitude of the error is in some cases as high as 6 to 7%. Earlier direct comparisons, in a tow tank (*2*) and against current meters in a low-head intake (*3*) did not show any evidence of such a systematic under-reading of flow rates. The present version of the ASFM differs in both hardware and software from the earlier version used in the direct comparisons. A review of the changes made to the instrument, and of the circumstances under which the comparisons and measurements were made produced two hypotheses for the source of the apparent systematic errors: deviations from the specified element separations in the transducer arrays, and variations in the distribution of small-scale turbulence in the intakes.

4.1.1 Transducer Element Separation

Measuring flow velocity by acoustic scintillation requires measuring the time delay, Δt, associated with the peak of the cross-correlation between the time series of fluctuating acoustic amplitudes observed on two closely spaced propagation paths crossing the intake flow (*2*). The laterally averaged flow velocity normal to the beam pair is then computed as

$$V = \Delta x/\Delta t,$$

where Δx is the separation between the paths and is determined by the separation of the elements within the arrays. The accuracy of the calculated velocity depends directly on the accuracy of Δx, and hence on the accuracy of the element separations in the arrays. The physical element separations were specified to be 35 mm ± 0.08 mm (± 0.25%). Systematic errors could arise if the effective acoustic separation is not the geometric separation. Since the direct comparisons referred to above, the design of the transducer arrays has changed, thereby raising the possibility that the design changes had introduced an error in the element separation.

A laboratory method has been developed to measure the effective acoustic separations. The results of the laboratory measurements and field trials for verification are described in (*4*). Data on the distributions of element separations are included in Figure 4 for two different transducer types. The distribution for the type A arrays (heavy solid line), associated with early versions of the ASFM, has a peak at 35 mm, but its mean value is 35.34 mm, 1% higher than the nominal separation, and with a standard deviation of 1.5 mm. Two distributions are included in the Figure for the type B transducers incorporated in the current *Advantage* ASFM instrument. One of these distributions (the medium-weight solid line) is representative of units produced in 2001. It shows a much narrower distribution relative to the type A results with a mean value of 35.1 mm (0.3% high) and a standard deviation of about 0.4 mm. This distribution also includes a sprinkling of widely scattered separation values that fall well outside the Gaussian curve representing the bulk of the results. Considerable efforts have been made to eliminate the latter "outliers". The effects of these efforts are evident in the much narrower distribution achieved from a more recent (July - August, 2002) production run as represented by the broken line (type B_{new}) curve. In this case, the mean separation was, again, 35.10 mm with a standard deviation of 0.15 mm.

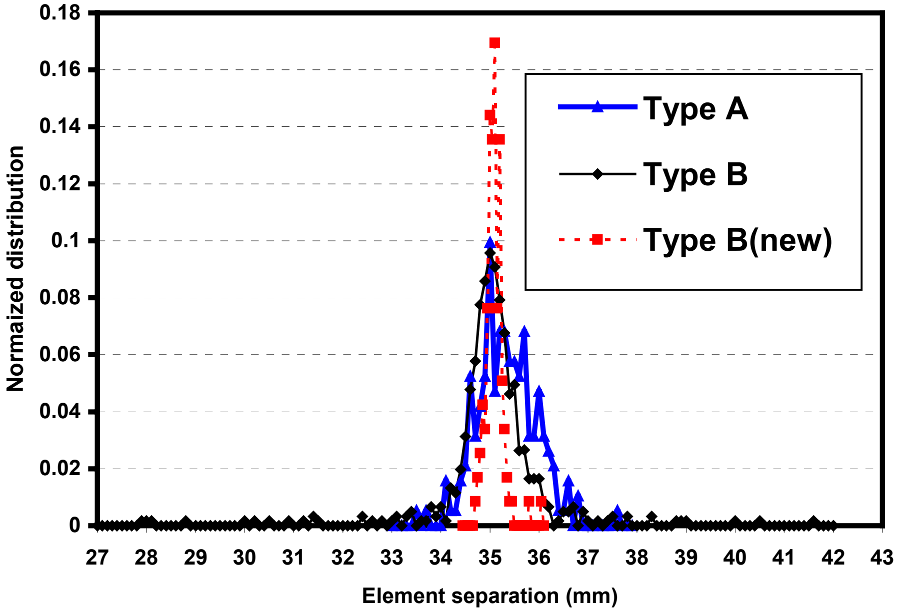

Fig. 4: Transducer distributions - Type A and Type B

The limited number of field verification tests (*4*) confirmed the results for the Type B transducers, but not for the Type A units. Recent laboratory tests suggest that the spacing measurements for Type A units are range dependent, while those for Type B are not. Work is currently under way to extend the laboratory measurements to longer ranges.

All ASFM units produced since October 2001 are equipped with Type B transducers, and include measured separation values for each unit, which will eliminate the separation as a source of systematic error. The distribution of path separations for Type A units at full range has yet to be determined, but field ASFM comparisons with type B units suggest early measurements made with these units could have introduced systematic underestimates of flow velocities up to several per cent in magnitude. Resolution of the uncertainties in the type A unit separations is essential to eliminating possible errors in previously obtained ASFM data sets.

4.1.2 Distribution of Small Scale Turbulence

As noted above, acoustic scintillation depends upon the effects of turbulence on the acoustic refractive index of the water flowing through an intake to achieve velocity measurements. The refractive index turbulence of interest arises from fluctuations in both the velocity and temperature in the flow. CFD simulations of the distribution of turbulent kinetic energy in a low-head intake suggest that a negative bias in ASFM flow measurements could arise from the increased levels of turbulence at both the sidewalls of the intake and downstream of entrance obstructions, such as large trashrack supports. The combination of increased turbulence in regions of reduced mean velocity can produce an underestimate of the true laterally averaged velocity. Oblique approach flows at the intake entrance are likely to increase such underestimate.

In their current state of development, CFD models are not capable of fully representing the spatial and spectral distribution of small-scale turbulence, and therefore confirmation of modelled results requires direct measurement of the turbulence field in a full-scale intake. As a first step, direct measurements of the mean velocity and velocity and temperature turbulence in the sidewall boundary layer of an intake were made at the intake of Lower Monumental dam on the Snake River in Washington State in January and February 2002.

The results of the initial analysis of the obtained data show that at this site, there is no significant bias arising from the sidewall boundary layers, as they are too thin, and the relevant components of the velocity turbulence are not sufficiently elevated to produce significant bias. The contribution of temperature fluctuations to the refractive index turbulence was found to be negligible, although that may not be the case at other times of year, when there is greater stratification present in the reservoir.

Evidence to date suggests that, if calibrated Type B transducers are used, any negative bias in flows measured by the ASFM likely arises from the effects of obstructions or oblique approach flows at the entrance to the intake. Examination of the estimated biases present in measurements taken to date at a number of low-head plants tends to support this hypothesis, with the greatest underestimates usually associated with plants having strongly oblique entrance flows and large trashrack supports. Further CFD modelling and field measurements are planned to confirm and quantify this effect.

4.2 Random Uncertainties

Based on our 2001 understanding of the ASFM accuracy issues, the random uncertainty at the 95% confidence level was estimated at about ±0.27%, and consisted of uncertainties due to time delay measurement, frame vibration and velocity fluctuations in time (*1)*.

During the past 12 months, ASFM repeat tests have been carried out at the John Day, The Dalles and Lower Monumental projects on the Columbia and Snake River in the northwest United States. The results from the January/February 2002 repeat tests at Lower Monumental dam are presented in the following paragraphs.

It must be recognized that these repeat tests did not fully comply with the requirements of the IEC 41 for the Method B, which stipulate that at least 5 runs should be made at the same operating condition. Rather, the 27 Lower Monumental repeat tests are a mixture of on-cam off-cam tests, with one three-repeat, four two-repeats and the remaining 16 one-repeat tests. The individual test blade/vane openings were not always identical, with differences of up to 0.8%, and no corrections were applied for these differences. The head varied during the tests by up to 1.3%, and was individually corrected to the specified condition.

For these 27 repeat tests, the sample standard deviation is ±0.37% and the random uncertainty at the 95% confidence level is ±2.056*0.37 = ±0.76%.

In order to better interpret the results from these tests, the relation between the changes in generation output (also corrected to specified condition) and the changes in the ASFM flow results was examined. As the generation output is measured independently from the measurement of the flow, and as the efficiency near the best cam position can be expected to remain nearly constant for the small blade or vane changes, correcting for such blade or gate non-repeatability by using the generation output appears to be justified. With the ASFM measured flow results corrected in this manner, the sample standard deviation reduces from ±0.37% to ±0.24% and the random uncertainty at the 95% confidence level reduces from ±0.76% to ±0.49%. Because of the relative ease with which ASFM flow measurements are performed in the field, further reductions in the random uncertainty can be achieved, if desired, by repeating the tests.

It is important to recognize that the Lower Monumental repeat tests included flow conditions with and without the fish screens. If only the repeat tests without the screens are considered, the sample standard deviation is further reduced, from ±0.37% to ±0.29% (before the generation output correction) and from ±0.24% to ±0.15% (after the correction). For the repeat tests with the fish screens installed, the sample standard deviation increases slightly from ±0.37% to ±0.39% (before the correction) and from ±0.24% to ±0.26% (after the correction).

These results are entirely consistent with the expectation that fish screens installations worsen hydraulic flow conditions (Fig. 5). Additional repeat testing will be required before the random uncertainty associated with the ASFM flow measurement can be confirmed. Nevertheless, it is postulated that the Lower Monumental repeat testing demonstrated clearly that the ASFM produces repeatable results and acceptable accuracy under the adverse hydraulic flow conditions associated with short, rapidly converging intakes. This repeatability appears to be maintained even when the intakes are equipped with fish screens, and even when no flow improvements are attempted by the installations of false roofs and fairings or by blocking the gate openings.

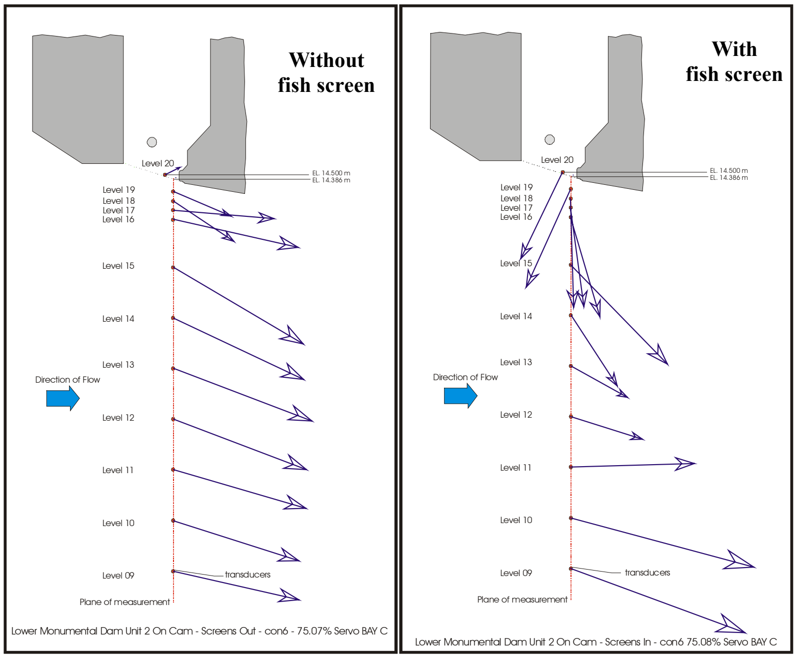

Fig. 5: Influence of fish screens on sampled velocity vectors

5. Conclusions

In the last year, a significant progress has been made in our understanding of systematic uncertainties associated with the ASFM flow measurement at short intakes of low-head plants, particularly as to why as much as 6 to 7% negative bias was occurring at some intakes. It has been verified that for the currently used Type B transducers, no significant bias is attributable to the array separation deviations. However, for the older (Type A) transducers, a larger negative bias may be present, particularly for the profiling applications, where one pair of transducers was used at all measurement levels. It has also been verified that for intakes with straight entrance flows and relatively minor trashrack supports, there is no significant negative bias resulting from the boundary layer or obstruction turbulence. The temperature variations have been ruled out as a contributor to the negative bias, at least during cold winter months with little reservoir stratification. This points to the negative bias being the result of strongly oblique entrance flows and/or large trashrack supports located in close proximity to the measurement plane. Both of these effects are being investigated by CFD modeling and by direct field measurements, and the results will be reported in future publications.

As for random uncertainties, the recent tests have demonstrated that the ASFM produces repeatable results and acceptably small random errors when used for flow measurements in short, rapidly converging intakes of low-head plants, even when these intakes are equipped with fish screens. Nevertheless, further ASFM repeat tests are planned in order to improve its acceptance by the industry and ultimately by the international performance test codes.

6. Acknowledgments

The authors wish to thank the personnel at Lower Monumental plant, as well as those at all other plants where the ASFM has been used for flow measurement and special testing, for their cooperation and assistance. Special thanks to Charlie Almquist, Principia Research Corporation, Tennessee, for his helpful suggestions. Without these people the testing program and this paper would not have been possible.

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