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MEASURING HYDRAULIC TURBINE DISCHARGE WITH THE ACOUSTIC SCINTILLATION FLOWMETER

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Abstract

Hydraulic turbine discharges in low-head hydroelectric plants, and plants with awkward intake geometries can be measured relatively easily with the Acoustic Scintillation Flowmeter (ASFM). The ASFM is non-intrusive, and may be deployed in intake gate slots in a straightforward manner, lending itself to multiple measurements in the same plant. Examples of measurements in two generating stations are presented. Tow-tank tests have shown the current speed measured by the ASFM to be accurate to within ±0.3% over a range of towing speeds from 0.5 to 5.0 m/sec. A recent comparison of discharge measured by an ASFM and an acoustic time-of-travel meter, made at B.C. Hydro's Revelstoke Dam this spring was invalid due to installation problems. The factors affecting the accuracy of ASFM discharge measurements are discussed, and plans for further comparison testing are outlined.

Résumé

Le débit de turbines à basse chute, ou à travers des prises d'eau à géometrie compliquée, peut être mesuré directement avec la méthode par scintillation acoustique "ASFM". L'instrumentation “ASFM” peut être déployée facilement dans les guides de vannes de prise d'eau, ce qui permet de faire des mesures multiples dans une même usine. L'example de mesures effectuées dans deux usines hydroélectriques est presenté. Des essais de remorquage dans un bassin ont demontré que la précision des mesures est de l'ordre de ±0.3% pour des vitesses de remorquage entre 0.5 et 5.0 m/s. Une comparaison du débit mesuré par "ASFM" et par une méthode mesurant le temps de trajet d'un signal acoustique été effectuée par BC Hydro au barrage de Revelstoke le printemps passeé. Malhereusement, des difficultés d'installation n'ont permis des mesures qu'on peut utiliser pour faire des comparaisons. Les facteurs influençant la précision des mesures par "ASFM" sont discutés, et des projets pour d'autres essais sont expliqués.

Introduction

The Acoustic Scintillation Flowmeter (ASFM) measures the flow in a turbulent medium, such as water, by transmitting sound signals across the channel or passage in which the flow is to be measured. The turbulence in the flow causes random fluctuations (referred to as scintillations) in the amplitude and phase of the sound as it travels through the water. The speed with which the water is moving is measured by observing the transverse drift of scintillations across two closely-spaced propagation paths. The method has been used for atmospheric and ionospheric winds (Ishimaru, 1978; Lawrence, Ochs & Clifford, 1972; Wang, Ochs & Lawrence, 1981) and for measuring currents and turbulence in ocean channels (Clifford & Farmer, 1983; Farmer & Clifford, 1986; Farmer, Clifford & Verrall, 1987; Lemon & Farmer, 1990; Lemon, 1993); its derivation is well-established.

Figure 1 shows a schematic representation of an ASFM in use. Two transmitters are placed at one side of the channel, 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 of the mean current. If the paths are sufficiently closely-spaced, the turbulence may be regarded as being embedded in the mean flow, and then the pattern of scintillations at the downstream receiver will be nearly identical to that at the upstream receiver, except for a time delay, *?t*. The delay is found by computing the time-lagged cross-correlation between the signal amplitudes at the two receivers over some suitable length of record. *?t* is then the lag at which the peak of the cross-correlation function is found, and the mean flow speed perpendicular to the acoustic beams is *?x/?t*, where *?*x is the separation between the beams.

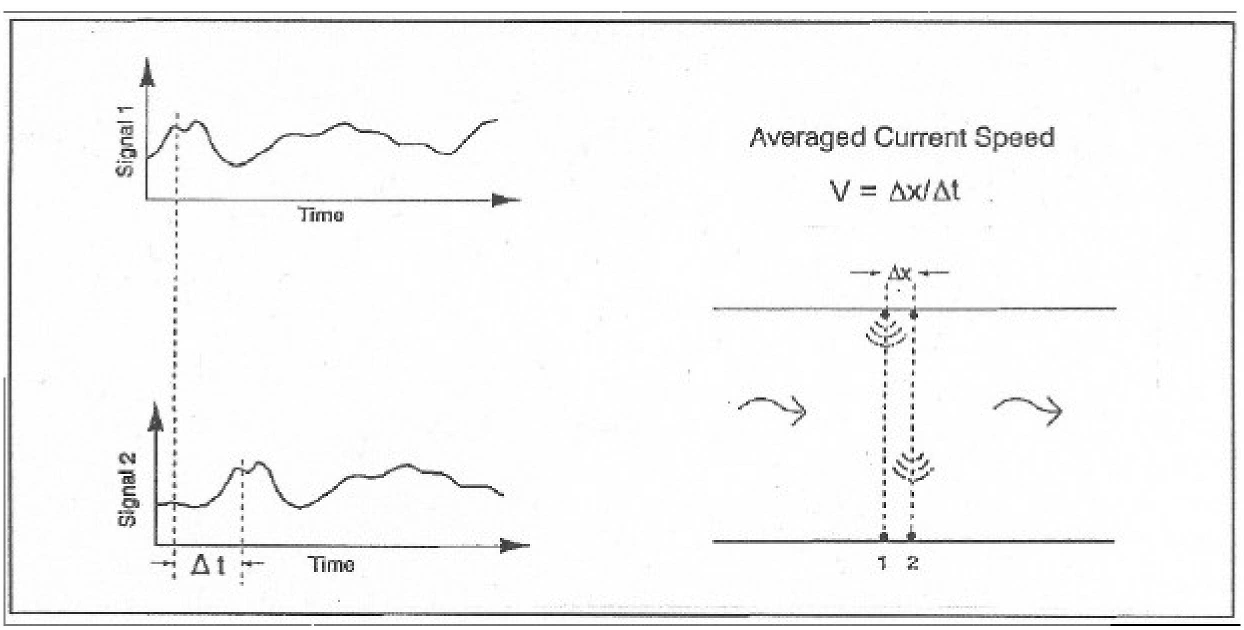

Figure 1 - Schematic representation of current measurement by acoustic scintillation.

The ASFM measures the lateral (i.e. along-path) average of the component of the flow perpendicular to the acoustic path. It is therefore well-suited for collecting data for discharge measurements, since the product of the path length with the lateral average of the normal component of flow gives the element of discharge at the depth of the path. Sampling at several levels in the vertical and integrating then gives the discharge.

Application to Hydroelectric Plants

The ASFM's inherent capability for discharge measurements, combined with its non-intrusive nature results in a number of advantages for measuring the discharge through turbines. The discharge measurement can be made in an intake gate slot, as it requires only that the transducers be installed at several levels along the sides. This can be a great advantage for low-head plants, where intake tunnels are often short, and do not have substantial straight segments with constant cross-section. The spatial averaging which is part of the ASFM measurement means also that large-scale eddies and meandering do not bias the measurement.

Using the ASFM in a hydroelectric intake requires transmitting and receiving arrays with three elements rather than two, since the direction of the laterally-averaged current in the tunnel is not usually horizontal, and may vary with height as well. Adding the third element to the array allows both the horizontal and vertical components of the laterally-averaged flow to be measured, once the orientation of the array has been determined by leveling the horizontal arm (Birch & Lemon, 1993).

Measurement of the discharge for a turbine requires that a location in the intake be chosen to define the measurement plane, and a number of sampling paths be established across it. The transducer arrays can either be fixed to the intake walls, for a permanent installation, or attached to a frame deployed into a gate slot, if one is available. Using a frame in a gate slot allows the ASFM to be moved from one unit to another relatively quickly and easily, if the slots are all the same size. The number of paths required to sample in the vertical is achieved either by placing arrays at every desired height on the frame, or by using fewer arrays and moving the frame to the required elevations. The latter approach, while requiring less equipment is less desirable since sampling all the levels requires more time during which the flow conditions could change. The degree of flow interference caused by the frame may also change if it is moved.

To date, measurements have been made at two low-head plants: Rocky Reach Dam, operated by Public Utility District No. 1 of Chelan County, and Lower Granite Dam on the Snake River, operated by the Walla Walla District of the US Army Corps of Engineers. The measurements at Rocky Reach Dam were performed in January, 1992 to collect data for modelling studies needed to design fish diversion screens. The flow information was desired in the form of the lateral average of the current at a number of levels spanning the height of the intake tunnel. Each turbine intake at Rocky Reach is divided into three bays, each of which is 6.1 m wide and 15.2 m high. The laterally-averaged current was measured at 11 elevations in each bay of four of the turbines at the plant.

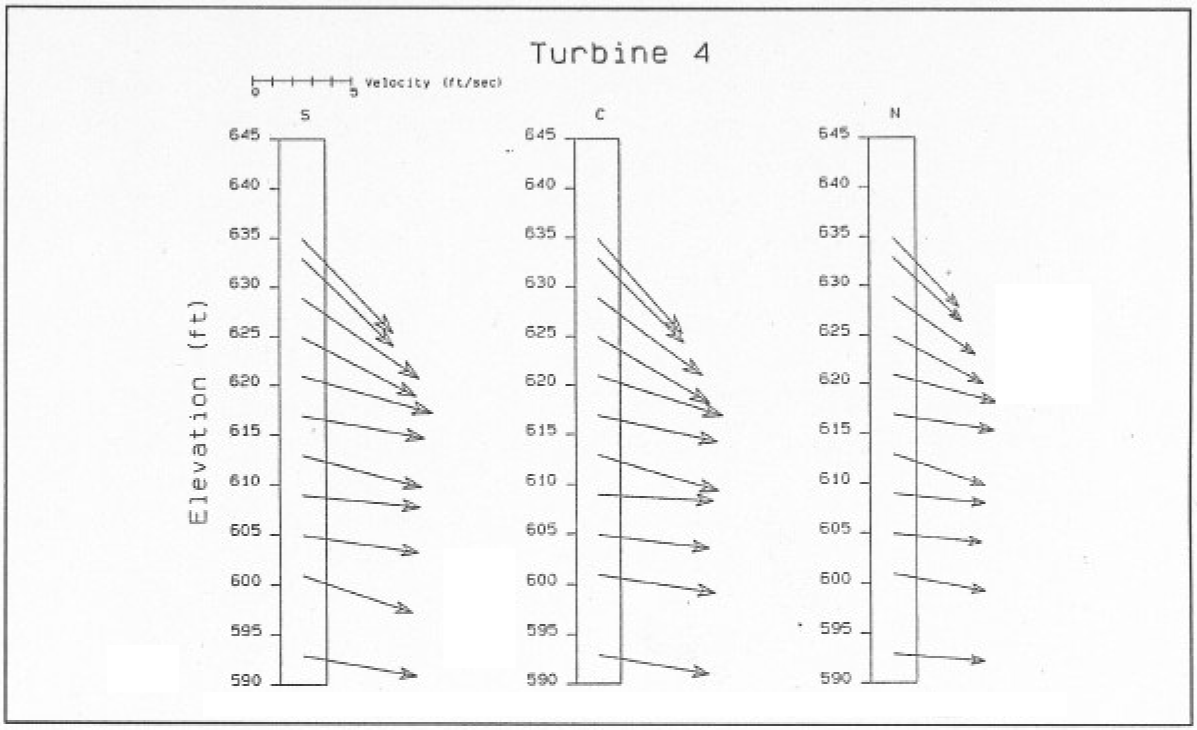

Figure 2 - Flow speed and angle for each bay, Turbine 4, Rocky Reach Dam.

An example of the results is shown in Figure 2. The Rocky Reach work was done before a version of the ASFM designed for hydroelectric work had been developed. The instrument which was used had been designed for oceanographic work, and consisted of two underwater cylinders (one for transmission, the other for receiving), each with a two-transducer array mounted at one end and a surface cable at the other. They were mounted on the lower section of an existing fish net frame which had been shortened and modified by the removal of all the vertical members except the two sides to reduce flow interference. The frame was then positioned at each measurement level and a three minute data sequence collected. Since the arrays consisted of only two transducers, the horizontal and vertical components of the current had to be measured in two separate passes.

The measurements at Lower Granite Dam were made with the current version of the ASFM which was designed for work in hydroeletric applications (see Figure 6). Data were collected in one bay of one turbine, in conjunction with an index test. Lower Granite Dam is equipped with Kaplan turbines, each of which has three intake bays feeding into the scroll case. The quantities to be measured were the laterally-averaged flow speed and angle at ten levels and the discharge through the bay. The ASFM was equipped with five paths, each equipped with two 3-element arrays. The arrays were mounted on a frame designed to fit into the intake gate slot. They were spaced at twice the vertical sampling interval, so that by moving the frame up or down by one increment, all ten levels could be sampled in two sequential sets. The ASFM is capable of recording data from one path (level) only at a time; the recording equipment at the surface is switched from one level to the next sequentially. Ninety seconds of acoustic data were collected on each path; each full vertical profile therefore required approximately 15 minutes to complete, with an additional 5 minutes required to change wicket gate settings and, periodically, the turbine blade angle.

Figure 3 shows the horizontal component of the laterally-averaged velocity for an on-cam measurement series as a function of elevation above the tunnel floor. The total discharge through the tunnel at the plane defined by the ASFM frame is then:

$$Q = \overset{H}{\underset{0}{?}} v(z)\ cos\ [?(z)]\ L(z)\ dz \qquad (1)$$

where *?* is the elevation angle of the laterally-averaged flow, L(z) is the tunnel width as a function of height and H is the height of the tunnel roof above the floor. Computing Q then requires estimation of the integral in Equation 1, which was done using an adaptive Romberg integration algorithm, with a cubic spline interpolation in the integrand between the measured points. The boundary layers at the roof and floor were approximated by fitting a standard curve for boundary layers in high Reynolds Number flows (shown as the dotted lines in Figure 3*).*

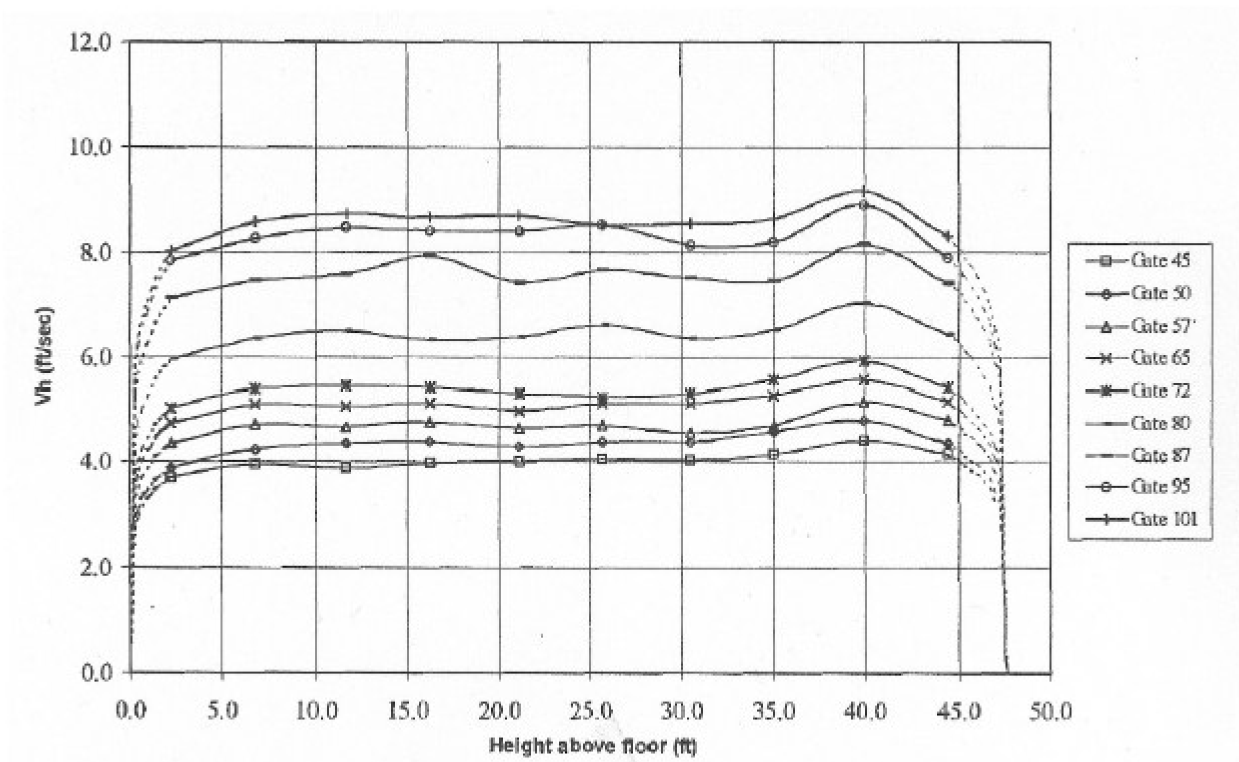

Figure 3 - Horizontal component of laterally-averaged flow, cam-on.

Discharge was measured using other methods as well; however at present, the only comparison data available are the measurements from the Winter-Kennedy taps at the turbine itself, which provide only a relative measure of the total discharge from all three bays. The comparison is useful as an indication of the performance of the ASFM for discharge measurement. The two discharges are shown plotted as a function of wicket gate setting in Figure 4. The Winter-Kennedy values have been scaled to the ASFM discharges using a constant factor computed from the least-squares fit of one data set against the other. The scaled Winter-Kennedy values deviate from the ASFM by approximately +1% for gate settings above 85%, and by -1% for gate settings below 60%.

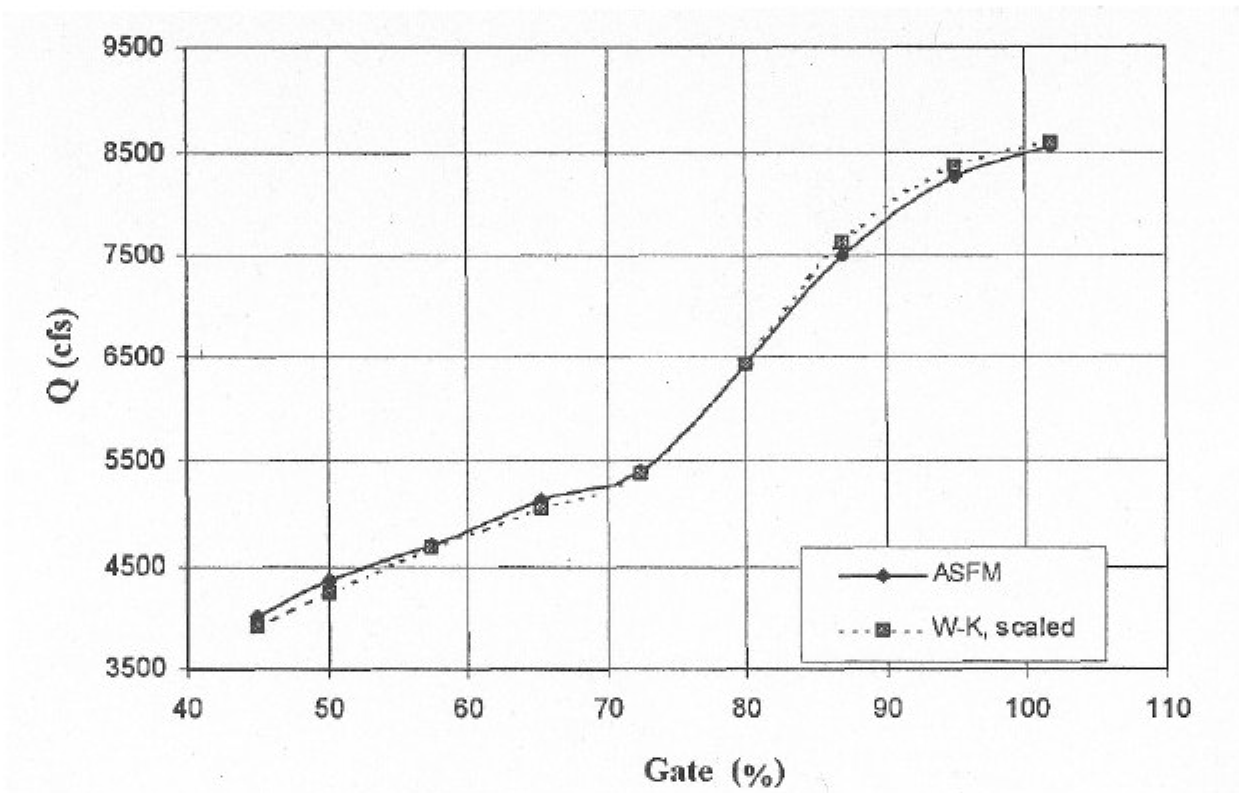

Figure 4 - Relative discharge, ASFM and Winter-Kennedy taps, Lower Granite Dam.

Discharge Measurement Accuracy

The potential utility of the ASFM for hydroelectric applications depends upon the accuracy to which it measures the discharge. To be applicable in all cases the systematic uncertainty should be within ±1%, and the random uncertainty much less. There are two fundamental components to the discharge measurement accuracy: first, the accuracy of the flow velocity measurement, and second, the accuracy with which the individual velocity measurements can be combined to calculate the discharge.

The accuracy of the velocity measurement was established by a set of tow-tank tests (Lemon, 1995). The ASFM was mounted on a carriage and towed through a tank at speeds between 0.5 and 5.0 m/sec. Figure 5 shows the ASFM speed plotted against the carriage speed. The solid line shows the least~squares fit to the data:

$$V_{ASFM} = 1.0031 V_{carriage} \qquad (2)$$

The correlation coefficient *r* for the fit is 0.9997. The two dotted lines show the ±1% limits.

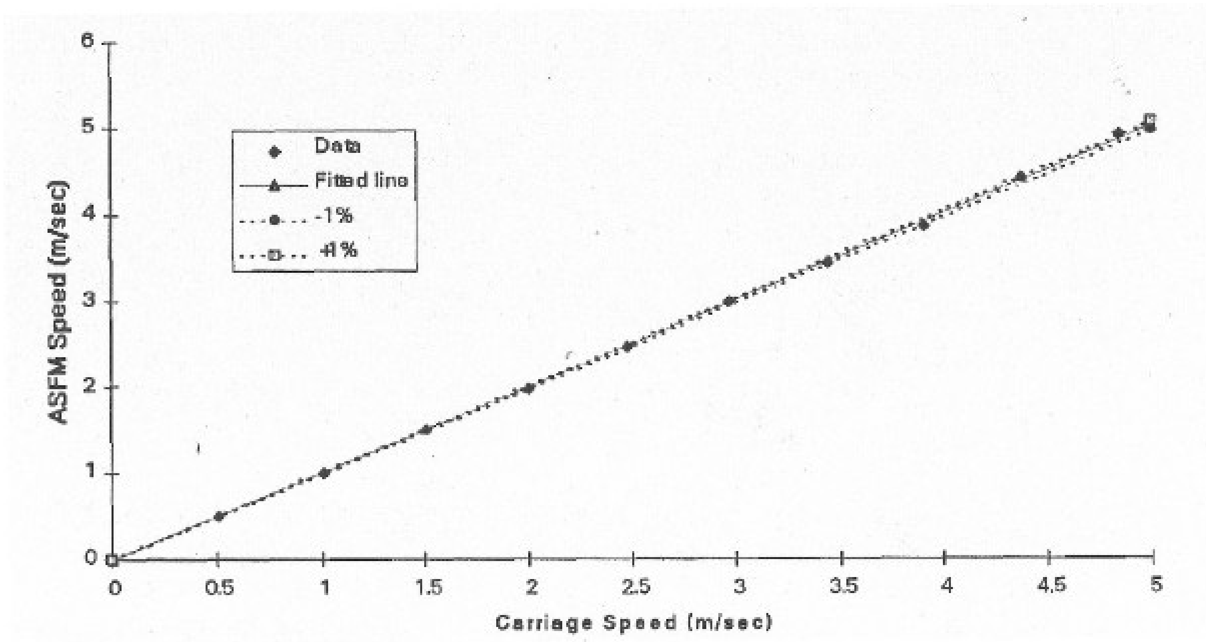

Figure 5 - Current speed measured by ASFM vs towing speed.

Determining the accuracy of the ASFM discharge measurement requires a reference to which it may be compared. In practice, the reference measurement itself will always contain uncertainties, both random and systematic, and therefore in making comparisons, a site must be chosen where the uncertainties in the reference measurement are well-known, and well within the bounds of acceptability for turbine efficiency measurements. Because of the difficulties involved in making accurate discharge measurements in a low-head plant, the only locations where such a comparison could be made is in a high-head plant. B.C. Hydro's Kootenay Canal plant has been used several times in the past for evaluating a number of different discharge measurement methods, and as a result their uncertainties at that site are well-known. Operational constraints at Kootenay Canal did not permit a set of tests with the ASFM to be performed before late 1996; the Revelstoke plant was therefore chosen as an alternate for tests in April 1996. The Revelstoke generating station is situated on the Columbia River, and is equipped with four Francis turbines, with a total generation capacity of 1840 MW. The plant has a head of approximately 135 m. The penstocks leading to the turbines are each fed by a single intake of rectangular cross-section, 9.1 metres high by 6.85 metres wide at the bulkhead gate slot. At peak discharge, the water speed in the intake exceeds 7 m/sec, The comparison tests were done on Unit 3, which is equipped with the transducers for a Caldon Model 8300 Leading Edge Flow Meter (LEFM).

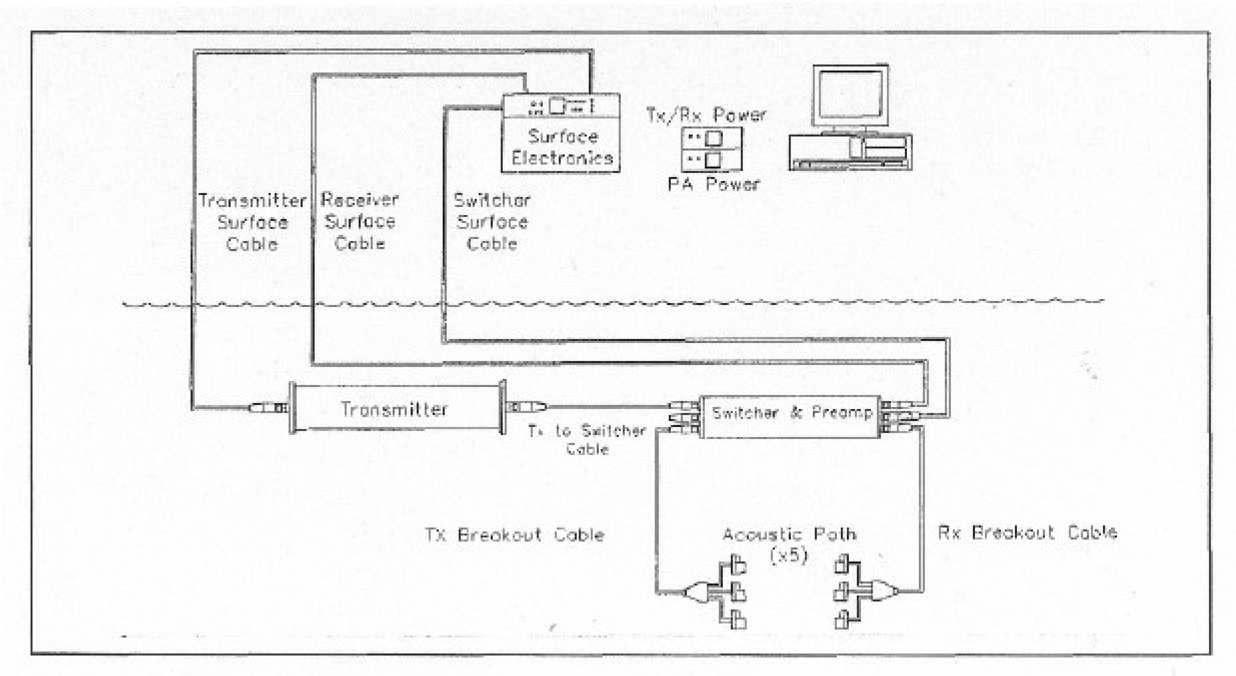

Figure 6 - Components of the ASFM.

The installation consists of two planes, each with four paths spaced at Gaussian intervals and placed at angles of -65° and +65° to the axis of the penstock. The LEFM is 5.5 m downstream of a 53° bend and a reduction in penstock diameter from 7.92 m to 7.32 m.

The ASFM was mounted on a frame designed to fit into Unit 3's bulkhead gate slot. Figure 6 shows the configuration of the ASFM. As was the case at Lower Granite Dam, it was equipped with 5 sets of arrays; because of the smaller vertical extent of the intake, 5 paths were expected to be sufficient for adequate sampling in the vertical.

Conclusive results could not be obtained from these tests because of deployment and installation problems encountered with the frame. Lateral vibrations of its side-members were so great that they interfered severely with the operation of the ASFM. Such modifications as were possible were made on-site, but did not improve the characteristics of the frame sufficiently to allow useful data to be collected, even at the limited lower-flow conditions obtainable with the Francis turbine. (The turbine's rough operating zone precluded measurements between 30% and 50% gate settings.) Figure 7 shows an example of the vibrations, whose characteristics could be measured using the ASFM itself. Fluctuations in the position of the transducers of such magnitude overwhelmed the signal from the turbulence.

Despite the fact that no useful data were obtained at Revelstoke, our experience there served to highlight some factors which are important in making use of the ASFM as a discharge measuring instrument. If the advantages of flexibility and portability inherent in using the ASFM in a gate slot are to be realized, the design of the support frame is of critical importance. The measurements made at Lower Granite Dam demonstrate that installing the ASFM by means of a frame in the gate slot is feasible and practical.

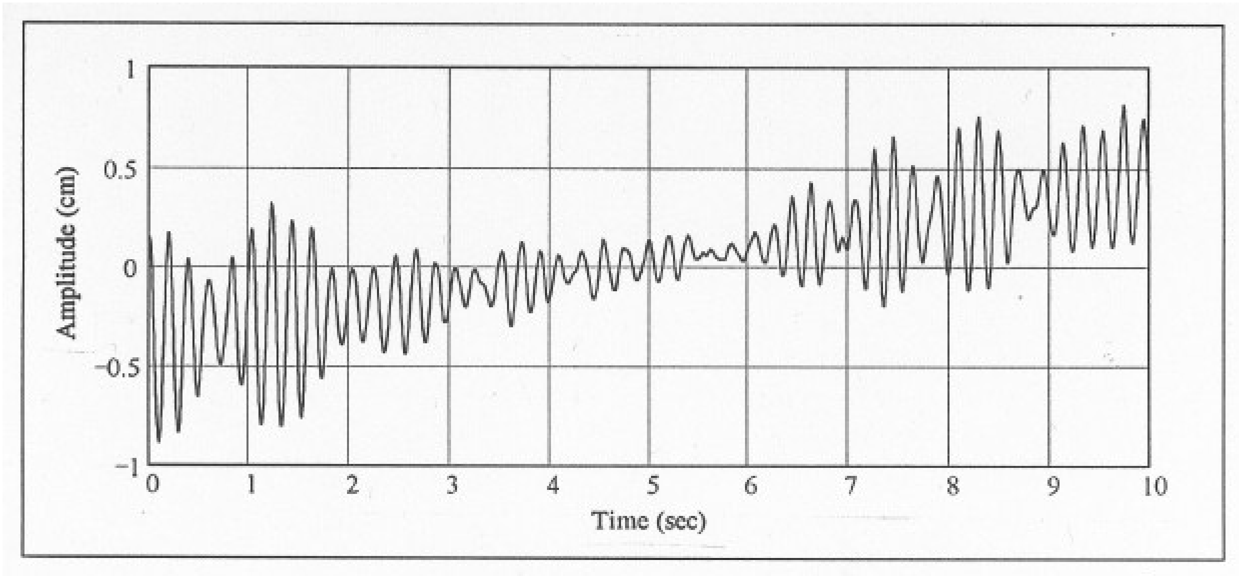

Figure 7 - Example of lateral frame vibrations observed at Revelstoke.

The important differences in the design of the frames used at the two different sites were the fact that the Lower Granite frame was heavier, stiffer and more massive than the Revelstoke version, and that its sides were sheeted over to form a flush surface with the intake walls once it was installed in the slot. In contrast, the Revelstoke frame, in an attempt to avoid exposure of its members to the higher-velocity flows which would be encountered there, was of much lighter construction, with smaller members, less reinforcement, and did not include sheeting on the sides to form a flush surface with the sidewalls.

Sources for Uncertainties in the Discharge Measurement

The vibration interference encountered at Revelstoke was an anomaly, and under normal circumstances would not contribute to uncertainty in the ASFM discharge. While without the availability of valid measurements for comparison the accuracy of the measurement cannot be verified, it is possible to estimate the source and magnitude of major contributions to the discharge uncertainty.

Systematic Uncertainties

Possible sources for systematic uncertainties in the ASFM's measured discharge are: i) flow around the sides or top of the frame; ii) the integration method and the approximation used for the boundary layer at the floor and roof of the tunnel; and iii) any systematic uncertainty in the laterally-averaged velocities, arising from dimensional and angular measurement inaccuracies, or bias in the instrument electronics.

Bypass Flow

At Revelstoke, the clearances between the frame and the side-walls limited possible escapement around the frame to 0.2% or less, while with a fully enclosed frame such as the one used at Lower Granite, the effect would probably have been smaller. At the top of the gate slot, the flow can expand beyond the upstream edge of the gate slot, which is the assumed upper boundary of the flow measurement section; however it is arguable whether this expansion would be translated to the uppermost measurement path in the short distance between the upstream edge of the gate slot and the transducer arrays. It is unlikely that this effect would exceed any escapement around the sides of the frame; this aspect may warrant further investigation, possibly via a mathematical hydrodynamic model.

Integration Method

Systematic uncertainties due to the integration technique relate to the number of measurement paths, the integration technique used, and the assumption regarding the boundary layer. The effect on discharge measurement accuracy of the number of measurement paths for the case of a distorted flow profile has been examined by Taylor (1987) for the Gaussian Quadrature technique as applied by the LEFM. This analysis showed that increasing the number of paths from four to six or eight, significantly reduced the integration error. With five paths, the outer limits of the integration error were +0.4 to -0.2%. The effect of the number of measurement paths has only been investigated in a preliminary fashion for the Romberg integration as used by the ASFM, but the results, as might be expected, are similar to those obtained for the Gaussian Quadrature technique.

The actual thickness of the boundary layer depends upon the distance from the intake entrance to the measurement section, and therefore the $z^{1/7}$ curve may not represent fully accurately the profile of the boundary layer. The boundary layer discharge using this approximation amounts to 0.4% of the total flow; the possible systematic uncertainty introduced is unlikely to be greater than ±0.2%.

Laterally-Averaged Velocities

The results of the tow-tank tests show that systematic uncertainty in the laterally-averaged velocity is ±0.3% or less on each path. This uncertainty results from the combination of the uncertainties in the measurement of the transducer spacings, the array orientations and of timing by the instrument electronics. The first two are independent among the paths, and therefore their effect will be reduced when the integration is performed. Measurement uncertainties in the path positions and path lengths on the frame are approximately ±0.1%. Any flow distortion effects caused by the transducers protruding into the flow should be eliminated by designing the frame for flush mounting; if there is some protrusion, part of the boundary layer will not be sampled, and there may be some flow diversion. These effects would be of opposite sign, and tend to cancel each other.

Random Uncertainties

The random uncertainty in the discharge measurement is best defined in terms of the repeatability of discharge measurements at a fixed wicket gate setting and head. To date there are insufficient data for the ASFM to evaluate this uncertainty. Some of the factors that will contribute to this uncertainty are: i) random uncertainty in the laterally-averaged velocity; ii) the variability of the discharge and flow distribution with time; iii) uncertainty in the angle of the flow introduced by off-axis components; iv) movement of the frame in the gate slot; and v) electronic uncertainties. Items iv) and iv) are not significant compared with i) to iii).

The random uncertainty in the laterally-averaged velocity arises from the uncertainty inherent in the operation of the instrument. The calibration tests in the tow-tank allow the former to be estimated it is ± 0.4% for a 30-second data segment. In a 90-second segment (normally used), the uncertainty is reduced to ±0.3%. The major contribution to this uncertainty is in determining the location of the peak of the cross-correlation curve.

The random uncertainty due to the variability of the discharge and flow pattern with time must be evaluated very carefully as velocity variation recorded on one path may be compensated by velocity variations on other paths. Thus variation of the measured discharge with time will be less than the variation in the individual path velocities. Data for the LEFM taken during the Revelstoke tests and shown on Table 1 demonstrates this. In this case, the time variations in the flow pattern are also affected by the rotational flow and thus the variation in the average of the discharges for the two flow meters is less than the average for each flow meter. Note that the standard deviation of the discharge (average of two flow meters) is a measure of the flow variability and not necessarily the repeatability of the discharge measurements from test to test.

The effects on individual ASFM velocity measurements of short-term flow variability can be estimated from the statistics of the individual velocity estimates made within the duration of each sample. In the measurements at Lower Granite Dam, the uncertainty in the mean varied between ±0.7% and ±1.0%, the increase beyond ±0.3% being attributable to the short-term flow variability.

The discharge computed by the ASFM is proportional, in the first order, to the mean of the N laterally averaged velocities (N is the number of levels in the vertical) multiplied by the passage cross-sectional area. The random uncertainty in the ASFM discharge arising from the variability of the individual velocities is therefore $(N-1)^{-1/2}$ times the random uncertainty in the individual laterally-averaged velocities. At Lower Granite, that was between ±0.2% and ±0.3%, assuming that there were no additional random uncertainties caused by the sequential measurement of the paths.

The effect of off-axis flow components may be estimated from the tow-tank tests where runs were made with the arrays rotated by 45º to simulate the worst case. The results showed a small increase in the random uncertainty of the horizontal velocity component, from ±0.4% to ±0.5%.

Table 1

Comparison of Discharge Velocity Variations for LEFM

Test No.	Flowmeter 1						Flowmeter 2						Discharge (Average Flowmeters 1 & 2)
	Discharge m^3/s	Velocity (m/s)					Discharge m^3/s	Velocity m/s					
		Average	Path					Average	Path				
			1	2	3	4			1	2	3	4	
1	33.93 (1.44%)	.81 (1.44%)	.67 (6.48%)	.84 (2.36%)	.81 (3.99%)	.82 (11.09%)	32.65 (1.46%)	.78 (1.46%)	.65 (3.41%)	.80 (2.70%)	.80 (4.20%)	.73 (10.5%)	33.29 (0.84%)
2	133.63 (0.64%)	3.18 (0.64%)	2.59 (2.31%)	3.27 (1.28%)	3.12 (1.35%)	3.50 (2.69%)	131.89 (0.64%)	3.13 (0.64%)	2.59 (1.93%)	3.27 (1.19%)	3.30 (1.29%)	2.65 (2.24%)	132.76 (0.36%)
3	134.16 (0.56%)	3.19 (0.56%)	2.66 (1.91%)	3.30 (1.34%)	3.11 (1.29%)	3.63 (3.29%)	132.02 (0.59%)	3.14 (0.59%)	2.64 (1.74%)	3.27 (1.15%)	3.30 (1.37%)	2.64 (2.59%)	133.09 (0.31%)

NOTE: Numbers in brackets refer to the standard deviation of the quantity expressed as a percentage.

Discussion

The ASFM offers unique advantages for flow measurement applications in a number of hydroelectric applications. It has the potential to lower installation costs and decrease downtime, and increase portability and flexibility in carrying out discharge measurements in comparison to existing methods. It is particularly applicable to low-head dams, where the geometry of the intakes makes utilization of other non-intrusive methods extremely difficult or impossible.

The ASFM has been installed in two low-head Kaplan plants, where it operated successfully over a wide range of flow and operating conditions. A review of potential sources of systematic and random uncertainties in the ASFM's measurement of discharge shows that it should be possible to keep the resulting uncertainties within the required bounds for turbine efficiency tests, i.e. systematic errors of less than ±1%, and random uncertainty significantly less. These figures remain estimates until comparison measurements against a standard can be made to verify them. The work done at Revelstoke, because of the vibration problems experienced with the frame, was not able to provide that comparison, but did serve to illustrate the importance of the mechanical design of frames used to mount the ASFM. These issues are most critical in plants with high heads and large flow velocities, where comparisons to verify the ASFM discharge accuracy will have to be made. They are less critical in low-head plants, where flow velocities are not as high. The results from the Lower Granite measurements show that, especially for low-head, Kaplan installations, frames can certainly be built which avoid vibration problems. The resulting benefits of portability between units within a plant and ease of installation would more than compensate for the relatively small increase in the cost of their construction.

Planning is currently under way to obtain a new set of comparisons within the next few months. The location has not been finalized, but it is hoped to be B.C. Hydro's Kootenay Canal plant, where several previous sets of comparison measurements for other discharge-measuring methods have been made, and the conditions are well understood.

Acknowledgments

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