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Measuring Intake Flows in Hydroelectric Plants with an Acoustic Scintillation Flowmeter

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Abstract

The Acoustic Scintillation Flowmeter (ASFM) offers some unique advantages for measuring intake flows in hydroelectric plants. The method is non-intrusive, resulting in a minimum of flow interference and is well-suited to use in low-head dams and other applications where intake tunnels are short or have awkward geometries. Deployment in intake gate slots is straightforward, allowing data to be collected quickly and easily, with a minimum of plant down-time. An example of such flow measurements is shown. Interest in assessing the capability of the ASFM to make the highly-accurate measurements suitable for system efficiency evaluations led to our performing a series of tow-tank tests. Over a range of speeds from 0.5 to 5.0 m/sec, the mean deviation between the towing speed and the ASFM measurements was less than 0.5%. Measurements at an instrumented dam site are planned as the next stage in the accuracy assessment.

Introduction

The Acoustic Scintillation Flowmeter (ASFM) is a new instrument which offers some unique advantages for measuring intake flows in hydroelectric plants. It is non-intrusive; no instruments are required in the measurement zone. Because the acoustic paths can be oriented at any angle across the passage, including perpendicular to the tunnel axis, the ASFM can be used in low-head dams and other applications where intake tunnels are short or have awkward geometries. The ASFM can, for example, be deployed through an intake gate slot. As a result, data can be collected quickly and easily, with a minimum of plant down-time.

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Applications to other difficult areas such as spillway flow measurement are also possible.

Until recently, research into and development of applications of the ASFM have been limited to measuring currents and associated properties such as turbulence in tidal channels and rivers. It was first used in a hydroelectric plant in 1992 to make intake flow measurements to verify design modification studies carried out with models. That led to interest developing in the possibility of using the ASFM to make highly accurate intake flow measurements for system efficiency assessments.

In order, however, for the ASFM to gain acceptance in the hydroelectric industry for these applications, quite stringent standards for accuracy, reliability and repeatability must be met. A set of calibration and comparison tests has been undertaken to determine if the ASFM is in principle capable of meeting those standards, and what modifications and refinements of the present prototype instruments would be required to do so. The results of the first stage, tests in a towing tank, are presented here.

Principles of Operation of the ASFM

Acoustic scintillation drift is a technique for measuring flows in a turbulent medium, such as water or air, by analyzing the variations (with position and time) of sound which has passed through it. Scintillation in this context refers to random fluctuations in the amplitude and phase of the sound radiation caused by the variations of the refractive index in the water. Flow measurements are made by observing the transverse drift of scintillations across two relatively 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 acoustic scintillation flowmeter installed in a river or an ocean channel. Two transmitters are at one end of the path, and two equally-spaced receivers are at the other end. There is no cable connection between the receiver and the transmitter, nor is there any other communication between them beyond the acoustic signals. The system is arranged so that each receiver detects only the signal from the corresponding transmitter.

The acoustic wave-fronts propagating along the path from the transmitter to the receiver become distorted as they encounter refractive-index turbulence along the way. The distorted wave-fronts interfere with each other (the longer the path or the greater the strength of the fluctuations, the stronger the interference) resulting

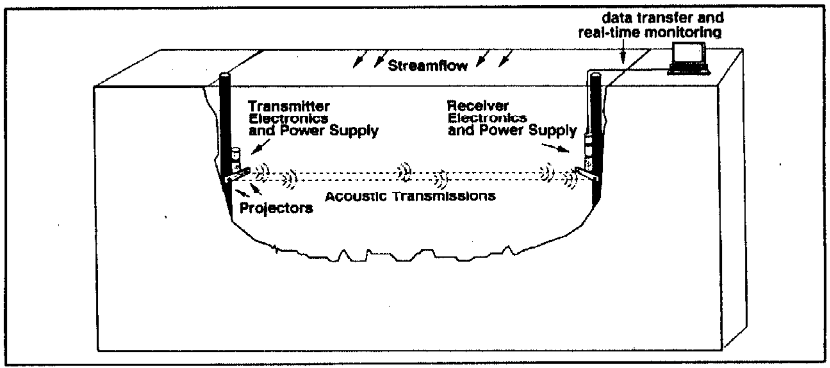

Figure 1. Schematic representation of acoustic scintillation current measurement.

in phase and amplitude scintillations at the receiver. The received phase and amplitude vary randomly as the distribution of refractive-index turbulence along the path changes with evolution and advection. If the paths are sufficiently closely-spaced that the turbulence does not evolve significantly during the time required to advect it across the interval between the paths, then the pattern of scintillations at the downstream receiver will be nearly identical to that at the upstream receiver, except for a time lag Δt. The lag Δt may be found by computing the cross-correlation (or the covariance) of the two signals over some suitable length of record. The lag is then simply equal to τ_0, the delay to the peak of the cross-correlation curve, and the mean flow speed normal to the acoustic beams is then $\Delta x/\tau_0$ where Δx is the separation between the beams.

Application to Hydroelectric Plants

The ASFM's inherent suitability for discharge measurements, coupled with its non-intrusive nature results in a number of advantages for its use in measuring flows in hydroelectric dams. Measuring turbine intake flows can be done in the intake gate slots, as it requires only that transducer arrays 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 lack sufficiently long straight sections for time-of-travel acoustic velocity meters to be used. The spatial averaging in the ASFM measurement means as well that large-scale eddies and meandering do not bias the measurement.

The January, 1992 flow measurements made in the turbine intakes at Rocky Reach Dam using an earlier model of the ASFM (Birch & Lemon, 1993) serve as an example of this application. The flow information was desired in the form of horizontal averages of the current at a number of levels spanning the height of the intake tunnel. Those measurements, although comparison data were not available, serve to demonstrate the use of the ASFM in hydroelectric applications.

Measurements were taken in the intake gate slots of turbines 1, 2, 3 and 4. Each turbine intake is divided into three bays (referred to as South, Centre and North). The bays are 6.1 m wide and 15.2 m high. The current (averaged across the width of the bay) was measured at 11 elevations in each bay (shown in Figure 4 in feet, relative to the local geodetic datum).

The flowmeter consisted of two cylinders, with two transducers mounted at one end and a surface cable at the other. They were mounted on the lower section of the existing fyke 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 three minutes of acoustic data were collected.

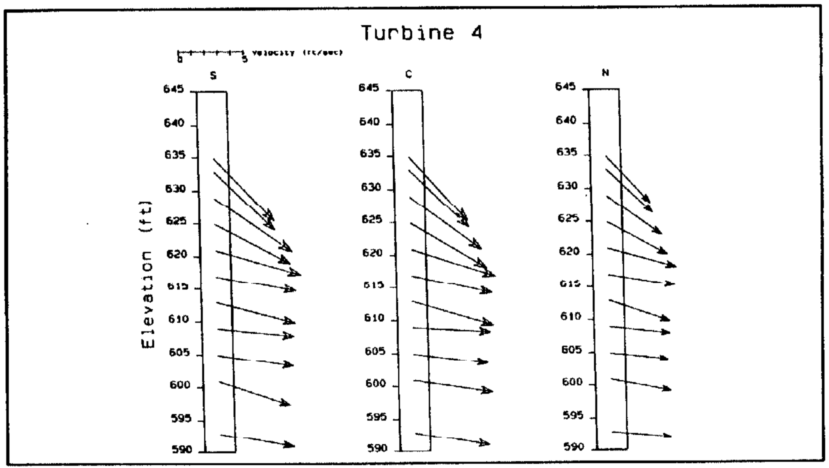

Figure 2. Flow speed and angle for each intake bay, Rocky Reach Dam.

Measurements were made with the transducer pairs oriented both horizontally and vertically, so that the orientation of the flow at each level could be measured. Figure 2 shows the magnitude and direction of the flow in each of the bays of Turbine 4. The length of the arrows is proportional to the flow speed as given by the scale in the upper left of the diagram. The inclination of each arrow shows the direction of the flow at that level. The horizontally-averaged flow was then integrated vertically to give the discharge through each bay.

These measurements were made to provide reference data for designing fish diversion screens. For other applications such as turbine efficiency measurements, the discharge must be measured to high accuracy, within 1% or better. In order to assess the ASFM's suitability for those purposes, it is necessary to determine the limits of its absolute accuracy. A means for calibrating it against an absolute standard was therefore required.

Calibration Test Procedure

Determining the measurement accuracy of a quantity like the mean current in a channel is always complicated by the difficulty of providing a standard. Traditional current meters sample the flow at a point, and the resulting estimate of the mean flow is subject to uncertainties arising from the effects of the limited number of sampling points, local variability in the flow and the effects of mooring or vessel motion while the data are being collected. Comparisons of the performance of the ASFM with mechanical current meters and acoustic Doppler profilers have been made, both in ocean channels (Farmer & Clifford, 1986) and in rivers (Lemon, 1993), and agreement on the order of 2% has been found. At that point, it becomes difficult to determine which of the methods is the more accurate, as both may be subject to error, and there is no independent standard by which to assess those potential errors. Point-measuring current meters can be calibrated in tow tank tests, but in comparing spatially-averaged flows or transports, there still remains the question of errors introduced by mooring or vessel motion and the discrete sampling in space. To date, all assessments of the accuracy of flow measurement by acoustic scintillation have been limited in this way.

Both types of uncertainties in the comparison may be eliminated by operating the ASFM in a full-scale towing tank. The towing speed is known accurately, and since the water in the tank is stationary while the ASFM moves through it, the towing speed and the horizontal average water speed measured by the ASFM are equivalent quantities. It is necessary, however, to create turbulence in the tank to provide the fluctuations in the acoustic signal necessary for the ASFM to function. Without the presence of an actual current, no natural turbulence is generated. Artificially-produced turbulence must be introduced without causing any currents to be set up in the tank; it must also possess the proper spectral characteristics, i.e. an inertial subrange, in order for the ASFM to function properly.

The tests were carried out in the main towing tank of the Ocean Engineering Centre, operated by B. C. Research Inc. in Vancouver, British Columbia. The main towing tank is shown in Figure 3, with its principal specifications. The towing carriage is large enough to carry the instrument and up to 3 operators. The configuration used for the speed calibrations is shown schematically in Figure 4. The ASFM transducer arrays were mounted on struts behind the carriage, braced and aligned to be within 0.5° of vertical, and equipped with fairings free to rotate into alignment with the current to reduce drag and vibration. The instrument parameters for the tests were as follows:

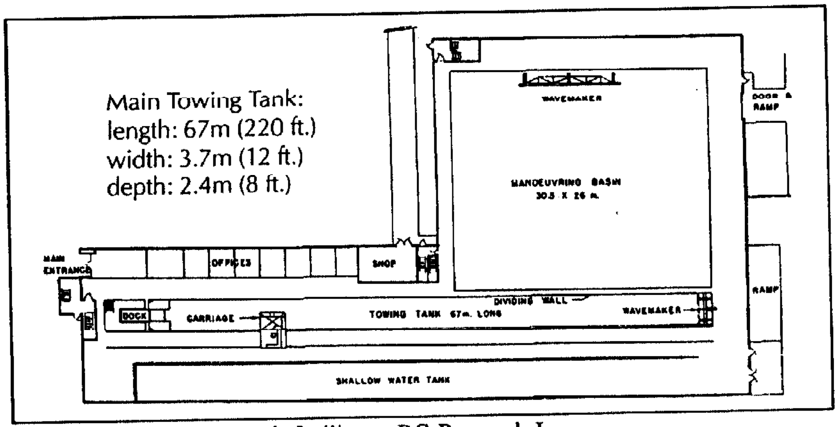

Figure 3. The towing tank facility at BC Research Inc.

Array depth:	0.61 m	*Path separation*:	0.0457 ± 0.0001m
Path length:	3.08 m	*Angular deviations*:	< 0.5°(all axes)
Acoustic frequency:	307.20 kHz	*Pulse width*:	32.6 µsec
Pinging frequency:	150 Hz (< 3.5 m/s) 200 Hz (> 3.5 m/s)	*Towing speeds*:	0.5 to 5.0 m/s

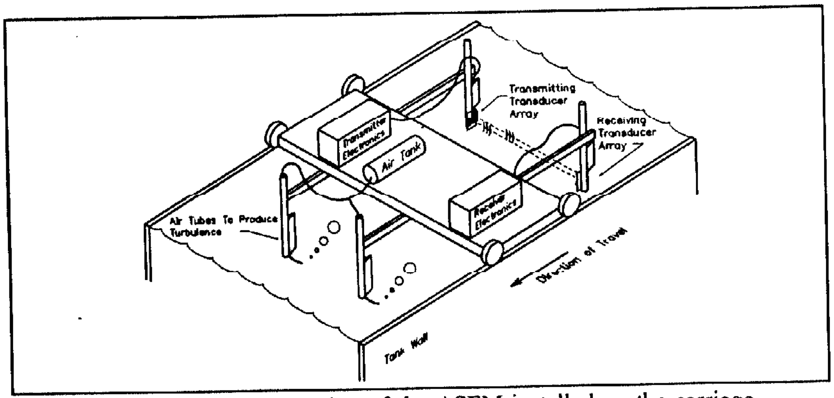

Figure 4. Schematic representation of the ASFM installed on the carriage.

Initially, a grid mounted at the leading edge of the carriage was used to stimulate turbulence in the water through which the arrays were to pass, as trial runs without the turbulence generator in place had confirmed that its presence was necessary. The grid proved to be unsuitable, as it produced too much vibration in the carriage and the arrays, and relatively low turbulence levels. It was therefore replaced by the system shown in Figure 4, which consisted of two vertical faired pipes mounted at the leading edge of the carriage (3 metres ahead of the ASFM arrays), connected to an on-board reservoir. Air from the reservoir was fed through a regulator set at 550 kPa into the lines, which were positioned to discharge at the depth of the transducer arrays. The bubbles formed by the air discharging into the water rose above the acoustic beams by the time they passed, but the residual turbulence left was sufficient for the operation of the ASFM. Spectra of the log-amplitude fluctuations recorded with the bubbler in operation and the carriage in motion showed the -8/3 slope and low-frequency plateau characteristic of the existence of an inertial subrange. The calibration measurements were therefore made using the bubbler to generate the required turbulence. Figure 5 shows the tow carriage in motion with the bubbler in place.

Figure 5. Towing carriage with ASFM and bubbler installed.

Calibration runs were made at nominal carriage speeds from 0.5 to 5.0 m/sec at 0.5 m/sec intervals. The carriage speed during each run was recorded from an analogue voltage signal, for which 1 volt = 0.861 m/sec. The carriage speed record was digitized simultaneously with the acoustic signals, and stored in a common data file. Since the digitizer had a maximum input of 5.0 volts, a voltage divider was added for speeds above 4.0 m/sec to maintain the carriage speed signal within the digitizer's range. The carriage speed signal is specified as accurate to ±1.5 cm/sec, or ±0.5%, whichever is greater.

Results

Allowing safety zones for stopping the carriage at either end of the tank, acceleration and deceleration reduces the distance travelled at constant speed during each run to approximately 40 metres. The time available for speed measurements during each run varied from 80 seconds at 0.5 m/sec to 8 seconds at 5.0 m/sec. The ASFM requires a time series at least a few hundred points in length in order to compute a meaningful correlation curve. The frequency content of the fluctuations in the acoustic signal increases with increasing current speed and therefore to avoid aliasing the sampling frequency of the ASFM must also increase. Below 3.5 m/sec towing speed, a sampling frequency of 150 Hz was used, with 200 Hz being used at the higher speeds. The data from the constant-speed section of each run was divided into 1024-point blocks, from each of which an ASFM speed and a mean towing speed were computed. The individual blocks for each run were then averaged to yield a mean ASFM velocity and a mean carriage speed. Repeat runs were made at higher speeds where the record was too short to yield more than one block; a minimum of three blocks were used for each carriage speed. Figure 6 shows the average ASFM speed plotted against the average carriage speed. The solid line shows the least-squares fit to the data:

$$V_{ASFM} = 1.0031 V_{carriage} \tag{1}$$

The correlation coefficient r for the fit is 0.9997. The two dotted lines show the ±1% limits. Figure 7 shows the relative difference between the ASFM speed and the carriage speed as a function of the carriage speed. The relative difference is shown as the percentage R = $100(V_{ASFM}/V_{carriage} - 1)$. The horizontal error bars (very small in the figure) show the specified error in $V_{carriage}$, as given above. The error bars for R are given by

$$\frac{\Delta R}{R+1} = 100\sqrt{\left(\frac{\Delta V_{asfm}}{V_{asfm}}\right)^2 + \left(\frac{\Delta V_{carriage}}{V_{carriage}}\right)^2} \tag{2}$$

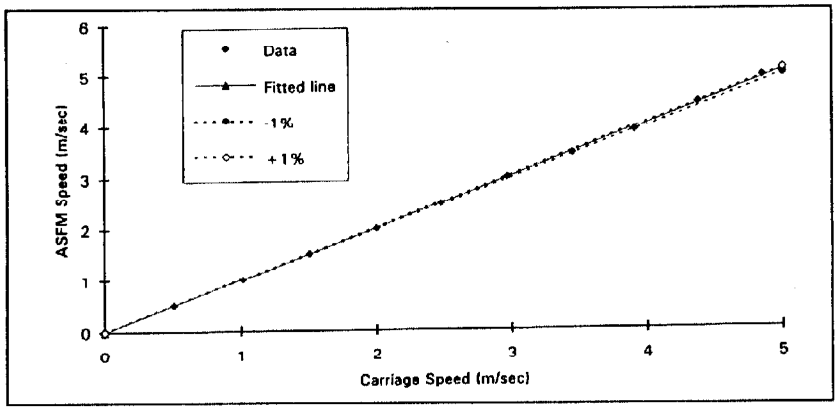

Figure 6. Current speed measured by ASFM vs. towing speed.

where $\Delta V_{ASFM} = \sigma/\sqrt{(N-1)}$ is the standard error in each mean ASFM speed, σ being the standard deviation and N the number of repetitions. The dashed line shows the mean difference. Within the indicated uncertainties in the relative difference, all values fall within the ±1% bounds. At speeds below 1 m/sec, the greater contribution to the indicated error in the difference comes from the carriage speed uncertainty; above 1 m/sec, the contributions from both sources are close to equal. The Spearman rank-order coefficient for the differences as a function of speed shows that there is no statistically significant trend with carriage speed.

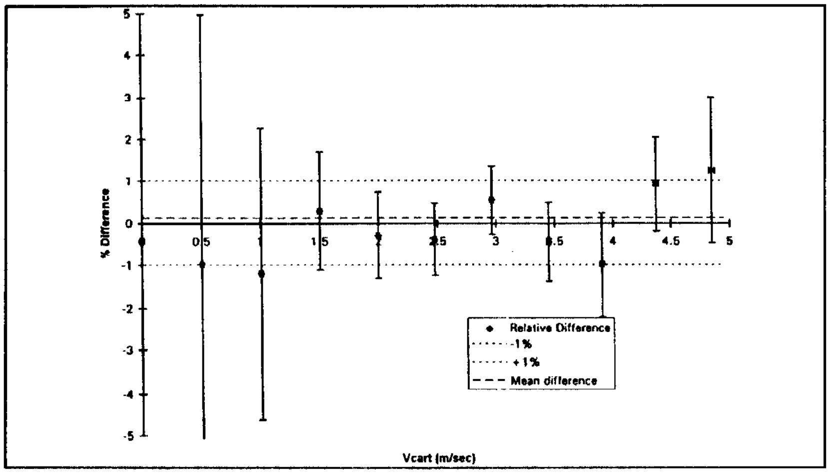

Figure 7. Relative difference, ASFM and carriage speeds.

Conclusions

The ASFM offers unique advantages for several flow measurement applications in hydroelectric plants. Because it measures the spatial average of the component of the current normal to the acoustic path pair, it is ideally suited to measuring discharges, either in turbine intakes or in spillways. Its non-intrusive geometry, and flexibility in path orientation offer practical advantages over traditional methods such as current meter arrays or time-of-travel acoustic velocity meters. Measurements of intake flows may be made in gate slots, requiring minimal down-time for installation and measurement, which is a particular advantage for low-head plants where it may be very difficult to find other points to install flow-measuring equipment.

Tow-tank tests have demonstrated the ASFM to be accurate, considering both systematic and random differences, to within 1% in measuring the spatially-averaged currents under controlled conditions. Comparison measurements at an instrumented dam site are planned for the spring of 1995 to extend these tests to operational conditions.

Acknowledgements

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