DEVELOPING AN ACOUSTIC METHOD OF TURBINE CALIBRATION

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SUMMARY

The paper introduces an innovative approach to discharge metering for low head hydroelectric plants. The proposed method employs transit time acoustic velocimetry to obtain high frequency line average velocities. The innovation is to traverse this instrumentation across the turbine intake to approach a true integration of the complex velocity profile typical to low head plants rather than using a number of fixed line averages and invoke assumptions about the profile. Laboratory testing of the technique is underway at the Hydraulics Research & Testing Facility (HRTF) at the University of Manitoba, Canada. The paper includes an introductory discussion of acoustic velocimetry, a description of the proposed discharge measurement technique, and a description of the instrumentation and laboratory testing program.

Résumé

Cet article présente une approche novatrice pour mesurer le débit aux installations hydro–électriques à faible chute. La méthode proposée utilise le temps de parcours d'un signal acoustique pour obtenir les vitesses moyennes. L'innovation dans la méthode consiste dans l'installation de l'instrumentation à l'entrée de la turbine de façon à obtenir une intégration précise du profil complexe de vitesse typique des installations à faible chute plutôt que d'utiliser un nombre fixe de vitesses et d'en supposer un profil. Afin de valider la technique de mesure, des essais en laboratoire sont présentement en cours au *Hydraulic Research & Testing Facility* (HRTF) de l'université du Manitoba. Cet article comporte une discussion d'introduction sur la mesure de vitesse par la méthode acoustique, une description ainsi qu'une description de l'instrumentation et du programme d'essai en laboratoire.

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INTRODUCTION

The economic and efficient operation of a hydroelectric generating station requires an accurate description of the head-power-discharge and efficiency-discharge relationships for each unit. These relationships are used to determine the optimum setting of the turbine wicket gates, corresponding to peak absolute efficiency, commonly referred to as 'best gate.' Substantial loss of generation revenues can result from the inaccurate definition of these relationships. For example, a 1% error in the gate setting for a 29.5 MW unit at Manitoba Hydro's Seven Sisters plant translates to a 1.3% loss of efficiency or approximately $50,000 per year for each unit. When considering an entire hydroelectric utility, this impact could be substantial. The ability to accurately define the point of optimal efficiency is, therefore, of paramount importance to the operation of a hydroelectric facility.

Definition of the head-power-discharge and efficiency-discharge relationships requires measurement of hydraulic head, power output, and absolute unit discharge. Of this trio, absolute discharge data is typically the most difficult to acquire and the most susceptible to measurement error. The restrictive conditions of low head plants (*i.e.*, short, irregular intake conduits) limit the available discharge measurement techniques. Similar to many other utilities operating low head plants, Manitoba Hydro employs the 'velocity-area' technique, which involves traversing an array of propeller-type (Ott type A) flow meters mounted on a rigid frame down the stop-log guides to obtain 'point' velocity estimates which are 'integrated' over the flow area to estimate discharge. It has been estimated that this method is accurate to approximately 2% (Mikhail, 1994). A number of limitations of this method, which are outlined herein, along with the desire to obtain more accurate discharge measurements have prompted research into developing a new discharge measurement technique for low head applications.

Transit time acoustic velocimetry has been successfully applied to turbine metering for many years. Very accurate discharge measurements (0.5% error) have been documented under favorable flow conditions. With this in mind, and considering the additional advantages of acoustic velocimetry, such as: it is relatively non intrusive, and the technology enables high frequency sampling, it is reasonable to expect that acoustics will continue to grow in this field. However, accurate integration of very complex profiles, typical to low head plants, using stationary acoustic methods is questionable. The paper outlines the conceptual development of a new approach to metering low head plants via acoustic velocimetry. In essence, the proposed technique involves traversing the intake area with acoustic transit time instrumentation to obtain a true integration of velocity across the metering plane. This eliminates the need for assumptions about the flow profile, a requirement for fixed level acoustic discharge metering. The technique is being laboratory tested in the Hydraulics Research and Testing Facility (HRTF) at the University of Manitoba, Canada.

BACKGROUND: ACOUSTIC VELOCIMETRY

In general, three acoustic velocimetry techniques have been developed: Doppler shift, acoustic scintillation, and transit time. Doppler velocimetry is based on the principle that the frequency shift of an acoustic echo is directly proportional to the velocity component of flow along the acoustic beam axis. The theory has been employed in a number of applications such as laboratory point velocity meters and for large scale current profiling (Birch and Lemon, 1995; Simpson *et al.*, 1993).

Acoustic scintillation velocity measurement is a correlation sonar technique that has been used to measure flows in turbulent media by analyzing the time record of scintillations between two acoustic paths separated by a known distance. Acoustic scintillations are random fluctuations of the amplitude and phase of sound caused by variations in the refractive index of the medium which results from turbulence in the flow. Numerous applications of this theory have been documented, such as wind velocity and river and tidal turbulence/velocity measurement. The applicability of acoustic scintillation to discharge measurement at hydroelectric plants is currently under study (Birch and Lemon, 1995; Lemon, 1995). The technique has strong potential for hydroelectric application since it is non-intrusive and is suited to the restrictive geometry and complex velocity profiles typical to low head plants.

Transit time acoustic velocimetry, the focus of this research, is gaining popularity in performance testing of hydroelectric turbines. The method operates on the principle that the velocity of an acoustic signal is influenced by the velocity component of the medium parallel to the direction of acoustic propagation (Figure 1). Sound pulses traveling upstream (relative) impeded by the flow resulting in increased travel times, conversely, downstream travel times are reduced. The average water velocity along a path between a pair of acoustic transducers is proportional to the difference between the acoustic transit times of upstream and downstream traveling pulses. The average water velocity normal to the flow area can be estimated as

$$U_m = \frac{c^2}{2L}\frac{(t_{12} - t_{21})}{\cos\theta} \qquad (1)$$

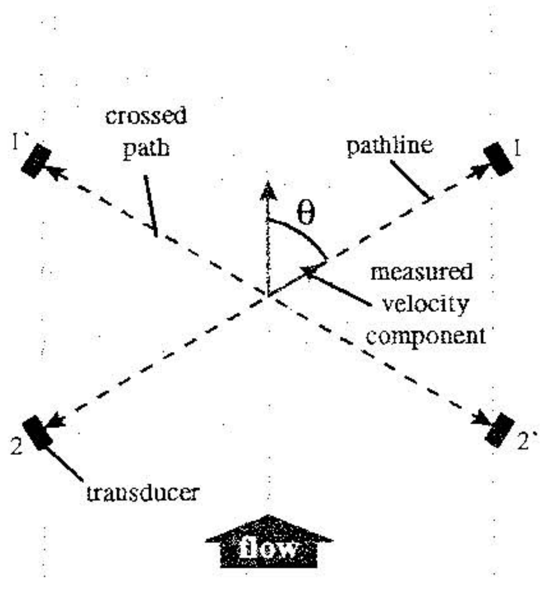

Figure 1. Line averages of velocity are obtained between acoustic transducers via the transit time principle. The crossed path is used to minimize cross-flow error since the exact orientation of flow lines is difficult to determine under real flow conditions.

where c, the speed of sound in water is given by

$$c = \frac{2L}{t_{12} + t_{21}}. \quad (2)$$

t_{12} and t_{21} are the upstream and downstream travel times, respectively, and θ is the acoustic path orientation relative to the flow.

Knowing the orientation of the paths relative to the flow, the normal velocity profile can be deconvolved and integrated over the flow area to determine total discharge. For applications where the streamline direction is difficult to specify, for example, when the measurement section is too close to an upstream bend, transition, or obstruction that causes asymmetrical and/or diverging streamlines, crossed path configurations are employed. Adding the crossed path considerably reduces cross-flow error when deconvolving the flow profile.

Generally, transit time metering installations consist of a number of metering levels (typically four) defined by pairs of transducers fixed to the walls of the conduit. Velocities are obtained for each level and quadrature integration (Gauss-Legendre or Gauss-Jacobi) (IEC, 1991) is used to estimate discharge. Advocates of this technique (*e.g.*, Spencer, 1986) have documented errors of 0.5% and lower under favorable flow conditions (*i.e.*, well developed velocity profile). Voser *et al.* (1996), in a laboratory environment, assessed the accuracy of the technique for disturbed flow fields by introducing characteristic pipe elements (elbows, cones, vane, and swirl generators) at varying distances upstream of an Accusonic four path flow meter (model 7410); errors in the range of 1.0% were documented. However, these levels of accuracy have not been documented for low head field applications, partly due to the inaccuracy of reference discharge measurement techniques available. ORE, a manufacturer of acoustic instrumentation, and Alden Research Laboratories (Walsh, 1993) conducted an inter-comparison between the acoustic transit time and velocity-area (propeller meter) methods for a low head plant and documented a 2.1% error band between the methods. The author indicated that testing was performed under favorable low head hydraulic conditions, meaning: long intake structure, modest taper of the intake ceiling, and straight vertical walls (relative to other low head plants). The author cautioned that shorter intakes with more severe taper would decrease the accuracy of the acoustic method.

DEVELOPMENT OF CONCEPT

A number of well established discharge measurement techniques have been used to meter hydroelectric plants, examples being: Gibson pressure-time; tracer dilution; and Allen salt velocity methods. However, for various reasons, these methods are not well suited to low head plant conditions. For example, low head plants typically have short conduit systems resulting in brief transit times which limit the accuracy of the salt velocity method.

The velocity-area method has traditionally been employed at low head plants. A grid of point velocities is obtained at the intake, either by installing a grid of propeller type meters in the conduit or by traversing an array of meters down the stoplog guides to meter point velocities at predefined stations within the intake. The appropriate summation of velocities times their respective areas in the metering plane yields an estimate of total discharge. Potential problems associated with the velocity-area method include:

1) the inability of a sample of point velocity measurements to accurately represent complex flow profiles typical to low head plants;
2) the disruption of the flow field by the traversing apparatus;
3) the inability to resolve high frequency fluctuations in the flow field (which can be used to investigate turbine behavior);
4) misrepresentative velocity profiles may be produced due to influences from perturbations shortly upstream of the meters (*e.g.*, trash rack beams);
5) difficulty detecting flow reversals using conventional Ott meter technology; and
6) the cost of purchasing and calibrating each flow meter.

Acoustic velocimetry is being applied to low head hydroelectric plants. The aforementioned acoustic scintillation technique has been tow-tank and field tested (Lemon, 1995). However, fixed level transit time installations are more prevalent in the hydroelectric field and have been code accepted (IEC, 1991). The high level of accuracy of this approach has been well documented for favorable flow conditions, however the ability to integrate very complex flow profiles using a limited number of fixed level velocity measurements is questionable. Complex flow profiles are common at low head plants due to trash and trash rack flow disturbances, influences from adjacent units, rapid convergence of the intake, and the shortness of the conduit.

The technique proposed herein is in essence a hybrid version of the traversing point velocity profiling method and acoustic transit time velocimetry. It is proposed that an array of acoustic paths be configured to obtain line averages of velocity at a high sampling frequency. By traversing this array across the intake, virtually the entire flow profile can be sampled. A more complete integration of the velocity profile should provide a very accurate discharge estimate. Employing acoustic velocimetry will also provide information about high frequency fluctuations and reversals in the flow field.

Figure 2 illustrates a single 'acoustic cell' consisting of two pairs of acoustic transducers in a crossed path configuration. For each transducer pair, the travel times of upstream and downstream traveling acoustic pulses are measured and an average line velocity is obtained between the transducers. A number of these acoustic cells are to be mounted adjacently as depicted in Figure 3. The carriage of transducers would be traversed down the stop log guides, in a similar fashion to the velocity-area technique, to vertically integrate the velocity profile. Accurate vertical positioning is central to the accuracy of this method. In the field, this would be accomplished by monitoring cable feed, upward/downward looking sensor, or a pressure sensor.

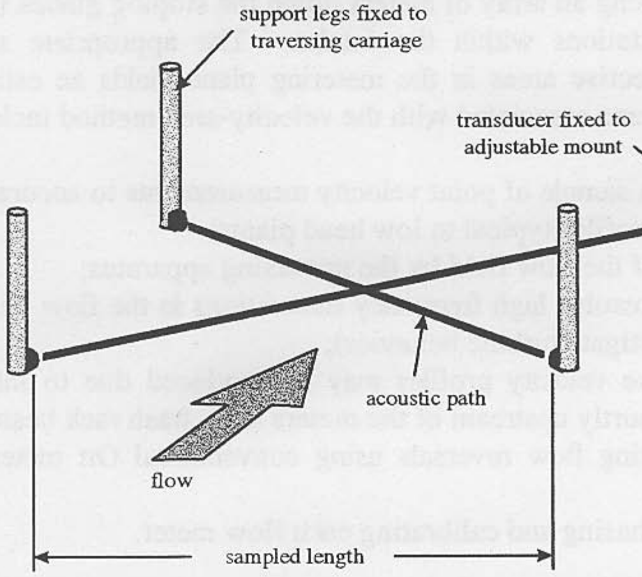

Figure 2. A single acoustic cell, consisting of four transducers, is being laboratory tested.

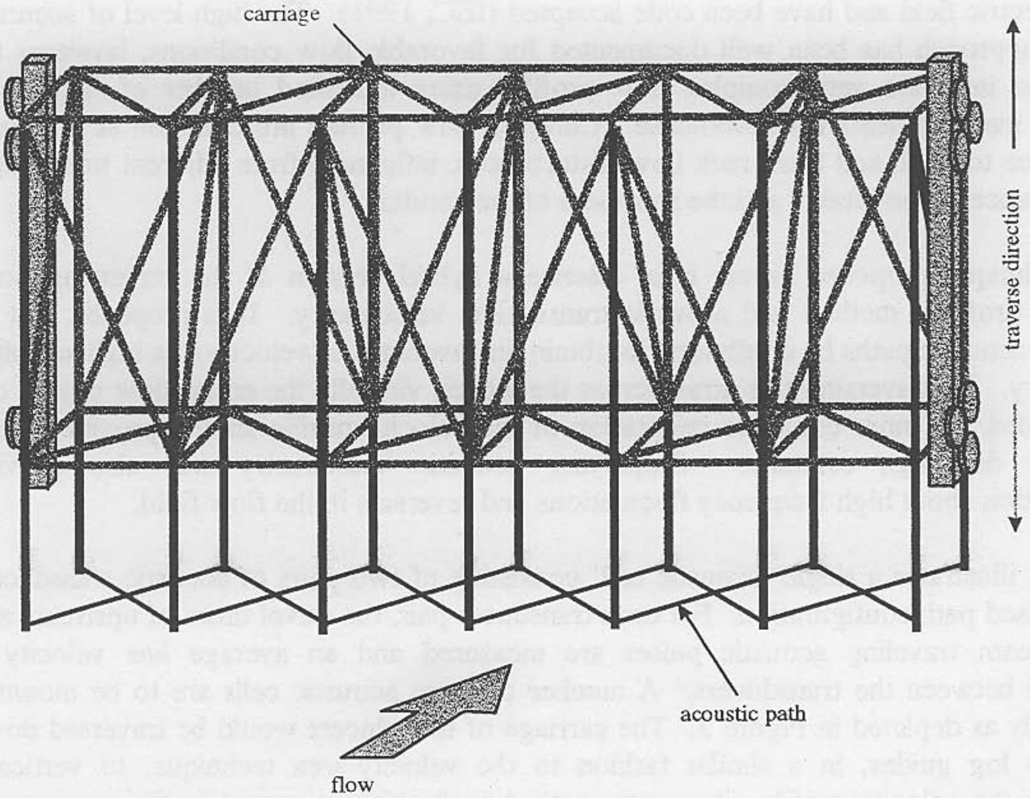

Figure 3. Conceptual array of acoustic cells: adjacent pathlines would be traversed across the intake to integrate the velocity profile.

INSTRUMENTATION AND LABORATORY TESTING

Single Acoustic Cell

A large scale acoustic cell consisting of four transducers in a crossed path configuration has been assembled for this research effort. The acoustic transducers consist of 0.75 inch diameter, 1 MHz piezoceramic elements potted in custom machined stainless steel housings. The transducers were designed to fit off the shelf two-axis adjustable optical mounts for precise alignment of the transducer pairs. The transducer pairs are mounted on legs extending from a rigid carriage which is raised and lowered using a single axis positioning system. The preliminary geometry to be tested has 1.20 m path lengths crossing the flow axis at 57 degrees.

Signal Generation, Timing, and Communication Electronics

Signal generation and timing electronics have been adopted from the Velocity-Density-Vorticity (VDV) oceanographic sensor technology developed by Focal Technologies, Inc., Dartmouth, Nova Scotia (Trivett *et al.*, 1996; Trivett *et al.*, 1995).

Figure 4 shows a block diagram of the standard VDV electronics. While the original VDV transmits through transducers at 5MHz, the setup for our testing was modified to use 1MHz transducers. The modified VDV electronics will ultimately be capable of making measurements from several cells in a power plant intake. The current setup samples velocity at 10Hz, and transmits the data via an RS-232 serial data link to a PC or Laptop computer for display and logging. The instrument can be set to operate autonomously for some applications. The complete electronics package fits inside a 5cm diameter PVC pipe, 32cm in length.

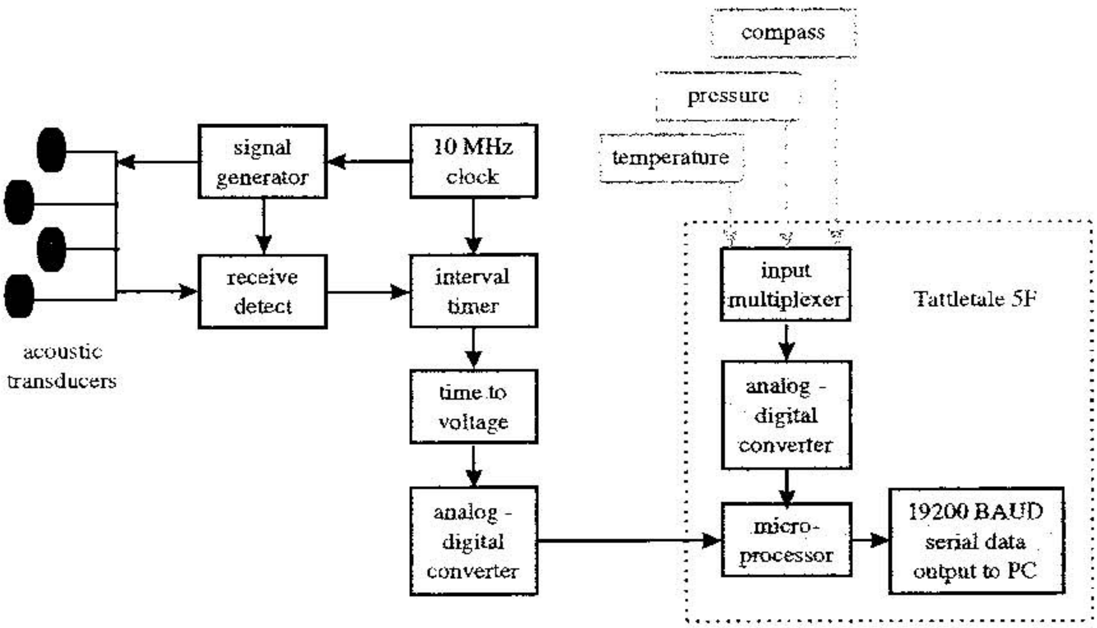

Figure 4. Block diagram of VDV electronics (Trivett *et al.*, 1995).

Four independent measurements are obtained in our current configuration. These are two velocity components, and two sound speed measurements. The data is displayed in real-time in engineering units, and the raw data is simultaneously stored to disk by a compiled C program provided by Focal Technologies Inc.

Laboratory Testing Program

Hydraulic testing of a single acoustic cell is currently underway in the HRTF. The performance of the technique will be assessed based primarily on a discharge measurement comparison with known lab discharges (up to a capacity of approximately 0.45 cms). The reference laboratory discharge is monitored using an in-line magnetic flowmeter which is calibrated volumetrically. Test results will be used to determine:

1) the accuracy of a single cell system;
2) an appropriate sampling strategy (*i.e.*, frequency of sampling and traverse rates);
3) the influence of turbulence of various scales on the accuracy of the discharge measurement;
4) susceptibility to error due to flow induced vibration; and
5) susceptibility to error due to non parallel flow conditions.

A 1 m by 1 m mock intake has been constructed to define a metering plane. The intake rapidly converges downstream of the metering plane to force nonparallel flow within the metering area thereby replicating field conditions. A servo motor, equipped with an optical encoder, drives a leadscrew apparatus to accurately traverse the metering area. VDV and Tattletale circuitry is used to excite the transducers, time the sound pulse arrivals, and transmit digital data to a PC. A simple integration of the velocity is used to calculate discharge.

SUMMARY

We are currently developing an acoustic method of measuring discharge for use at low head hydroelectric plants. The technique involves traversing the flow area with transit time acoustic instrumentation in order to obtain a complete integration of complex velocity profiles common to low head plants. Testing is being carried out in the HRTF to assess the accuracy of the technique. Potential benefits from this research effort include:

1) improved estimation of absolute discharge under low head conditions;
2) ability to better define the head-power-discharge and discharge-efficiency relationships, leading to a more accurate definition of best gate and thereby improved operating efficiency; this clearly has economic benefits;
3) ability to more accurately calibrate relative discharge measurement facilities (*i.e.*, Winter-Kennedy taps);
4) ability to better determine the gains of rerunnering in acceptance tests; and
5) high frequency flow phenomena and flow reversals will be detectable.

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