Turbine flow measurement for low-head plants – Owners' options for the 21st century

Josef Lampa and David Lemon
ASL AQFlow Inc.
Sidney,
British Columbia

Pierre Lamy
Hydro-Québec
Montreal,
Québec,
Canada

John Taylor
B. C. Hydro
Vancouver,
British Columbia

Presented at Hydro 2007, Granada, Spain, October 2007

Introduction

Low-head hydropower plants frequently do not run at their optimal operational settings due to lack of data on the actual unit performance necessary to determine the best operating conditions.

Determination of the optimum operating conditions of a plant requires absolute flow measurements. For low-head plants, both large and small, absolute flow measurements have traditionally been prohibitively expensive. Plant owners/operators often do not have the resources or the financial justification to perform these measurements.

The paper describes recent developments addressing the needs of large and small low-head plant owners through the judicious utilization of the available technologies suitable for the short, rapidly converging intakes typical for these plants:

- One time measurements with multiple lines of current-meters on stationary supports
- One time measurements with multiple pairs of acoustic scintillation sensors on stationary frames
- One time measurements with single or double lines of current-meters and/or pairs of acoustic scintillation sensors on moving frames
- Continuous monitoring with multiple pairs of time-of-flight acoustic sensors on the walls of the intake
- Continuous monitoring with multiple pairs of acoustic scintillation sensors on the walls of the intake

1. Background

Increasing demands on water resources and shrinking operating budgets dictate that hydroelectric utilities optimize hydraulic performance of their plants in a cost-effective manner. Determination of the optimum operating conditions of a plant requires absolute flow measurements. For low-head plants, absolute flow measurements have traditionally been difficult and expensive. In a report prepared for the First Workshop on Turbine Flow Measurement, Hydro 2004, Portugal, the ASME PTC-18 committee put it this way: *"For low-head units, characterized by the short, rectangular, multi-bay intakes, such as the one shown in both the IEC and ASME Codes (*Fig. 1*), there is not to be found a practical way to conduct a performance test on this type of unit in either of the two test codes. The difficulty lies in flow measurement" (1).*

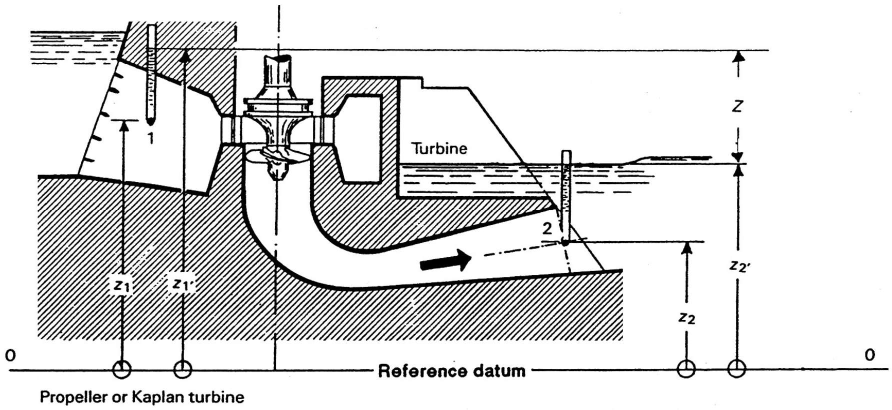

Fig. 1 – Transverse section through typical Kaplan unit (from IEC 600041)

Clearly, the need ”*to simplify measurements of large quantities of water in the short conduits of low-head plants”* as recognized as far back as 1970 by J. Guthrie Brown (*2)*, still exists today. Earlier this year, the US Army Corps of Engineers issued a notice of interest in new methods *“to accurately measure absolute water flow rates in its short-intake Kaplan turbines” (3).*

One only needs to look at the acoustic time-of-flight method’s history to realize how long it takes for a new method to be accepted by the hydroelectric industry, and how unlikely it is therefore for a totally new method to emerge, and be accepted, in the foreseeable future. Recognizing all these factors, three methods were identified in 2004 and again in 2006 *(4)* by the ASME PTC-18 committee as having demonstrated the potential for achieving Code-accepted status:

- The current-meter method
- The acoustic time-of-flight method
- The acoustic scintillation method

Advancements in the recent development and field application of these three methods are described in the following paragraphs, with the aim of helping the owner of a low-head plant to select a method most appropriate for his needs.

The references listed at the end provide further details.

2. One time measurements with current-meters on stationary supports

The current-meter method has been used in hundreds of applications by different parties over the years.

The method consists in measuring the fluid velocity at specified locations using propeller-type current-meters. Flow is subsequently obtained from the integration of these individual velocities over the gauging section. The number of measurement points, as well as their location, is in part dictated by the need to adequately define the velocity profile at the measurement section.

In practical applications, the more regular in time and space is the velocity distribution, the better the measurement accuracy to be expected. For this reason the current-meters are often placed inside a conduit at a location where the flow environment is expected to better meet these two conditions.

In such applications the current-meters are generally placed on fixed support rods attached to the internal surfaces of the water conduit (Fig. 2). A significant blockage effect may result, however, particularly in smaller cross-sections. The unit will have to be taken out of service for a period in the order of 5 or more days so that scaffolds can be erected and the current-meters and their support frames installed. A second down time of the unit will be required following the tests for retrieving the instruments. The tests will preferably be done over a single day to avoid instrument malfunctions caused for example by debris contacting a current-meter.

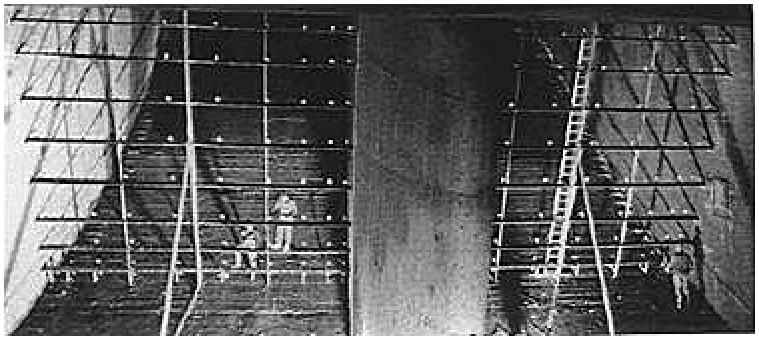

Fig. 2 – Current-meters at Formin plant (courtesy Turboinstitut - IGHEM 1996)

Comparative tests have shown this method to give good results in low-head plants (*5*). Results from measurements at several European plants are reported in terms of accuracy, repeatability and test time in (*6, 7 and 8*).

Although "no existing standard deals with discharge measurements in short penstocks or intakes, especially for low-head plants" (*9*), standards such as IEC 600041 and ISO 3354 nevertheless recognize that the current-meters were until now the only method applicable, and attempt to provide recommendations for appropriate remedial measures. For example, flow straightening devices and special measuring techniques are recommended in IEC 600041 to deal with uneven and/or unstable velocity distributions and oblique flow to the current-meters.

3. One time measurements with acoustic scintillation on stationary frames

The acoustic scintillation method utilizes the natural turbulence embedded in the flow. In its simplest form, two transmitters are placed at one side of the intake, and two receivers at the other (Fig. 3).

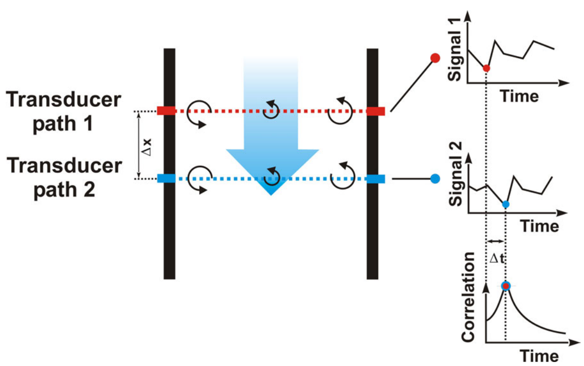

Fig. 3 – Acoustic scintillation: representation of operation

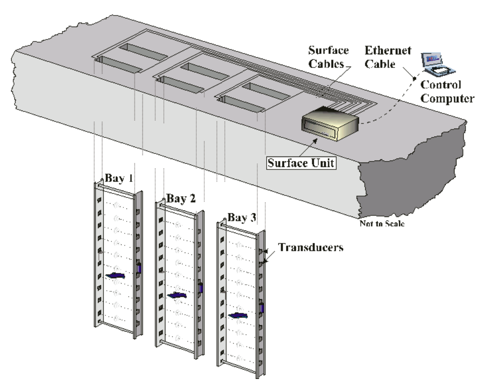

Fig. 4 – Acoustic scintillation: typical installation

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 at the downstream receiver will be nearly identical to that at the upstream receiver, except for a time delay (Δt). This time delay corresponds to the position of the peak in the cross-correlation function calculated for the two signals. 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 flow is then calculated by integrating the horizontal component of the average velocity at several pre-selected levels over the total cross-sectional area of the intake. Fig. 4 shows the arrangement for installation in a 3-bay intake.

Acoustic transducers are mounted on the opposite sides of a frame, which is then lowered into the existing intake stoplog or gate slot. Thus the acoustic scintillation method can be used in very short intakes and without dewatering for installation and removal. In multiple unit plants, a fully instrumented frame can be moved from intake to intake, saving plant downtime. No instruments are exposed to debris impact, no instruments interfere with the measured flow and there are no moving parts requiring maintenance and frequent calibration, saving further plant downtime.

During the last 10 years, the acoustic scintillation method has been used successfully in more than 30 plants. Several relative and absolute flow measurements with this method were described in (*10 and 11*), performance testing of multiple units in (*12),* comparison of absolute flow measurements with other methods in (*13, 14 and 15),* field deployment methods in (*16*), advances in measurement bias resolution in (*17).*

4. One time measurements with current-meters/acoustic scintillation on moving frames

In plants where the geometry of the intake is favourable, or where the water conduit is simply too short or practically nonexistent, the use of current-meters, installed on a mobile frame at the unit intake, has often been used with success (for example at La Grande 1 and Laforge plants). In this type of application the frame can be light weight, composed of one or two current-meter support rods and can travel the full height of the intake entrance. Similarly, the acoustic scintillation method has also been used in this way, either on its own or in combination with current-meters (Fig. 5).

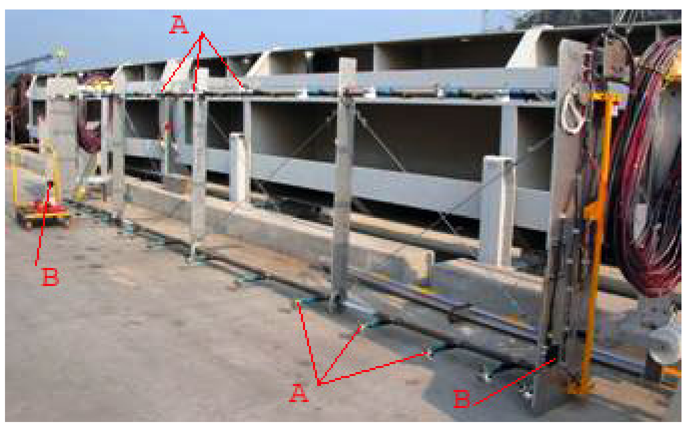

Fig. 5 – Current-meters (A) and acoustic scintillation transducers (B) on moving frame (courtesy HQ)

Traditionally, the frame would be stopped at each measurement level for the duration of the measurement (*18*). However, technical personnel at Hydro Québec found that by using very slow (much slower than the flow velocity) and constant travel speeds, the frame can continuously sweep the total vertical dimension of the intake while a continuous velocity measurement is done with each current-meter. In this way a number of vertically averaged velocities are obtained, multiplied by the height of the intake and integrated over the horizontal dimension of the intake to obtain flow. Having compared the results from approximately 15 measurements with a stopping frame with 15 measurements with continuously moving frame, Hydro Québec found that using a continuously moving frame reduces the time required for performing the measurements while producing results that appear to be comparable or better than when stopping the frame at different elevations (*19 and 20*).

Each moving frame can also be equipped with a mechanism that continuously changes the horizontal angle of the current-meters as they travel along the vertical dimension of the intake. In this way the current-meters are kept better aligned with the expected fluid streamlines to improve measurement accuracy.

For the acoustic scintillation, the frame is placed at successive vertical positions where a measurement of the average horizontal velocity is done. These are subsequently integrated over the cross-sectional area to produce flow. Where the acoustic scintillation transducers are mounted on the same frame as the current-meters, slow travel speeds can be maintained and continuous measurements taken just like for the current-meters alone.

The main advantage of making flow measurements with frames at the unit intake is that the unit downtime is greatly reduced, generally to that required for connecting the power measurement instruments. In addition, in the event of equipment malfunction, the frames can simply be pulled out of the water and corrective measures taken. The measurements proper can generally be done over a one or two day period. One disadvantage is that it requires a rather complex set of lifting mechanisms and frames particularly in plants where there are two or three large individual bays per unit. On the other hand, the portability of fully instrumented frames between individual intakes of plants with multiple intakes will save considerable time. The design of the trash racks and their supports can also negatively affect measurement accuracy in some installations.

The main advantage of combining current-meters with acoustic scintillation on a single frame is that comparative measurements can be obtained this way at a very small incremental cost. This will be particularly important during the early applications of these techniques in short intakes. Technical personnel at Hydro Québec have pioneered this combined method at 7 selected plants (*14 and 15*).

5. Continuous monitoring with acoustic time-of flight

The acoustic time-of-flight method is well-known for its successful penstock applications at medium and higher head hydroelectric plants. It is based on the principle that the fluid velocity alters ultrasonic pulse transit times: transit times of pulses propagated downstream are reduced, while the transit times of pulses propagated upstream are increased. A typical arrangement of the acoustic paths is shown in Fig 6.

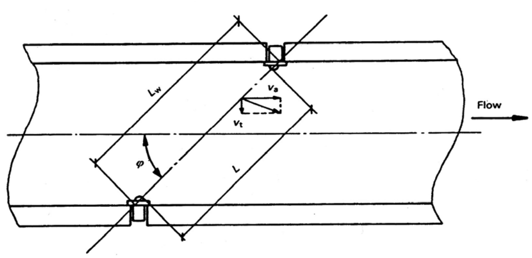

Fig. 6 – Acoustic time-of flight: diagram to illustrate principle (from IEC 600041)

The average flow velocities measured at several pre-selected elevations are integrated over the cross-sectional area of the conduit to obtain the total flow.

Advantages offered by the characteristics and positioning of the acoustic time-of-flight sensors include virtually no interference with the flow (no head loss), no exposure to debris impact and no re-calibration requirements. This permits the acoustic time-of-flight method to be used not only for one-time flow measurements, but also for a long-time monitoring of the flow. The fact that the transducers are located at 45 to 65 or 75 degrees upstream and downstream of each other means that the measurement section is longer than for the current-meters and acoustic scintillation which both measure perpendicularly to the intake axis. This may present a problem at low-head plants where the intakes do not have much length with uniform cross-section.

Multiple cross-paths configurations have been used effectively for accurate flow measurements in a number of intakes of low-head units with reasonably uniform cross-sections *(21*). In short converging sections typical of low-head plants the accuracy has yet to be established (*22)*. The results of a comparative flow measurement (acoustic time-of-flight and acoustic scintillation) are described in (*23 and 24)*.

6. Continuous monitoring with acoustic scintillation

In addition to the frame based applications described earlier, the acoustic scintillation method has also been successfully used for continuous on-line unit monitoring. The transmitting and receiving transducers are mounted on the opposite walls of the intake (Fig. 7), similar to the acoustic time-of-flight installations.

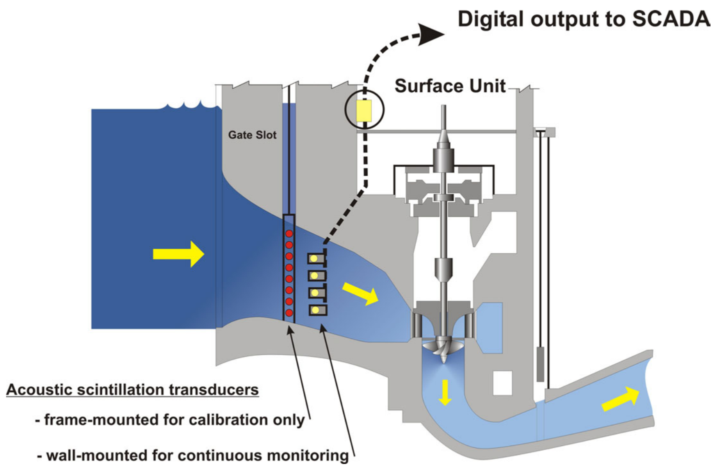

Fig. 7 – Acoustic scintillation monitor – schematic arrangement

The only difference is that the measurement paths are oriented at 90 degrees to the longitudinal axis of the intake, rather than angled at 45 to 75 degrees as for the acoustic time-of-flight method. This represents a significant advantage in the very short intakes so often accompanying Kaplan and bulb turbine installations. Once calibrated with current-meters or acoustic scintillation, this method provides accurate and repeatable flow monitoring with as few as 3 to 5 pairs of transducers.

Two applications of the acoustic scintillation method for continuous monitoring of hydroelectric units are described in (*25 and 26)*.

7. Summary

The difficult, non-uniform hydraulic conditions typical in the irregular, rapidly converging intakes of low-head plants are problematic for the use of the traditional flow measurement methods, since these methods were developed for the use in well-conditioned flow regimes. Despite the difficulty of measurement, owners need to know the unit performance characteristics. The knowledge of flow is required not only for optimal dispatch but also increasingly, for operation within environmental and regulatory constraints. The benefits from operation within environmental and regulatory constraints can be significant (penalties for non-compliance can even include jail in severe cases), but are difficult to express in monetary terms. Improved operational efficiencies are easier to calculate, and can also be rather significant: one or two percent efficiency gains have been reported as resulting from field measurements (*10 and 11*). As an example, a one percent efficiency improvement for a plant which produces 50MW is worth about $200,000 extra from the same amount of water each year.

The flow measurement choices for short intake plant owners are limited:

- Using relative methods such as Winter Kennedy taps which will provide the MW output at which peak efficiency occurs but will not establish the magnitude of the efficiency. For plants with multiple units, the magnitudes of the unit efficiencies are needed for optimal dispatch.
- Using civil structures such as weirs that may be available near the plant. Experience shows that the uncertainty of the measurement through these devices is usually unacceptably high.
- Relying on information supplied by a turbine manufacturer. Even if the information is reasonably correct to start with, it will become increasingly incorrect during the life of the plant. The efficiencies of individual units will not decrease uniformly among the units.
- Testing with methods that are not yet code accepted, but which nevertheless provide useful data.

Given the increasing needs for maximizing power plant output and for efficient use of water resources, the search for better – accurate, repeatable and cost-effective - absolute flow measurement methods suitable for the short intakes of low-head plants will continue. The ASME PTC-18, and more recently the IEC 600041 code committees are actively encouraging further development and verification of flow measurement methods at low-head plants. It should be noted that a major stumbling block for having a new flow measurement method adopted in a code has always been the absence of sufficient field application results, in particular the scarcity of supportive comparative test results. Hence there is the need for further comparative testing.

In addition to the comparative tests referenced in this paper, there are several more large scale comparison tests being planned. In the fall of 2007 the acoustic scintillation method will be tested along with the frame mounted current-meter method at F.D.Roosevelt plant on the St. Lawrence River. For the fall of 2008, planning is well under way for a test of all three methods covered in this paper at B.C. Hydro's Kootenay Canal plant on the Kootenay River. This test will be a definite contribution to the process of code acceptance for the current-meter, acoustic time-of-flight and acoustic scintillation methods in short intakes, because it will compare measurements made with these three methods in a short intake with measurements made slightly downstream with a code-approved method and under code-approved conditions.

One relatively recent step in the process of continuous improvement of the flow measurement methods covered in this paper is the introduction of computational fluid dynamics (CFD) modelling. CFD can model difficult flow conditions prevalent in short intakes as an alternative to physical modelling. The combination of CFD modelling and field velocity and turbulence measurements can lead to better understanding of the fluid mechanics in short intakes. This knowledge can form the basis for locating current-meters or acoustic transducers to minimize errors and for estimation of measurement errors (*15, 27, 28 and 29*).

Flow measurement in hydroelectric plants requires specialized knowledge. Organizations which have this knowledge are turbine suppliers, hydroelectric consultants and large utilities. The operations and maintenance staff in small utilities may not know the options available nor even who to turn to for advice. For these small utilities, cost of obtaining performance data can be particularly prohibitive.

The test codes are meant to provide a standard for measurements but they tend to be written for people who are already familiar with the methodology. This paper is intended to provide options available as of 2007 to owners of low-head plants with short intakes. Cost, downtime and expected accuracy will always come into consideration. Table 1 puts into perspective some of the advantages/disadvantages of each method and may thus be helpful in reaching a decision.

	Current-meters on stationary supports	**Acoustic scintillation on stationary frames**	**Current-meters/acoustic scintillation on moving frames**	**Acoustic time-of-flight on intake walls**	**Acoustic scintillation on intake walls**
Require intake dewatering/rewatering	**yes**	**no**	**no/no**	**yes**	**yes**
Flow obstruction/debris impact vulnerability	**yes**	**no**	**yes/no**	**no**	**no**

Portable between intakes	**no**	**yes**	**yes/yes**	**no**	**no**
Suitable for continuous monitoring	**no**	**limited**	**no/no**	**yes**	**yes**
Suitable for very short intakes	**yes**	**yes**	**yes**	**limited**	**yes**
Mechanical maintenance required	**yes**	**no**	**yes/no**	**no**	**no**
Code approved for short intakes	**not yet**	**not yet**	**not yet**	**not yet**	**not yet**
Downtime	**very high**	**low**	**very low**	**very high**	**very high**
Relative cost	**high**	**medium**	**low**	**high**	**high**

Table 1: Simplified comparison of flow measurement methods for short intakes

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Authors:

Josef Lampa, Dipl. Ing., P. Eng., F.I.C.E., graduated in Hydrotechnical Engineering from the Czech Technical University, Prague, in 1961. He has worked on hydro projects all over the world, and has been hydroelectric consultant to AQFlow since his retirement from B.C. Hydro, Vancouver

David Lemon, M.Sc., graduated in Oceanography from the University of British Columbia, Vancouver, in 1975. He is President of ASL AQFlow Inc., Victoria, B.C., with responsibility for internal research and development. He has been responsible for the development of the acoustic scintillation method

Pierre Lamy, B. Eng., Ing., graduated from Sir George Williams University, Montreal, in 1972. He has over 25 years experience in the field testing of hydraulic turbines at Hydro-Québec, Montreal

John Taylor, M.A.Sc., P. Eng., graduated from University of British Columbia in 1973. He has over 25 years experience in hydraulic structures, turbine testing and hydro operations at B.C. Hydro, Vancouver