Session five - Acoustic
6th International Conference on Innovation in Hydraulic Efficiency Measurements, July 30 – August 1 2006, Portland, Oregon, USA

Comparing Integration Uncertainty of an 8 and 18-Path Flowmeter at Grand Coulee Dam

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Abstract

When 8-path acoustic flowmeter systems (4 chordal paths in 2 planes) are installed in a long straight section of a penstock, the velocity distribution typically approaches a 1/n exponential or logarithmic shape. The Gauss-Chebychev integration technique, using 8 acoustic paths, can integrate these velocity profiles very accurately (on the order of 0.1%). Under the conditions prevalent downstream of a vertical bend, the momentum of the flow alters the velocity distribution so that it may not resemble an exponential or logarithmic shape. The uncertainty of the 8-path technique is greater when these distorted velocity distributions are integrated. Recently, an 18-acoustic path flowmeter was installed at the Grand Coulee Right Power House on unit G-17 for turbine acceptance testing. Field tests were performed to obtain the turbine efficiency of the unit using the 18-path flowmeter. The acoustic flowmeter is located one diameter downstream of a 21 degree reducing bend.

The data obtained showed evidence of secondary flow components indicative of velocity distributions downstream of an elbow. The 18-path data was used to estimate the total uncertainty of the 8-path flow measurement. These results suggest that more acoustic paths are required to integrate a distorted velocity distribution to achieve a higher degree of accuracy than can be achieved with a standard 8-path acoustic flowmeter. In addition, the data obtained during the 18-path testing at Grand Coulee was compared to data obtained during 18-path testing at the Robert Moses Power Plant. The 18-path acoustic flowmeter installed at the Robert Moses Power Plant was located 2 pipe diameters downstream of a 48 degree vertical elbow. Comparisons on the elbows' bend angle and their influence on the velocity distributions will be made in this paper.

Back Ground

A contract was awarded to rehabilitate the 18 turbines in the Left and Right Powerhouses at Grand Coulee Dam in Washington State. The rehabilitation includes a model tested hydraulic design, runners, wicket gates and stay vane modifications. The contract included efficiency guarantees for which penalties would be assessed if turbine efficiency measured in accordance with ASME's

PTC-18 Performance Test Code, Hydraulic Turbines and Pump-Turbines, with contractual exceptions listed, were not achieved.

Turbine efficiency testing uncertainties are, of course, dependant on the quality of the measurements of the important parameters. Any discussions concerning turbine testing between the purchaser and supplier of new or replacement turbine runners usually begin with the method of flow measurement.

The penstocks of the Grand Coulee turbines have a convenient location for the flowmeter transducers in an expansion joint alcove immediately upstream of the entrance to the spiral case. This location is one diameter downstream of an 18 to 15 foot, 21-degree reducing bend which does not meet the requirements of PTC-18 for the location of a flow measurement section. For this reason, it was decided to use an 18 path acoustic flow meter on one of the eighteen penstocks to better asses the velocity profile and the quality of flow measurement for each of the similar 17 penstocks. This is essentially calibrating 8 path flowmeters with the lower uncertainty 18 path flowmeter. The 18-path flowmeter measurements would be better than the contractually stipulated 8-path method.

Accusonic Technologies was hired to install 20 additional acoustic flow measurement transducers along with the 16 transducers previously installed in two crossing planes, take as-built measurements and operate the flowmeter consoles during the calibration process.

Upgrade of Existing 8-Path Acoustic Flowmeter

The installation of the standard 8-path flowmeter for G-17 was performed in December of 2004. The acoustic flowmeter is located one diameter downstream of a 21 degree reducing bend. The close proximity to the reducing bend introduced additional uncertainty to the flow measurement. In an effort to reduce this additional uncertainty, the existing 8-path flowmeter was upgraded to an 18-path flowmeter in September 2005. The 10 additional acoustic paths were installed at ± 72°, ± 36°, and 0° as shown below.

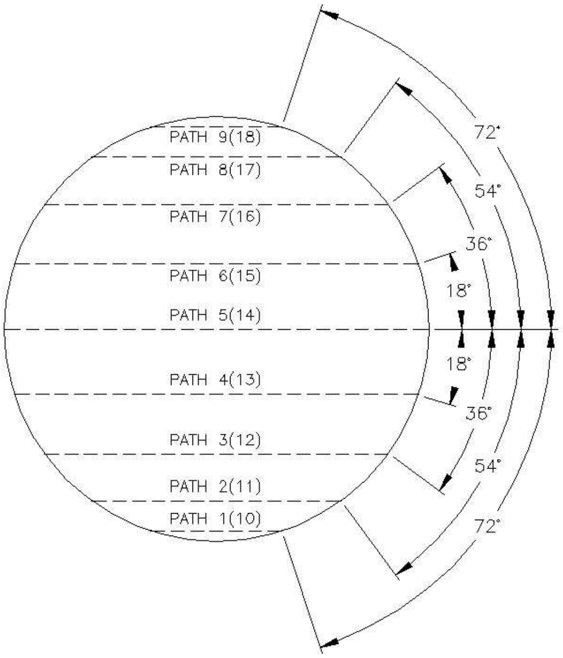

Figure 1 – View looking upstream

The existing 8 acoustic paths were installed at ± 54°, ± 18°. The Chebychev integration technique lends itself to adding additional acoustic paths because the abscissas repeat when dealing with four or more chordal elevations. Since the Chebychev abscissas repeat, the existing acoustic transducers did not need to be moved.

After installing the additional 10 acoustic paths, the ‘as-built’ measurements were taken for all 18 acoustic paths with the penstock dewatered. The path lengths, path angles, and penstock diameter were checked with the measurements taken during the original 8-path installation. These values were all within the tolerance of the physical measurement.

In addition to verifying the ‘as-built’ measurements of the original installation, Accusonic was asked to measure the outside circumference of the penstock at the acoustic flowmeter location. These measurements were taken with the penstock dewatered and watered to see if there was any significant difference. This difference, 0.14 inches larger than the dewatered measurement of 575.61 inches, was within the measurement’s tolerance. This difference in circumference relates to a 0.045 inch difference in the measured diameter of 179.928 inches (+ 0.025%). Since this difference was within tolerance, the dewatered ‘asbuilts’ were determined to be acceptable for use with the performance testing.

Acoustic Flowmeter Test Setup

One Model 7500 flowmeter and two Model 7520's were connected to the acoustic paths to provide a real time flow measurement using all 18 acoustic paths. Prior to the performance test, several quality assurance tests were completed to ensure the system was properly connected and operating. First the 7500 had to be programmed with the 'as-built' measurements taken during the upgrade installation.

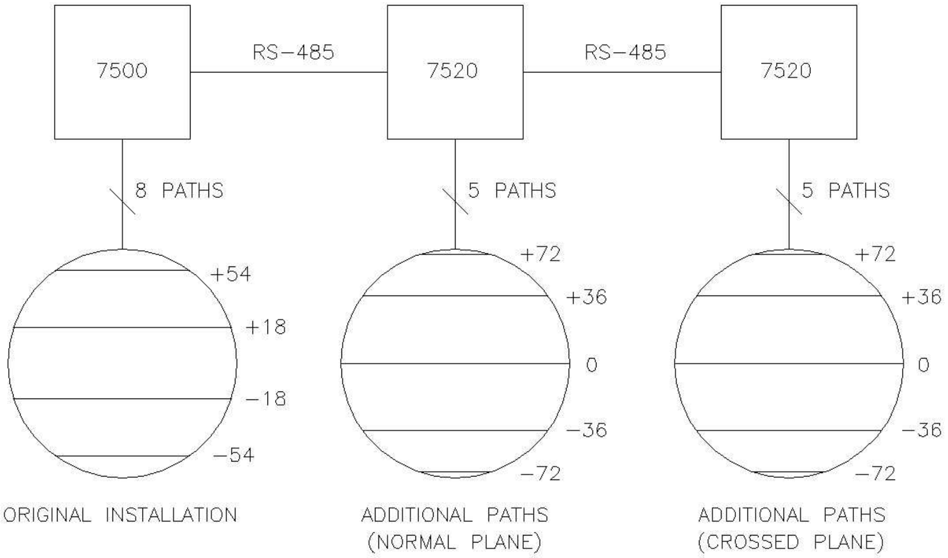

Figure 2 – Block diagram

After the 7500 flowmeter was properly programmed and verified, each acoustic signal was observed using an oscilloscope. All of the acoustic waveforms had amplitudes which would allow the 7500 to properly measure the individual velocities.

The last operational check was to record each path's velocity of sound calculation under static conditions. The velocity of sound on all paths did not differ by more than 0.05% from each other indicating that the path length and travel time measurements are well within tolerance.

After performing all of the operational checks, the system was considered fully operational. The flow records for each performance test run were evaluated to check for path failures. If any path's velocity reading failed during a test run, then the instantaneous discharge record was considered invalid and not used for the turbine discharge calculation.

Data collection

In all, 42 test runs were performed. The average difference between the 8 and 18 acoustic path measured discharge is 0.145%. The highest standard error of the mean found on run 20, is 0.058%. Based on the standard deviation of this and all of the other individual runs, the difference between the 8 and 18 acoustic path measured discharge is statistically significant.

Given the shape of the velocity distribution and the lack of distortion, it is not surprising that there is only a small difference between the 8 and 18 path methods of flow measurement. Shown below in Figure 3, the velocity distribution is graphed as a function of acoustic path position. The velocity distribution contains little evidence of distortion caused by secondary flow. The meter section is close to the elbow, but the angle of the hydraulically smooth elbow is not as severe as other elbows typical in hydro-electric installations. This suggests that distortion and secondary flow components vary with the degree of a bend as well as the distance the meter is installed downstream of an elbow.

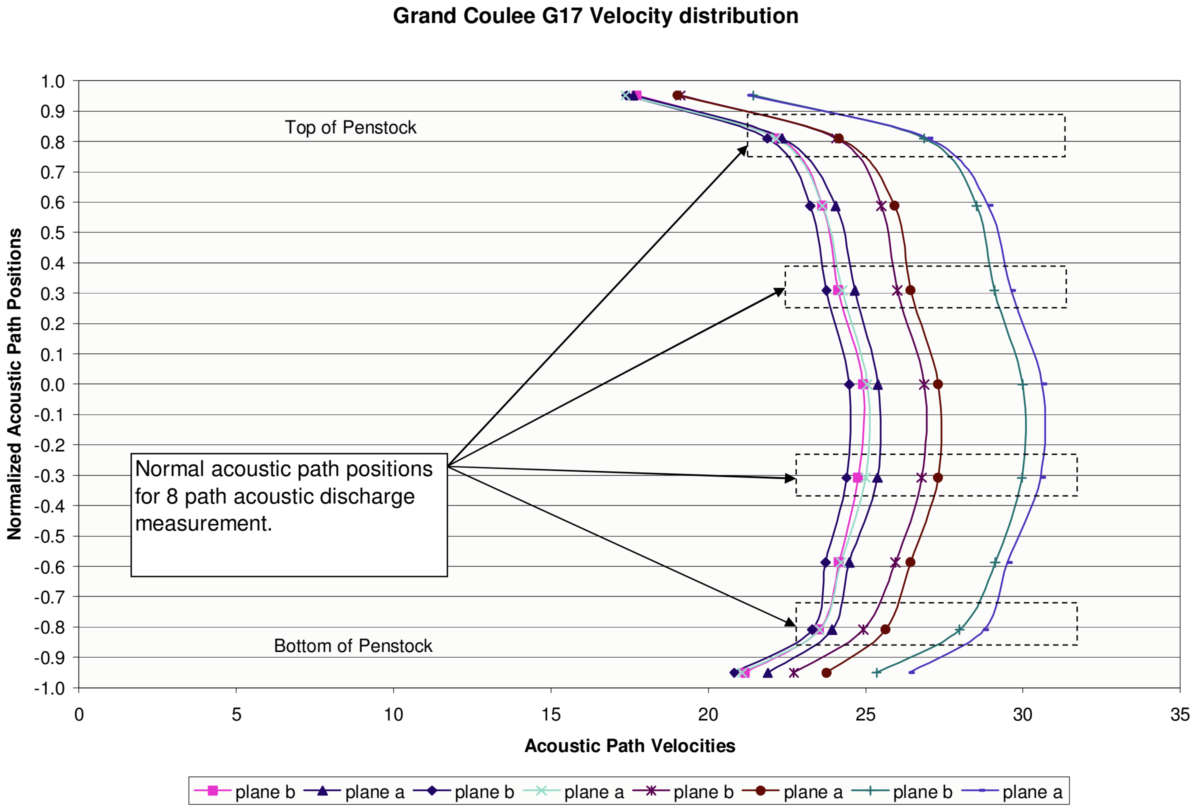

Figure 3 – Typical velocity distributions

In Figure 4, the average difference between the 8 and 18 path discharge measurement (for each individual run) and the average of the differences is plotted as a function of 18-path discharge. No correlation between the discharge value and the difference in the two discharge methods can be drawn. The scatter of the difference shown in Figure 4 is consistent with random errors calculated for the individual test runs.

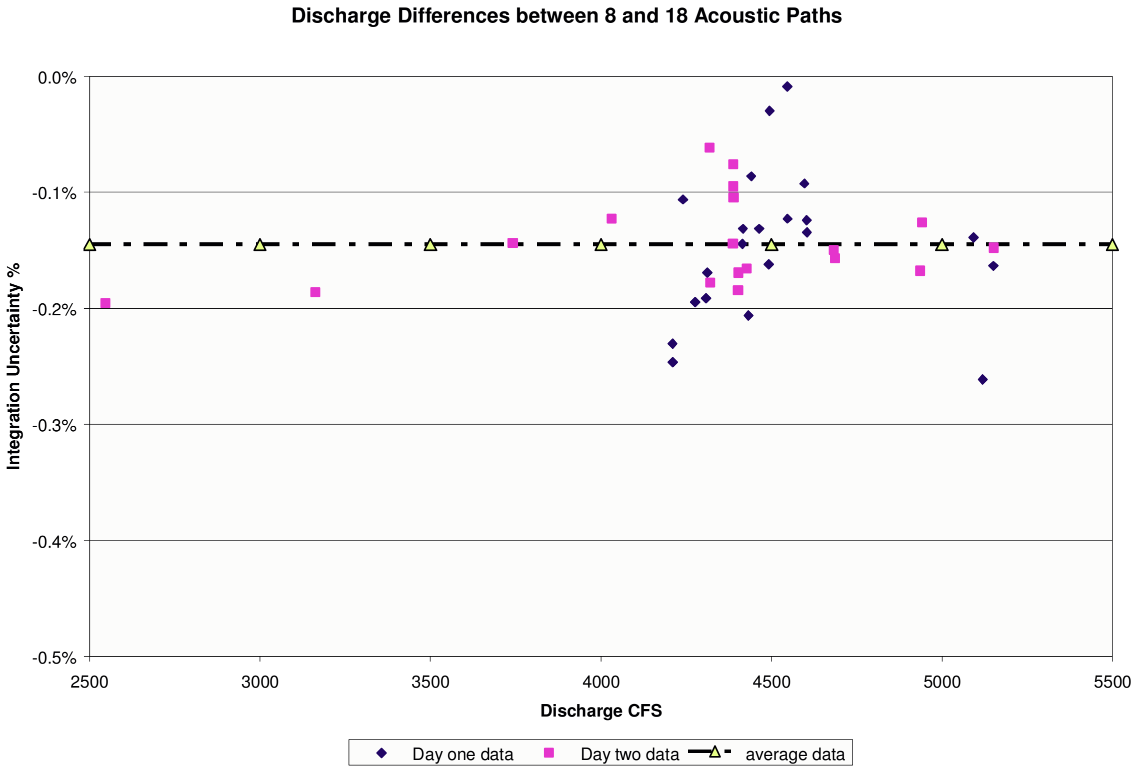

Figure 4 – Discharge differences

Data analysis

The data between the 8 and 18 path derived turbine discharge shows a bias of -0.145%. A small velocity deficit in the velocity profile accounts for this difference. When a detailed error analysis is performed, the main difference between the 8 and 18 path derived discharge is attributed to the integration uncertainty.

The discharge measurement has an uncertainty associated with the measurements taken during the installation of the transducers, the measurement of the acoustic travel times, and also integrating the velocity distribution which is influenced by penstock configurations either side of the meter section.

Error propagation in flowrate measurement is made up of several measured quantities. The three main sources of uncertainty are attributable to:

- Penstock area (Radius) measurement
- Velocity measurement
- Flowrate integration

When a measured quantity is comprised of several independent parameters *e.g.*

$$Q = f(a,b,c,...)$$

The variance of the mean individual measurements can be expressed as:

$$\sigma_{mq}^2 = (\partial Q/\partial a)^2\ \sigma_{ma}^2 + (\partial Q/\partial b)^2\ \sigma_{mb}^2 + (\partial Q/\partial c)^2\ \sigma_{mc}^2 + \ldots \qquad \textit{Equation 1}^1$$

where σ_{mq}^2 is the variance of the mean of Q and σ_{ma}^2 is the variance of the mean of parameter *a* and so forth.

When a set of as-builts of the flowmeter transducer positions are taken carefully, the uncertainties are small, particularly in a large diameter penstock. The uncertainty due to the as-built measurements can be calculated as shown below.

$$Q_{asbuilt} = \sqrt{}\ ((\text{Length } 8)^2+(\text{Angle } 8)^2) - ((\text{Length } 18)^2+(\text{Angle } 18)^2)$$

Where:

Length 8 -	the uncertainty in 8 path velocity measurement due to path length measurement
Angle 8 -	the uncertainty in 8 path velocity measurement due to path angle measurement
Length 18 -	the uncertainty in 18 path velocity measurement due to path length measurement
Angle 18 -	the uncertainty in 18 path velocity measurement due to path angle measurement

Or for Grand Coulee

$$=\sqrt{}\ ((0.002)^2+(0.003)^2) - ((0.0004)^2+(0.0003)^2)$$
$$=0.0036\%$$

The difference between the 8 path and 18 path flow rate measurements was found to be 0.145% on average. The difference between the readings taken with 8 paths versus 18 paths is due to integration and can be calculated by removing the uncertainty based on the as-built measurements. The remaining difference becomes the integration uncertainty or

$$Q_{int} =\sqrt{}\ (0.145)^2 - (0.00360)^2 \quad \text{or} \quad 0.1449\%\ .$$

Conclusions

It has been shown that the major difference between 8 and 18 path configurations is mainly due to integration uncertainties. In other papers presented previously[2], the difference between the two discharge measurement configurations was greater when the meter section was placed two diameters downstream of a hydraulically smooth 48º elbow. At Grand Coulee, the reducing elbow angle is 21º and the perturbations in the velocity distribution is insignificant.. This suggests that acoustic transit time flowmeters are influenced

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[1] Hugh D. Young, *Statistical Treatment of Experimental Data* (McGraw-Hill book Company NY) © 1962 pp 96-101.

[2] Walsh et.al *Performance of an 18 Path Acoustic Flowmeter at Robert Moses Niagara Power Plant Unit 13,* IGHEM -96 Montreal Canada

not only by the distance the meter section is installed downstream of an elbow, but the actual angle of the elbow as well. Based on the information previously presented; the head loss coefficient, which is both a function of elbow degree and ratio of the radius of the bend to the diameter, has a significant effect on the integration uncertainty of acoustic transit time flow meters.