Index Test Comparisons
Using Ultrasonic Flowmeters
at
Wells Hydroelectric Project

by
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Abstract

The Wells Hydroelectric Project is owned and operated by Douglas County Public Utilities District (Douglas PUD) and is located on the Columbia River in Chelan, Washington, USA. In August 1997, Unit 3 at Wells was fitted with acoustic paths in each of the three intake bays in order to determine turbine discharge. In Bays A (west) and C (east) the standard 8-path array of Accusonic model 7618 transducers were installed. Each array consisted of two intersecting planes of horizontal acoustic paths mounted at four elevations. In the center bay, 18 acoustic paths were installed because of the relatively short intake and because the elevation of the turbine is offset from the vertical centerline of the intake. The additional acoustic paths in Bay B are used to correct the turbine discharge by comparing the 8- and 18-path calculated flowrate. In Bays B and C the nominal angle of the acoustic path with respect to the vault walls is 68 degrees. In Bay A, the shorter intake necessitated a steeper angle of 78 degrees.

In October 1997, a series of index tests were run by Sulzer to obtain the relative efficiency of the installed turbine compared to the model and the Optimum wicket gate blade angle relationship. Jointly with those tests, Accusonic conducted flow measurements. During the 1997 tests, some of the acoustic paths were not working. In April 1998, Accusonic returned to repair the defective transducers. Douglas PUD decided to retest the unit in 1999.

Background

In April, 1999, the team of Douglas PUD, Accusonic, Sulzer, and DE&S conducted a series of performance tests on Unit 3 at the Wells Hydroelectric Project. These tests included: absolute flow measurement, off-cam index tests, low load “rough zone” vibration measurements, and reprogramming/testing the digital governor with an optimized 3-D cam.

During the week of April 19, 1999 the flow/index test engineering team arrived at the Wells

Hydroelectric Project. On Monday a meeting was held to review the objectives and methodology for all of the tests planned for the upcoming week. On Tuesday the team began the combined tests of directly measuring flow, power output, and net head to develop absolute efficiency, while simultaneously indexing Winter-Kennedy spiral case differential pressure as a function of flow. These measurements were made against the background of a classical Kaplan index test, consisting of holding a series of blade positions while varying wicket gate openings, in this case with positions set and recorded digitally through a laptop computer connected into the local governor panel. A total of 26 off-cam points were measured over a 10-hour period to develop smooth propeller curves at blade openings of 10, 40, 60, and 80 percent. Each point was held for a minimum of 12 minutes, with readings beginning 2 minutes after each load change, and data recorded and averaged over 10 minutes. Accusonic measured flow across the 3 intake bays for this unit using 34 sonic velocity paths (8-18-8), recorded the data continuously, integrated the data over each 10-minute test period, and shared the preliminary flow values with the team after each off-cam point. During the same test point periods, Sulzer recorded generator output, headwater, tailwater, net head, index differential pressure, along with blade and wicket gate position. Sulzer also estimated turbine output based on the generator manufacturer's electrical losses curve, and estimated relative flow based on its Adaptive Cam Curve (ACC) technology. The resulting absolute and indexed efficiency points were plotted against power to develop propeller curves and then those peaks were connected to develop an optimized on-cam efficiency curve. A preliminary analysis of the data indicated that the flow measurements taken by Accusonic were consistent, repeatable, and when reduced and plotted represent absolute efficiencies which appear reasonable in shape and magnitude, although slightly lower, when compared to the turbine manufacturer's performance guarantee. Preliminary analysis of the index test data taken by Sulzer also indicated values which were consistent and repeatable, and relative efficiencies which also appear reasonable in shape and in magnitude, and which lie between the values of Accusonic and the turbine manufacturer.

A new optimized cam curve in Unit 3 based on the index test results from earlier in the week was developed. Sulzer reviewed the new index data against a previous index test on Unit 3 that had been conducted in October 1997. The new index results showed almost identical correlation with the previous results, both of which indicated a slight departure and potential improvement from the hydraulic model cam curve developed for the Fuji replacement runner. Based on our previous index test of Unit 3, and confirmed by the new index test, Sulzer developed optimized cam curves and coordinates, consisting of 10 wicket gate positions at 5 net heads. With Douglas PUD approval, on April 22, 1999 the Unit 3 digital governor was reprogrammed with the new optimized efficiency cam curve data.

The Accusonic model 7500 system calculates flowrate by measuring velocity at each elevation in all intakes then numerically integrating each path by using weighting factors that correspond to acoustic path spacing. The weighting factors and spacing for the 8-path system are found in Table 4.119 under ASME Power Test Code PTC 18-1992. The Gauss-Legendre Method of integration was used since it is exact for rectangular cross sections. The 18-path system used the same numerical integration technique with more paths and elevations. The path spacing and weights can be found in several handbooks[1]. The spacing and weights used are found in Table 1.

1 Pg. 916, *Handbook of Mathematical Functions*, National Bureau of Standards, Applied Math Series, December 1995.

TABLE 1

Path		Elevation (Above and Below Centerline of Vault)	Weight (Bay A&C) 8 path	Weight 18 path
8	18			
	1,10	-0.968		0.081
1,5	2,11	-0.836	0.348	0.181
	3,12	-0.613		0.261
2,6	4,13	-0.324	0.652	0.312
	5,14	0.0 (Centerline of Vault)		0.330
3,7	6,15	+0.324	0.652	0.312
	7,16	+0.613		0.261
4,8	8,17	+0.836	0.348	0.181
	9,18	+0.968		0.081

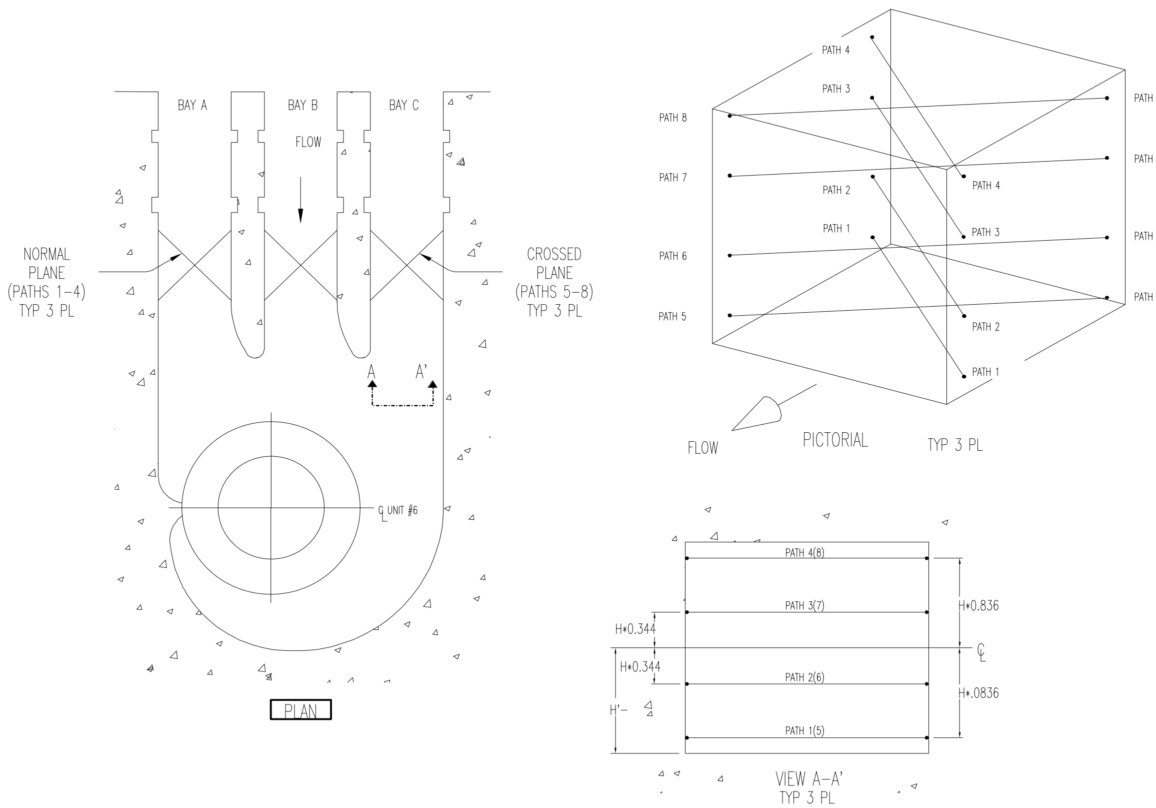


Figure 1 – General arrangement of acoustic paths

Each acoustic path velocity is multiplied by the weight, and the width of the intake, then summed and multiplied by half the intake height. A general arrangement of path placement is found in Figure 1.

Results of 1999 Testing

In April 1999, the test team repeated previous testing with some minor modifications. The main modification was to lengthen the test interval. Inherent to any acoustic flowmeter is the random component of the measured flow data, particularly in short intakes. During the 1997 tests, a two-minute interval was used for testing. After a review of the flow data in 1997, longer test intervals were used in 1998 in order to obtain higher confidence intervals. Based on the 1998 tests, a 10-minute test interval was suggested. The standard error of the mean could be reduced by 1 percent by going to a 10-minute test interval. In 1999, a 10-minute interval was chosen for discharge measurement.

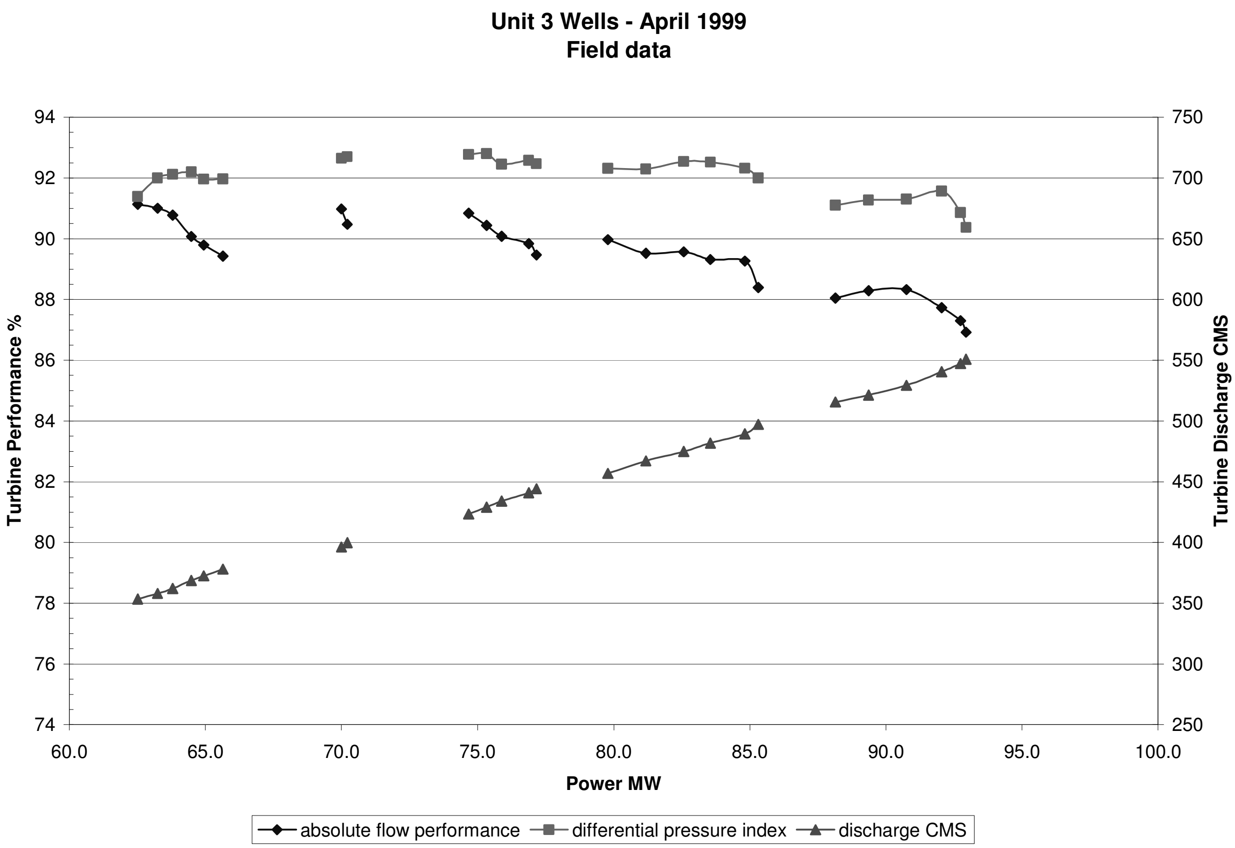


Figure 2 uncorrected field data

In 1999, the same data acquisition system was used that interfaced to the model 7500 flowmeter using RS-232. The data acquisition system obtains the flowrate data from each of the flow transmitters and averages the data over a time-stamped interval. At the conclusion of each interval, the average and standard deviation of the data were written to a hard disk drive.

Presented in Figure 2 is the turbine performance results using differential pressure and acoustic flowrate measurement from the April 1999 tests. The results are similar to the shape of the model performance curve. The field results are based on the 18-path calculated flowrate in Bay B and a correction factor of –4 percent in Bays A and C. This correction factor was based on the 1998 testing after all of the acoustic paths were properly functioning. Each test point was based on 5 sets of 2-minute runs for a total time of 10 minutes. Before each point, the blade angle was changed and the turbine was allowed to hydraulically stabilize for 2 to 4 minutes.

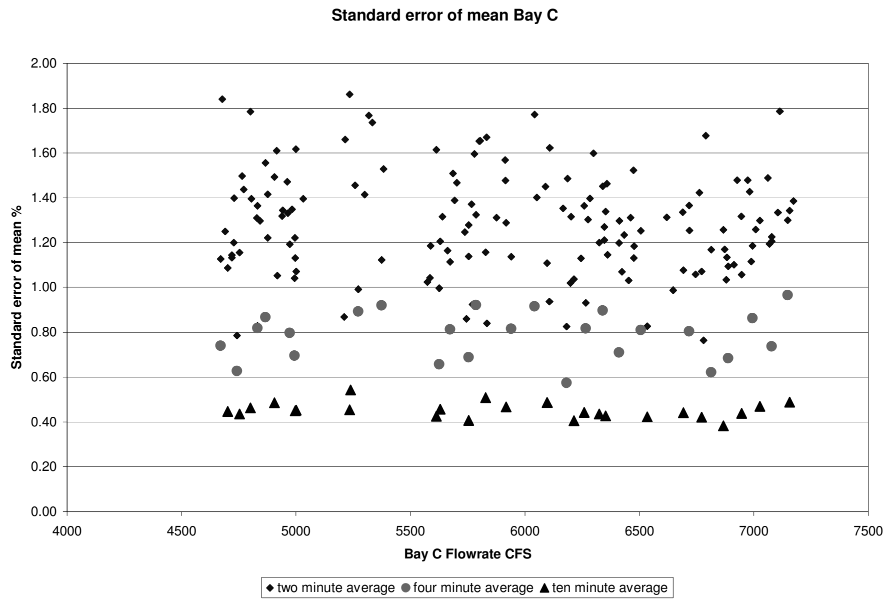


Figure 3 standard error of the mean using different test intervals

In Figure 3, the standard error of the mean of the calculated flow in Bay C is plotted as a function of Bay flowrate. The data acquisition system calculates the standard deviation of each bay flowrate over the test interval. Using the data, standard error of the mean was recalculated for each test run using a 4- and 10-minute interval. Clearly, the 10-minute data points illustrate the need for 10-minute test intervals. The standard error of the mean of the turbine discharge is less due to the additional acoustic paths in the other bays. The standard error of the mean for turbine discharge can be approximated by √ (paths in Bay C) / √(total paths) or ½. A more detailed analysis of this effect is beyond the scope of this paper. The effect is an overall reduction of the standard error to 0.2 percent which is what a flow signal based on differential pressure produces. The figure clearly shows that less dispersion is obtained using a ten-minute test interval. It has been shown in the past that the acoustic flowmeter variability is normally distributed[2.] This is also supported by the Central Limit Theorem[3] The Central Limit Theorem states that "any number of individual random components (acoustic path velocities) will tend to be normally distributed irrespective of their underlying distributions".

Flow Distributions

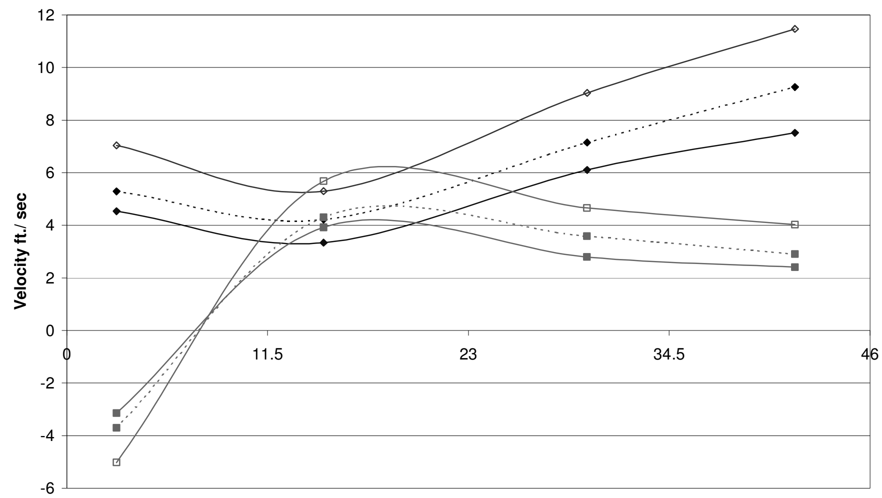
In Figures 4 through 6 the velocity distributions are plotted as a function of the acoustic path elevation. In all three graphs, the normal plane and crossed plane are plotted at high, medium, and low loads. The normal plane of transducers in each vault is formed with the upstream

[2] Unpublished Accusonic analysis of flowmeter variability, 1991 and 1995.

[3] Ang, A. H, Tang Wilson, *Probability Concepts in Engineering Planning and Design*, John Wiley and Sons, New York, 1975. Pp 189-190.

transducers mounted on the west wall. Since the acoustic path angles are the same, the average

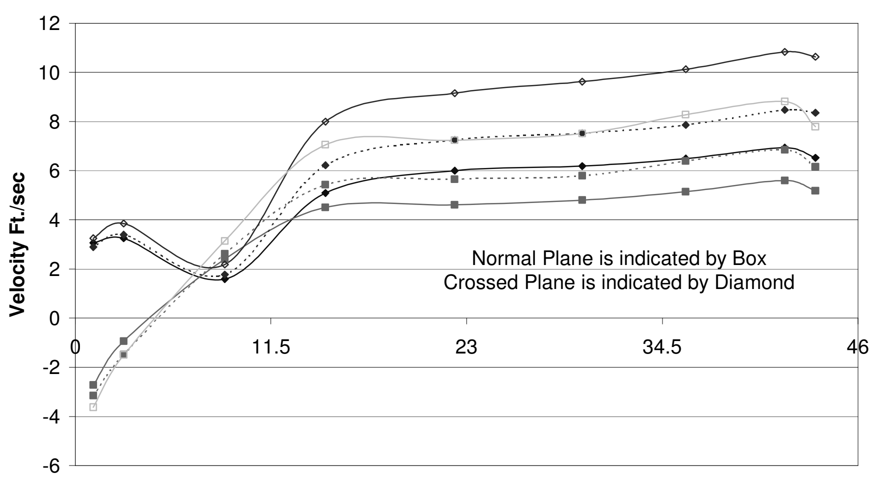
Figure 4
Wells Unit 3 - 1999 Bay A



of the two intersecting acoustic paths is the downstream component of velocity. It is not surprising that the velocity pattern shows little flow at the bottom of the vault, given the turbine position, high in the intake.

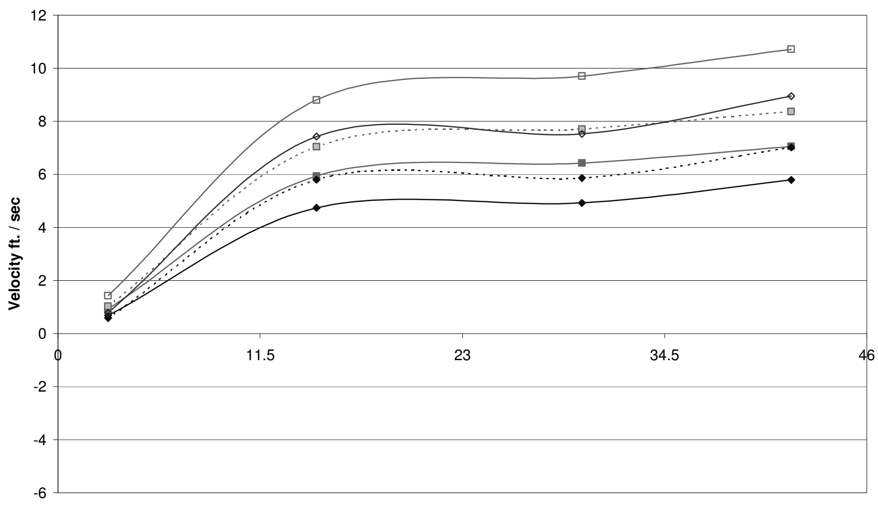
The divergence of the lower acoustic paths in Bays A and B is mainly due to crossflow. With the benefit of hindsight, the lower acoustic paths on the normal planes in Bays A and B are negative. This would be reasonable since the angle of the flow in the lower sections is more nearly parallel to the concrete apron which houses the draft tube liner. With such an extreme

Figure 5
Wells Unit 3 - 1999 Bay B



angle of velocity, the apparent velocity on path1 is negative. When the velocities are averaged with the crossed path velocities, a small positive downstream component of velocity occurs.

Figure 6
Wells Unit 3 - 1999 Bay C

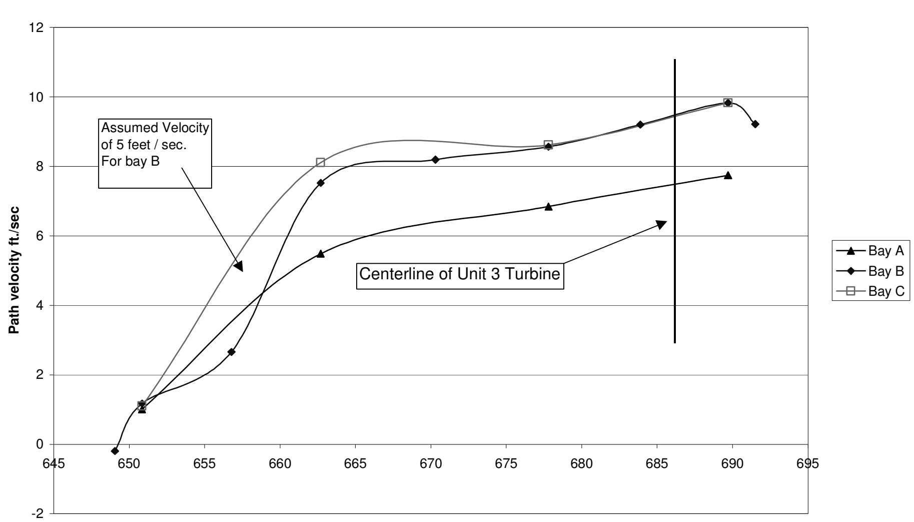


In Figure 7, the average of the planes is plotted at the highest turbine output (run 76). In each bay, the velocity distribution looks similar. The main difference between the 8-path derived flowrate and the 18-path flowrate is the velocity deficit at elevation 657. The difference between the 18 and 8 path derived flowrate ranged from 4 to 5%.

We can assess the effect this velocity deficit has on the 8-path flow by calculating a *hypothetical* flow in Bay B assuming there was **no** velocity deficit. Then we can calculate the difference in 18-path derived flow with and without the deficit.

Assuming there was no velocity deficit, we can calculate a flowrate using a hypothetical velocity

Figure 7
Wells Unit 3 distribution



of 5 feet per second for this path at elevation 657.

Five feet per second was chosen since this value lies on the spline curve between the acoustic paths at elevation 662 and 650. The difference in flow is:

$Q_{hypothetical} = (V_{hypothetical} - V_{actual})$ * weight * width * vault height

or

(5 – 2.65) * 0.261 * 22.5 * 44.58 /2

or

307 CFS

For run 76, the flow in Bay B (based on the 18-path flowmeter) is 6,776 CFS. Three hundred and seven cubic feet per second is 4.5 percent of the flow for that run, which accounts for the majority of the difference between the 18 and 8 path methods.

Uncertainty Analysis

It is extremely difficult to evaluate the accuracy of any absolute flowrate measurement. In an ultrasonic system, several papers[4] have dealt with this issue. Generally, the most unknown uncertainty issue is integration. Calculating the uncertainty in the velocity measurement is straightforward. The velocity depends on the acoustic path length, the angle the acoustic path makes with flow, and acoustic path travel time. The integration uncertainty can be bounded using the same sensitivity analysis performed above.

Integration Uncertainty – 18-Path

In performing the same hypothetical analysis as above, consider an acoustic measurement system with paths placed at 20 elevations (40 acoustic paths) in the same intake structure. In the cited references, the weights and abscissas are listed for $n = 20$. The location at the center of the vault has the highest weighting ($x_i = 0.07$; $w_i = 0.152$).

Consider a perturbation in the velocity pattern not seen by the 18-path meter that is seen by acoustic path placed at 40 path elevations. Again, referring to Figure 8, the worst-case velocity deficit (or surplus) can be ½ ft/sec departure from the 18-path spline fit. Assuming this perturbation occurs at the center of the vault, which has the greatest weighting, the additional flow is:

Velocity * weight * width * vault height

0.5 * 0.152 * 22.5 * 44.58 /2

or

38 CFS or one half percent of the flow in Bay B (run 76).

The difference between the discharge measured using the 8-path and 18-path varied between the April 1998 tests (performed independently by Accusonic) and the April 1999 tests. The 1998 tests yielded a difference of 4.3 percent. The 1999 test yielded 5.1 percent. Based on the above analysis, it is reasonable to conclude an 18-path integration uncertainty of +/- ¾ percent for Bay B.

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4 Eseerco Report Project 95-27 Performance Evaluation of an 18-path Acoustic Flowmeter November 1997 Walsh J. T. Ludewig et. Al.

Intake Geometry Uncertainty

The Bay intake area and acoustic path spacing were measured using steel tapes. Uncertainty can be calculated by taking the difference in the measurements. Typically, a ¾-inch uncertainty in 22½ feet is reasonable to expect. Since the vault area is directly proportional to the height and width, the sum of the squares of the uncertainty expressed over the measurement is the area uncertainty. The bay height was taken at several locations in each bay. A 1-inch uncertainty in 44½ feet is reasonable to expect. The total area uncertainty in each bay becomes:

$\sqrt{(\text{width uncertainty})^2 + (\text{height uncertainty})^2}$
width = (¾ / (12*22 ½)) = 0.0027
height = (1 / (12 * 44½)) = 0.0018
$\sqrt{(.0027)^2 + (.0018)^2} \quad * 100$
=0.35%

Velocity Uncertainty

The acoustic path angle is based on several tape measurements made after the transducers were installed in each vault. Axial, lateral, and transducer face to face measurements were made at each elevation corresponding to the acoustic paths in each vault. The law of cosines was used on each of the four triangles to determine the acoustic path angle. The law of cosines was also used to determine the error of closure in each triangle. Using these measurements we took the average uncertainty of 0.1 percent. The lengths have a similar uncertainty of 0.1 percent. This is calculated by taking the uncertainty of the length measurement (¼ inch) as a percent of the path length (24 feet). The timing uncertainty is considered nil.

The total uncertainty in velocity measurement in each bay becomes:

Path angle and length = $1/8 \sqrt{(8 * 0.1\%)^2 + (8 * 0.1\%)^2}$
= 0.16 %

Integration Uncertainty – 8-Path

The 8-path integration uncertainty is significantly reduced by the additional acoustic paths in Bay B. As mentioned above, the bias or correction factor varied from 4.3 to 5 percent in 1998 and 1999, respectively. For each run in 1999, the difference between the 8-path flow and 18-path flow was calculated. The standard deviation of the difference was calculated for the 76 runs in 1999 and was found to be 0.65 percent. Based on the data it is reasonable to assume integration uncertainty based on the 18-path uncertainty plus random component (2 standard deviations). Therefore the 8-path integration uncertainty is 0.75% + 2 * .6% = 1.95 %.
The uncertainty in discharge measurement each bay becomes:

$\sqrt{(\text{acoustic path})^2 + (\text{area})^2 + (\text{integration})^2}$
or
$\sqrt{(0.16)^2 + (0.35)^2 + (1.95)^2}$
or
2%

Conclusion

Ultra-sonic flowmeter measurement systems can be used in multiple bay turbine intakes with slightly asymmetrical and back flow hydraulic conditions as found in the units at the Wells Hydroelectric Project. We believe with the experience gained at the Wells Hydroelectric Project, refinements can be made to the installation and calibration of ultrasonic flowmeters in similar applications. These flow measurements are extremely useful in validating index efficiencies, determining absolute efficiencies, optimizing Kaplan cam curves, tuning governor and load controls systems, and ultimately effecting modest increases in energy production.