Performance of 18 path Acoustic Flowmeters
At
Robert Moses Niagara Power Plant Unit 13
La-Forge Power Plant
Hiawasse Pump Storage Plant

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Abstract

This paper discusses the integration uncertainty of multiple path acoustic flowrate measurement. When 8 path flowmeter systems (4 chordal paths in 2 planes) are installed in a long straight section of penstocks the velocity distribution typically approaches a 1/n exponential or logarithmic shape. The Gauss-Chebyshev integration technique, using 8 acoustic paths, can integrate these profiles very accurately (on the order of 0.1%). Under the conditions prevalent below a bend or downstream of a pump impeller, 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 appears greater when these distorted velocity distributions are integrated. This suggests that more paths are needed to define and integrate a distorted velocity distribution to achieve a high degree of accuracy. A brief discussion of the numerical analysis places bounds on the 8-path integration uncertainty of approximately 1% under adverse conditions. To achive a higher level of discharge measurement accuracy, the first 18-path flowmeter installed at Robert Moses is described. The test data show an average difference between the 8 and 18 path flowrate measurement in this application of 0.9%. The reasons for the differences are discussed. Data is also presented on other 18 path comparisons in La-Forge Power Plant in Quebec and Hiawasse in Tennessee.

Flowrate Measurement Background

Since 1967 multiple path acoustic flowmeters have been used in the water transport and hydroelectric market for a reliable and accurate measure of discharge. In the past decade, the acoustic flowmeter has been used as a primary method of discharge measurement for contractual performance testing of hydroelectric turbines. Typically, multiple chordal acoustic paths are installed in a penstock in accordance with the Gauss-Chebyshev integration technique. For applications such as performance testing, two planes each having 4 acoustic paths are installed at 4 unique elevations in the penstock.

Ultrasonic flowmeters measure flowrate by transmitting and receiving acoustic signals diagonally across moving water. The propagation time of acoustic pulses sent downstream will be shorter than a pulse sent upstream. Knowing the acoustic path length (l_p) and angle that is made with respect to the penstock centerline (Θ) and measuring the acoustic pulse travel times in both upstream and downstream directions, a spatially averaged axial velocity of the fluid can be determined[1](see figure 1). Flowrate is determined by integrating the velocity distribution across the penstock. Since the exact velocity distribution cannot be determined from a discrete number of samples, a numerical integration technique is used to determine volumetric flowrate.

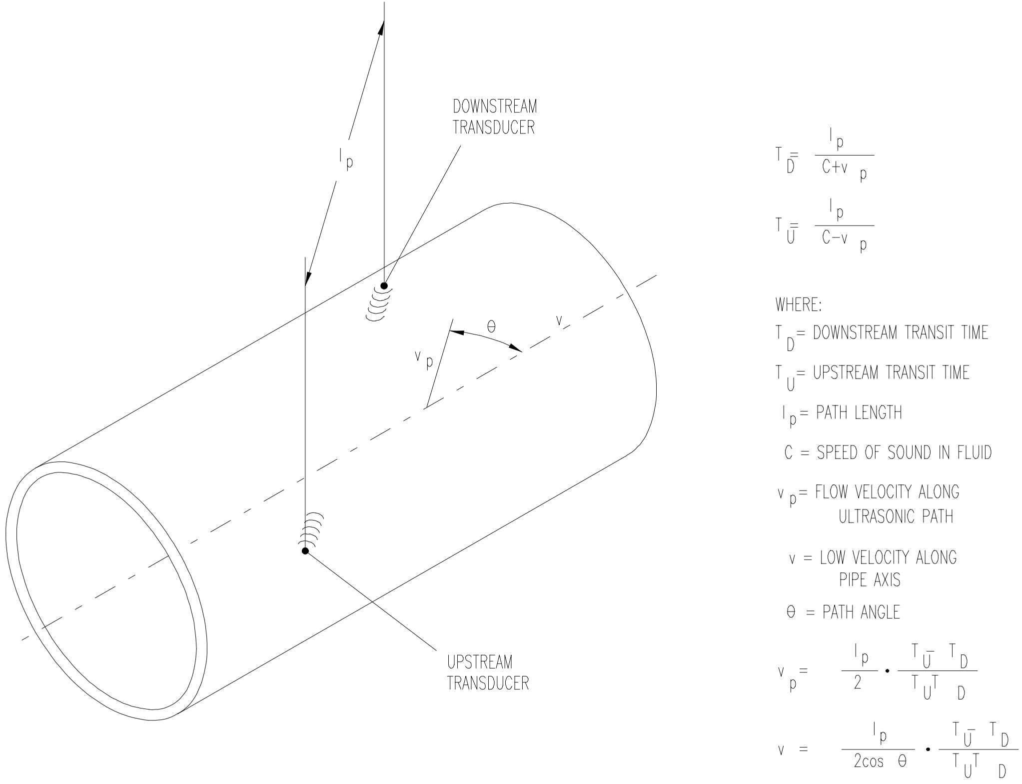

Figure 1 - Velocity of fluid measurement

Measurement section location

On most hydroelectric units, two intersecting planes each having 4 horizontal acoustic paths are positioned in the penstock such that a nominal acoustic path angle of 65 or 45 degrees is made with respect to the penstock centerline. The acoustic paths in each plane are positioned at 4 chords in the penstock at locations corresponding to normalized elevations of +/- 0.309 * R and +/- 0.809 * R (where R is the penstock radius). This can also be described as angles of +/-18 and 54 degrees with respect to

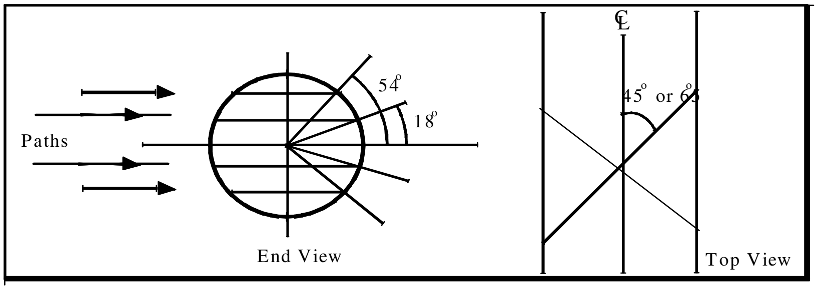

Figure 2 - Standard 8-path installation

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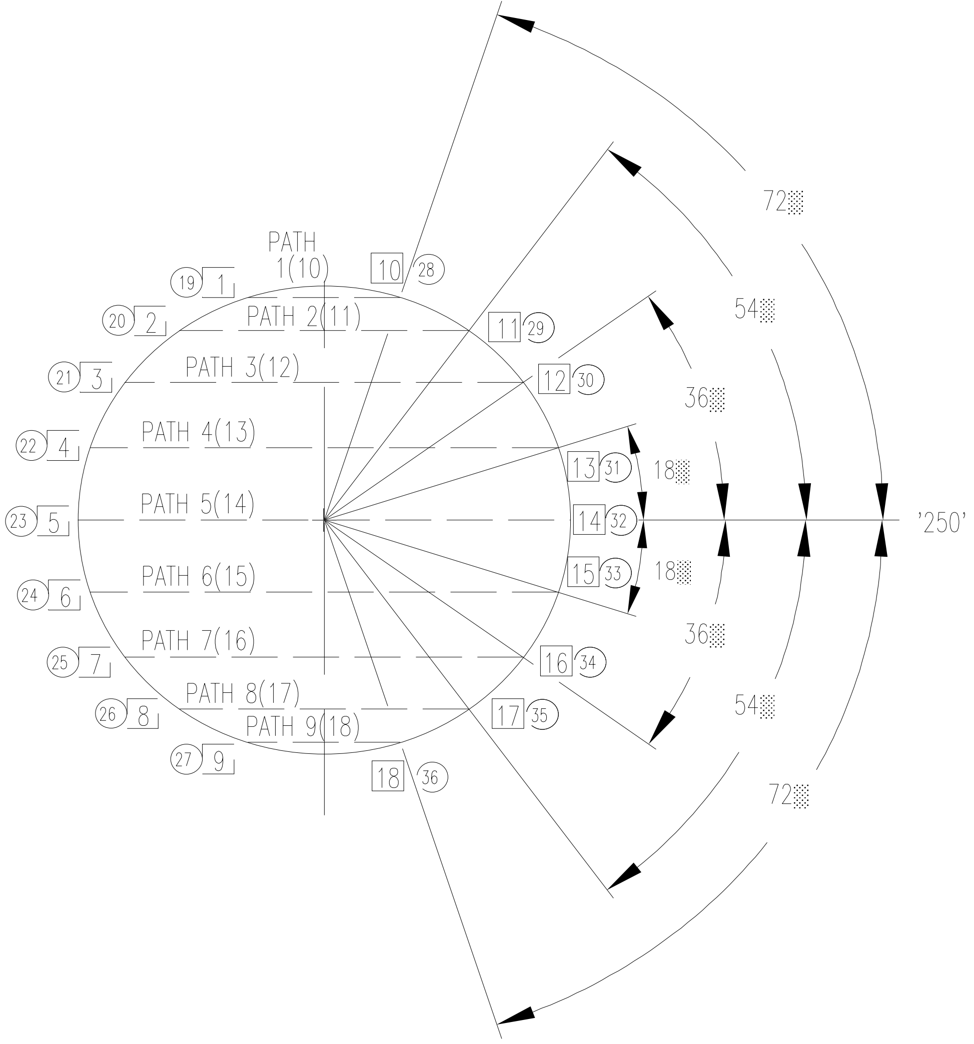
[1] Lowell, F.C. JR and Hirschfeld,F. ‘Acoustic flowmeters for pipeline flowrate’ *International Water Power & Dam Construction*, June 1979.

the centerline elevation of the penstock (see figure 2). The elevations and weights of the acoustic paths are determined by the Gauss-Chebyshev numerical integration technique. This flowrate measurement technique is in the international and American codes for turbine performance testing that specifies the path elevations and weighting (IEC Publication 41-1991 and ASME PTC -18 - 1992).

At most Power Projects the units are fitted with standard 8 path measurement sections. In unit 13 at Robert Moses an 18-path system (9 chordal paths per plane)was installed in April of 1994. The end view arrangement of the 18-path system is shown in Figure 3. All meter sections (e.g. transducer locations) are installed 2 diameters downstream from an elbow (as shown in figure 4). The 18-path meter section has additional paths located on the diameter, and in between the standard path locations and is described below (see figure 3).

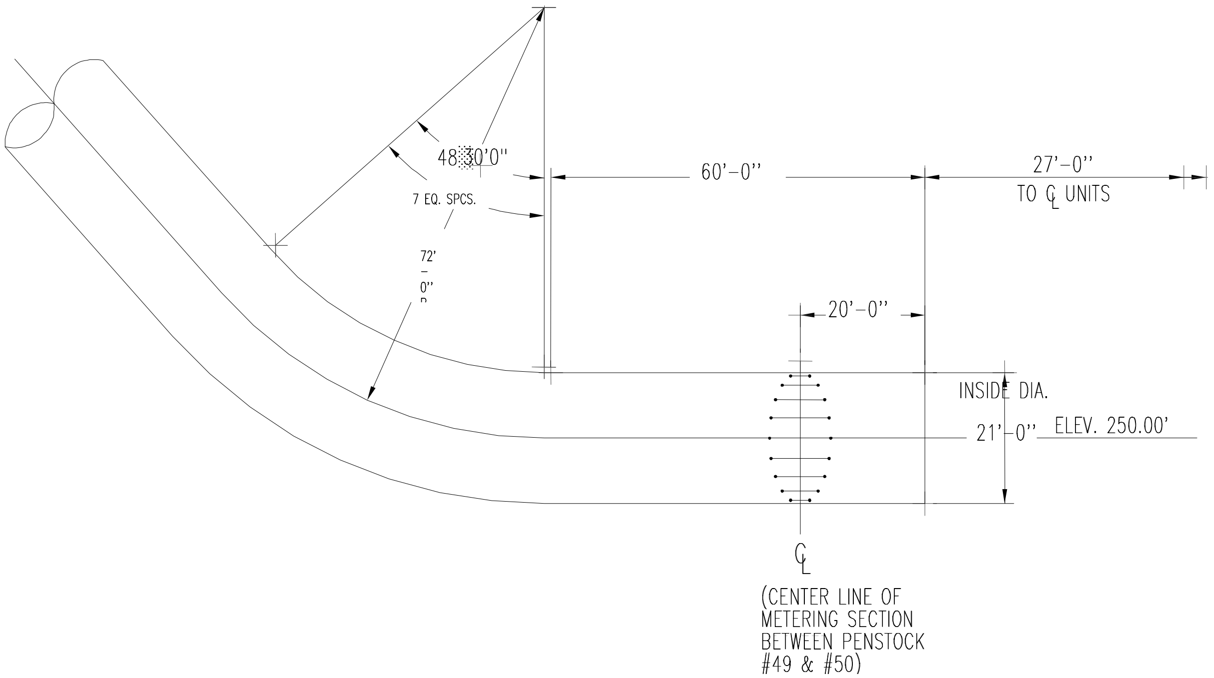
Figure 3 - End view of 18-path meter section showing chord elevations



In all cases the elevation of the 9 paths was determined by the same integration technique (see equation 4). Nine paths were chosen since 4 of the 9 elevations corresponded to the standard 4 path elevations as shown in figure 2. This is due to the sinusoidal function for path spacing. This arrangement allows direct comparison of the

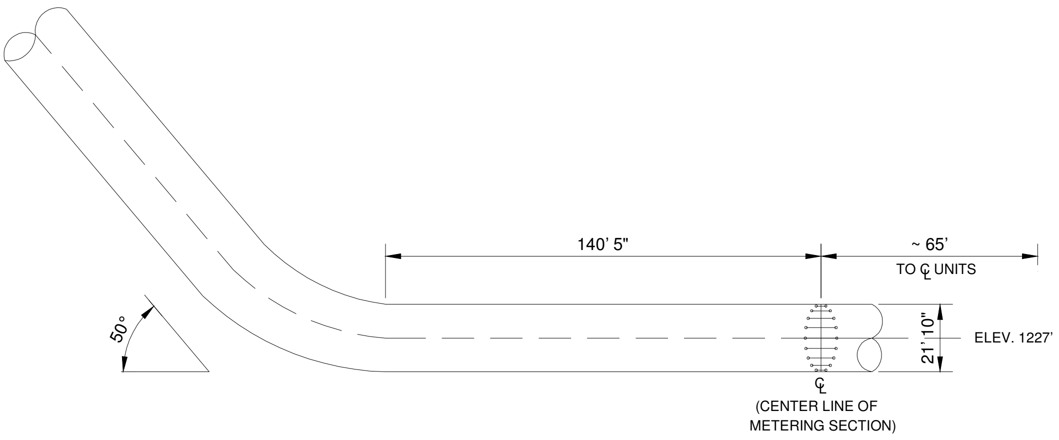
4-path measurement with the 9-path measurement. This arrangement is also included in the new ASME code which shall be available the early part of next year.

Figure 4 - Meter section location Robert Moses Power Plant



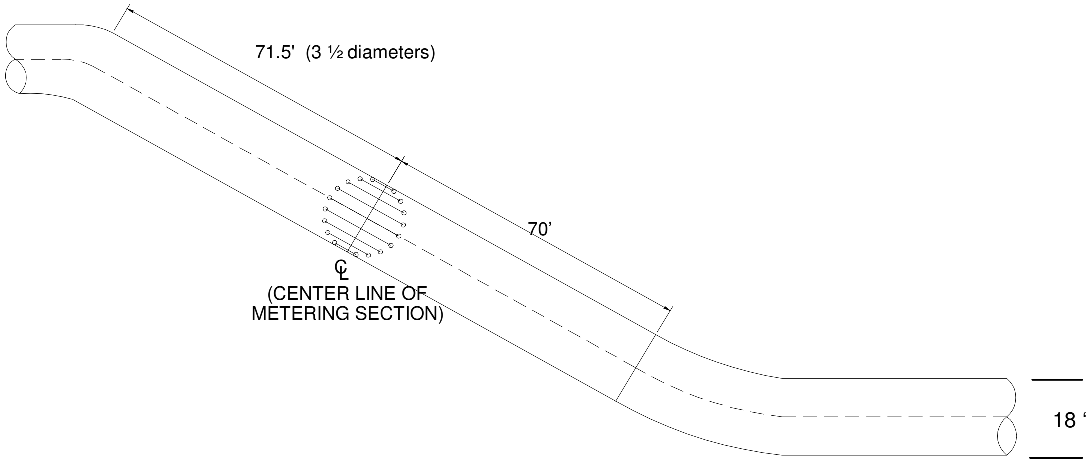
At all power plants, the tests were run concurrently with a turbine performance acceptance test. At Robert Moses Power Plant, the flowmeter section was placed in a convergent section just 2 diameters downstream of a hydraulically smooth elbow as shown above.

Figure 5 - Meter section location LaForge Power Plant



At La-Forge Power Plant, the flowmeter was installed in accordance with figure 5 in 22-foot diameter penstock 7 diameters downstream of a hydraulically smooth elbow. The comparative data shows no statistical difference between the 18 and 8 path measurement techniques.

Figure 6 Location of meter section at Hiawasse



At TVA Hiawasse Pump Storage Plant, the flowmeter was installed in accordance with Figure 6 in 18-foot diameter penstock 3.5 diameters downstream of a hydraulically smooth elbow. The main purpose of installing an 18-path meter was to access the pump and turbine discharge under less than ideal conditions.

Uncertainty

In any field measurement test there are always two categories of uncertainty. The bias, which influences the absolute results of the test, can usually have uncertainties assigned. There are also random uncertainties, which arise from repeating the same measurement numerous times, which do not and are not expected to agree.

Bias errors resulting from the installation of transducers and their effects on accuracy in flowrate measurements have been quantified[2] and generally are in the 0.1 % range. Since the transducers comprising the eight and eighteen path meters are installed in the same section of penstock, the radius bias cancels in both discharge measurements. The differences in the weighted path uncertainties among the 8 and 18 path length and angle measurements are negligible. This is because the length and angle uncertainties are in the one part per thousand ranges. Therefore, the remaining uncertainties in flowrate measurement are random and integration uncertainties. The integration uncertainty has been the subject of debate among various flowmeter manufacturers, utilities, and turbine suppliers. Prior to installing the eighteen-path flowmeter, several discussions between Accusonic and NYPA, Hydro Quebec and TVA were held to address the integration uncertainty when the velocity distribution was skewed

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[2] Voser, Alex CFD calculations of protrusion effects, IGHEM Proceedings, Montreal 1996. Walsh et.al Acoustic Transducer and conduit protrusion, IGHEM Proceedsing, Reno, 1998.

downstream of a bend. Skewed velocity distributions that take on forms that may be other than logarithmic, similar to profiles observed at Robert Moses were analyzed. A bound on the uncertainly of the integration technique was placed on the 8 path flowmeter and is described below.

The axial flow field v(x,y) can be represented in the penstock along an acoustic path as:

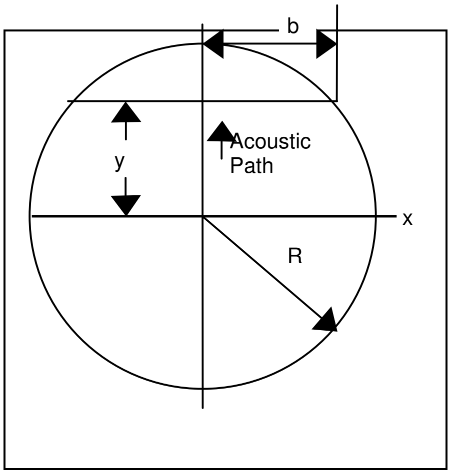

Figure 7

$$\overline{v}(y) = \tfrac{1}{2b} \int_{-b}^{+b} v(x,y)\,dx$$ *(equation 1)*

The flowrate is:

$$Q = \int_{-R}^{+R} 2b\,\overline{u}(y)\,dy$$ *(equation 2)*

with $b = \surd R^2 - y^2$
or

$$Q = 2R^2 \int_{-1}^{+1} \sqrt{1-z^2} * \overline{u}(z)\,dz$$ *(equation 3)*

where z = y/R

This takes the form of an established mathematical relationship[3] for the Gaussian integration method.

$$\int_{-1}^{+1} f(z) * \sqrt{1-z^2}\,dz \approx \sum_{i=1}^{N} w_i f(z_i)$$ *(equation 4)*

Where the weights (w_i) are given at locations at abscissas x_i (+/- 0.309 +/- 0.809). The velocity profile measured by the flowmeter is f(z) that represent the spatially averaged velocity along the acoustic path. In the integrand, the velocity function f(z) times the radical ($\surd 1-z^{2)}$ makes erratic functions more "well behaved". Hence, the function actually being integrated (f(z) *$\surd 1-z^2$) is smoother than the velocity profile f(z). This smoothing is significant because velocity profiles f(z) that may have several increases and or decreases along the penstock height are smoothed and rendered monatomic on the radii. In analysis performed by Ludewig[4], it has been shown that the integration uncertainty is bounded by about +-1 %. The Ludewig analysis was performed using several velocity distributions where no sharp corners occurred in f(z) and the shapes of the curves were similar to the field measured velocity distributions. These velocity distributions also included polynomial functions recognizing that this numerical technique is exact for certain classes of functions (that is polynomials of order 2n-1 or less where n is the number of paths on each plane).

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[3] M Abramowitz and Stegun , ed.,Handbook of Mathematical Functions Applied Mathematics Series 55 (US government printing office 1963), Pg. 889

[4] Ludewig, Peter, September 4, 1992 Analysis of Gauss-Chebyshev Integration technique

At numerous power plants, the random error in flowrate has been observed by taking instantaneous measurements of flowrate and analyzing the distribution of the data. In all cases, the distributions of the instantaneous readings approach a normal distribution with a mean and a standard deviation. This is supported by Chi square evaluations on instantaneous flowrate distributions that result in a high degree of certainty (greater than 90 %) that the normal statistical distribution can be used[5].

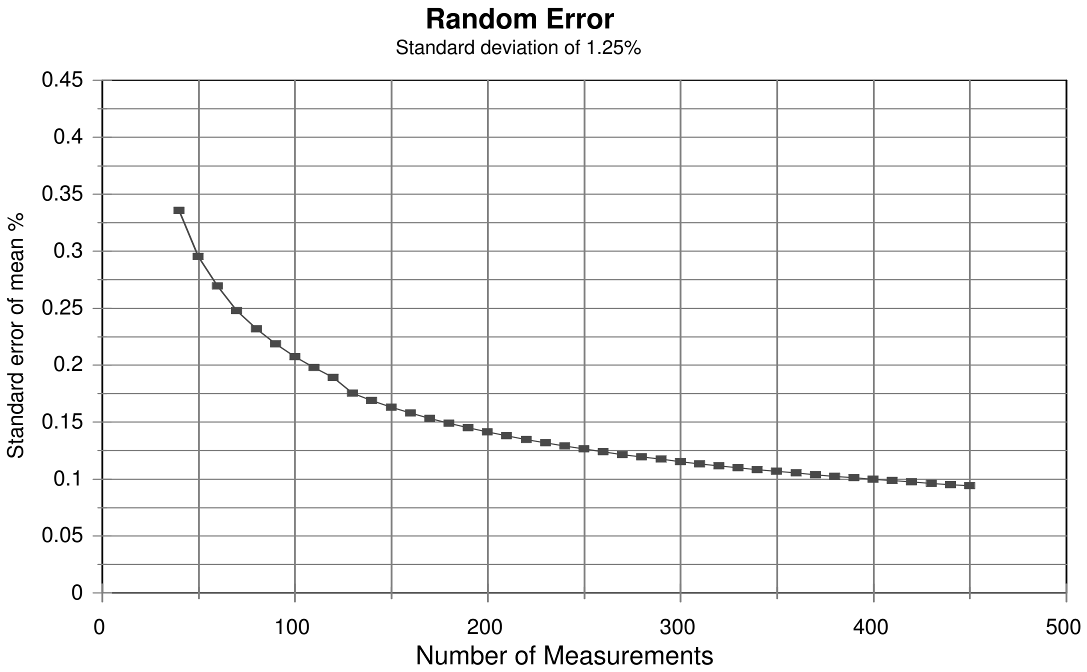

Figure 8- Number of measurement influence on the standard error

In the experience of Accusonic, the majority of applications the standard deviation is typically 1 to 1 ½ % of the mean. This is usually influenced by how far the meter is situated from hydraulic structures such as elbows and "Y" branches. Generally, meter sections installed in straight long sections of penstocks have lower reading to reading fluctuations and therefore lower standard deviations. For high accuracy applications, hundreds of readings must be used to minimize the standard error of the mean. A plot of the standard error of the mean assuming a standard deviation of 1.25 % of flowrate is illustrated in figure 8.

At Robert Moses, and LaForge each test was run over an interval of 15 minutes that yielded 450 readings. As shown in figure 8, the amount of readings minimizes the random component of the flowrate measurement. For statistical significance the differences between the 8 and 18 path flowmeter must exceed 0.13 %.

Field Data

Robert Moses

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[5] Walsh, James T. 1991 &1995 Internal analysis of flowmeter variability

Presented in figure 9 is the data from the first 60 runs performed at Robert Moses Power Plant Unit 13. This data was collected concurrent with a contractual performance test. Figure 9 shows the differences of the 18 and 8 path flowmeters as a function of flowrate indicating that there is no bias that is flowrate related. On average, the 18 path derived flowrate is 0.9% lower than the 8 path flowrate.

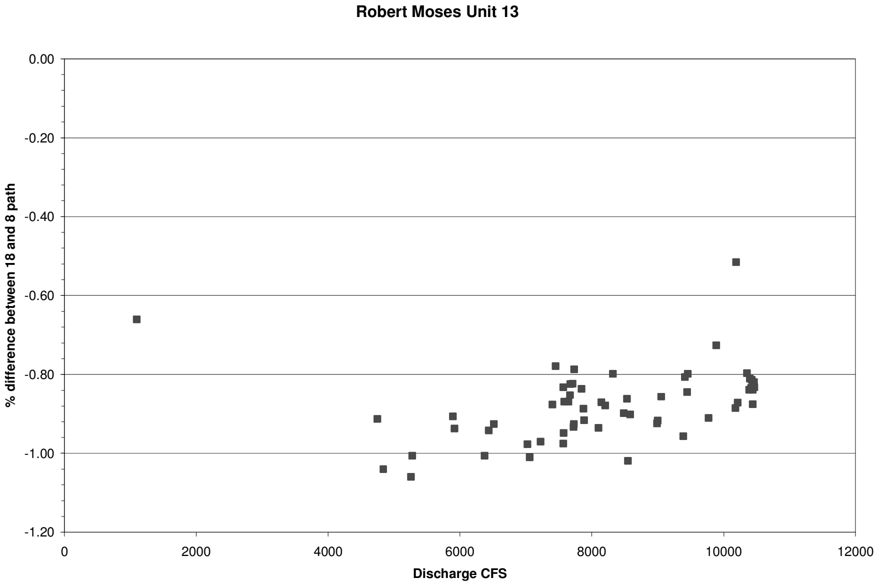
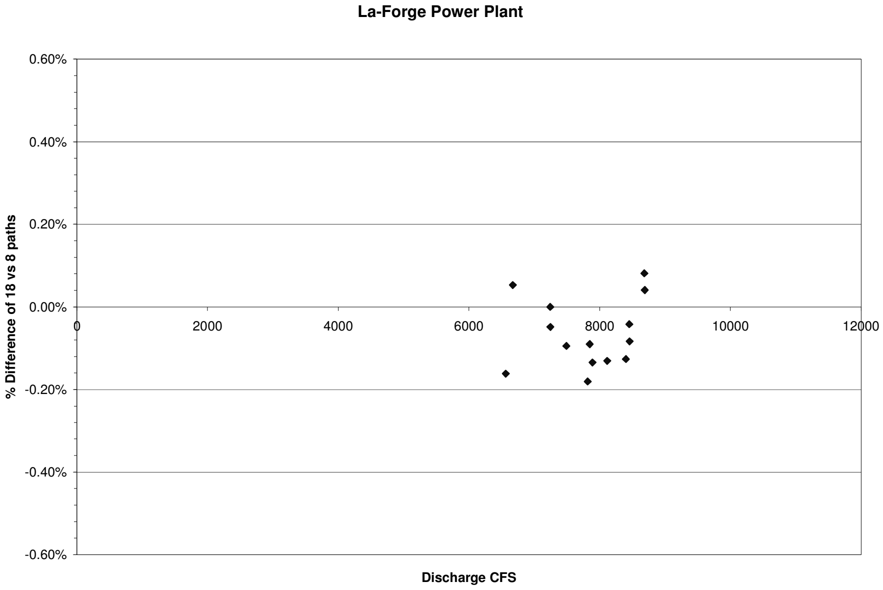


Figure 9 data from Robert Moses Power Plant

LaForge

Presented in Figure 10 is the data from La-Forge Power Plant. This data was also conducted concurrently with a contractual performance test. On Average the data shows no statistical significance (<0.1%) between the 18 and 8 path data.

Figure 10 – Flow data from La-Forge



Hiawasse

Presented in figure 11 is the turbine discharge data from Hiawasse Power Plant. This chart shows an average difference between the 18 path flow and the 8 path flow of less than 0.1%, however, there seems to be a second order effect of the difference between both the 18 path and 8 that varies with discharge. This may be due to the relatively short time interval for acquiring data. The pump data shows a fixed bias of -0.6%.

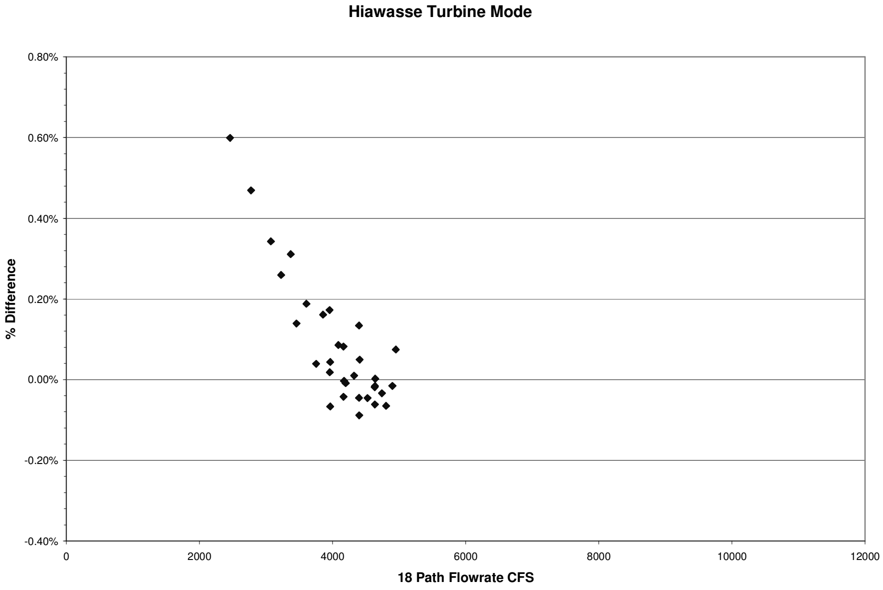


Figure 11 Turbine discharge data

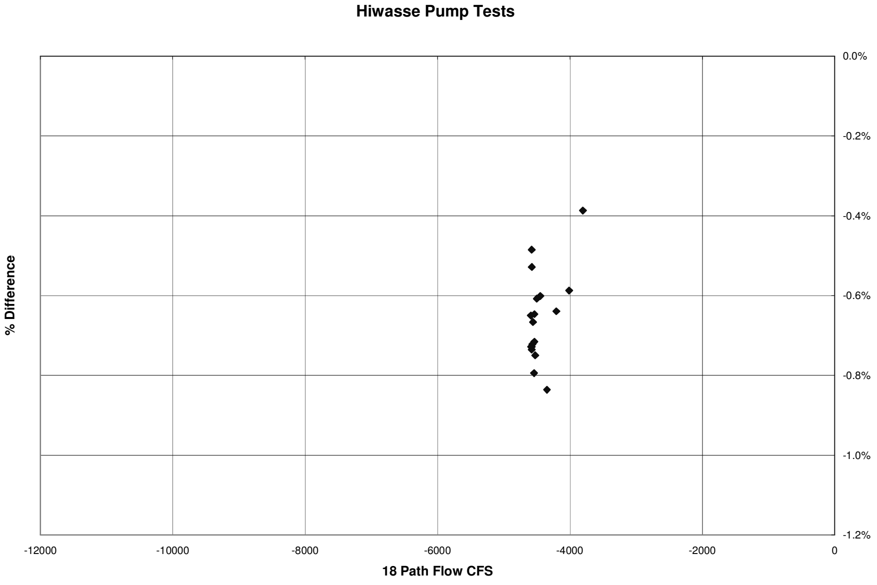
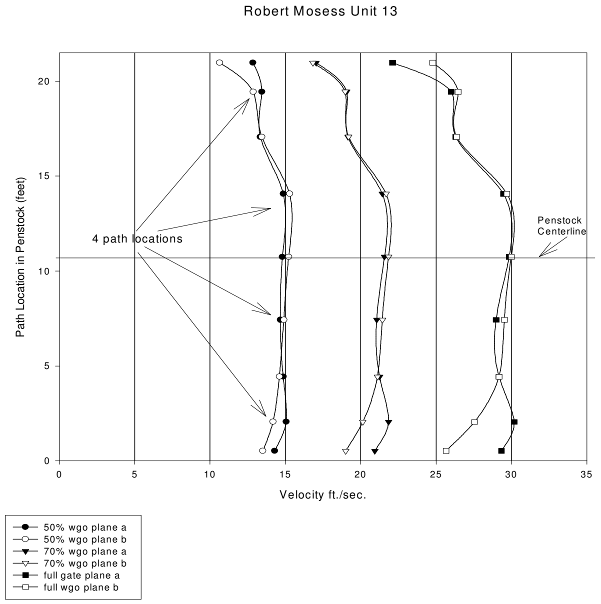


Figure 12 Pump discharge data

Analysis of Results



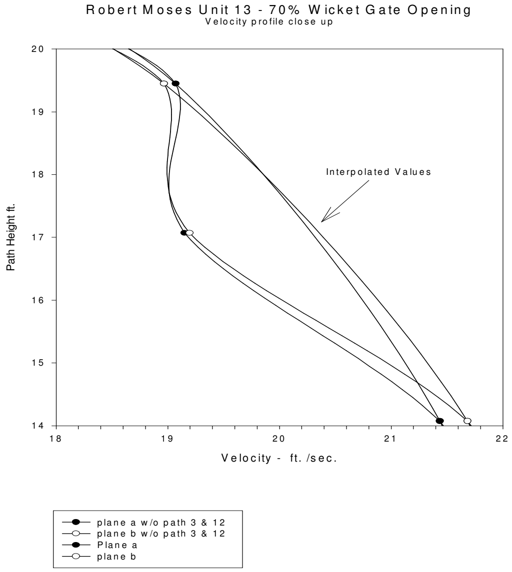


Figure 13 Typical velocity distributions at Robert Moses

Figure 14 velocity deficit detail

Typical velocity distributions are graphed for a full, low and best gate openings that illustrates a velocity deficit at the + 36 degree (path 3 and 12) elevation at Robert Moses. In figure 14 a detail of the velocity deficit is expanded for the flowrate at 70 % wicket gate opening. A spline fit is used to predict the axial velocity in the absences of the 36-degree velocity data. If this data is used in place of the 36 degree path velocity data, the difference between the 8 and 18 path data reduces to 0.1%. This indicates that the majority of the discrepancy lies with the velocity deficit. This velocity deficit is prevalent in all velocity distributions obtained for all ranges of discharges measured at Robert Moses.

At La-forge as expected the velocity distributions were symmetrical and exponential in shape. At Hiawasse, the velocity distributions were similar to what is shown at Robert Moses but not as extensive. In the pumping mode at Hiawasse, a similar perturbation in the velocity distribution was observed. Time did not allow an extensive analysis of this velocity deficit.

Results and Conclusions

It has been shown that there is a difference between the 18 and 8 path acoustic flowmeter 2 diameters downstream of the elbow at Robert Moses. This 0.9 %

difference is chiefly due to the velocity deficit as seen by the upper paths at the + 36 degree elevation (paths 3 and 12 on the 18 path flowmeter). In all cases, the major portion of the difference between the 18 and 8 path flowmeter is due to the velocity deficit.

At Hiawasse, the velocity distribution in the turbine mode looked similar to the velocity distribution at Robert Moses in figure 13 but the velocity deficit, was not as extensive. Clearly, the less perturbated velocity profile is due to increased length between the upstream bend and the meter section. In the turbine mode of operation, the meter section is nearly twice the distance from a bend as compared to Robert Moses. Since there is 3 ½ penstock diameters between the meter section and the elbow, one expects a smoother velocity distribution. The effect of secondary flow fields tends to perturbate the flow and will bias flowrate integration, particularly when placed in close proximity to an elbow.

At La-Forge the 18 path flowmeter is located 7 penstock diameters away from an elbow. The testing results suggest that an 8 path acoustic flowmeter is highly accurate when placed sufficiently downstream (> 7 diameters) of a disturbance.

In a separate analysis, a hypothetical velocity distribution was used to analyze the sensitivity of the 18 path (9 chord) numerical integration technique[6]. This analysis was performed and compared to the 19 chord integration technique. The results of this analysis indicate that the 18 path (9 chord) integation error has an upper limit of 0.1% uncertainty under highly perturbated velocity distributions.

We can deduce from the information above that the integration uncertainty varies with the distance the meter is located downstream of an elbow or distrubance. Based on the field testing we can state when an 8 path acoustic flowmeter is placed:

- Two diameters downstream of a bend the integration uncertainty will range from 0.8 to 1%.
- Four diameters downstream of a bend the integration uncertainty will range from 0.2 to 0.5 %
- Seven or more diameters downstream of a bend the integration uncertainty will be 0.1% or less

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[6] Internal Turbine Performance Test Reports by Walsh