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Laboratory and Field Evaluation of Acoustic Velocity Meters

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Abstract

A study was conducted to evaluate the performance of 27 acoustic flowmeters used at Hoover, Davis, and Parker Dams on the lower Colorado River. Field surveys and laboratory testing were used to evaluate and enhance the performance of the chordal-path acoustic velocity meters. A hydraulic model and a laser doppler anemometer were used to determine velocity distributions for two nonstandard flowmeter installations.

Introduction

The purpose of the study was to improve the performance of acoustic flow meters at the major dams along the lower Colorado River, namely Hoover, Davis, and Parker Dams. This study was only one of many being conducted in support of the LCRAS (Lower Colorado River Accounting System) program. LCRAS is a water management computer program which is used by Reclamation to manage water resources in the Lower Colorado River Basin. LCRAS has been developed to estimate water consumption by tracking consumptive use by: crops and phreatophytes, reservoir evaporation, municipal and industrial users, and groundwater recharge.

In an effort to improve the accuracy of flow measurement at Hoover, Davis, and Parker Dams, a two stage study was initiated. The first stage was to evaluate the existing flow measurement

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system which consists of AVMs (acoustic velocity meters) with four or eight acoustic paths. A field survey was conducted to determine if all 27 AVM installations conformed to ANSI/ASME Standards and ASME's Performance Test Code 18. The second stage was to determine if nonstandard AVM installations were performing to manufacturer's specified accuracies of ±0.5 percent of the true discharge. A physical model was used to determine the penstock velocity distributions at the AVM measurement section and to verify the flowmeters integration techniques when applied to an asymmetrical velocity distribution,. Model study results were be used to establish error bounds on discharge measurements and identify modifications which would reduce discharge measurement errors.

Field Surveys

To determine the accuracy of flow measurement at Hoover, Davis, and Parker Dams field surveys were conducted in September, 1992 to document and review: AVM equipment, AVM system parameters, as-built drawings, and perceived system performance. Each of the 27 AVM sites and installations was evaluated using ANSI/ASME Standard MFC-5M-1985, entitled *Measurement of Liquid Flow in Closed Conduits using Transit-Time Ultrasonic Flowmeters*. Likewise, ASME's Performance Test Code for Hydraulic Turbines (ASME PTC 18-1992) was used in evaluations because it is more stringent than the ANSI/ASME standard. Surveys at Hoover, Davis, and Parker Dams resulted in a large amount of site specific data and personal opinions as to how the AVM systems were performing. Survey information is summarized as follows:

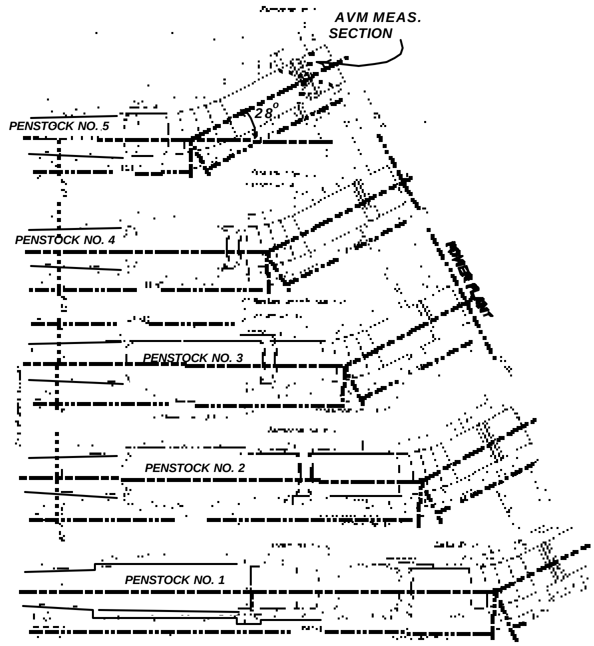
Hoover Dam - Eighteen AVMs at Hoover Dam were installed over the period of 1989 to 1991. A review of AVM equipment, system parameters, and as-built drawings at Hoover Dam revealed that all AVM installations were according to standards and were configured properly. However, there were a few installations which had numbers transposed in the path length and/or angle entries. These types of setup errors can result in significant discharge errors, but they were easily corrected.

Davis Dam - Five AVMs were installed in 1989. A review of AVM equipment, system parameters, and as-built drawings for Davis Dam revealed that all five AVM installations were nonstandard because of inadequate length of straight pipe upstream of the meter section - 10 pipe diameters is the recommended minimum length in the ANSI standard. The amount of straight pipe upstream from the meter section ranged from ½ to 1-½ diameters, for each of the five, 6.7-m-diameter penstocks. However, these AVM locations could not be avoided because of short penstocks. All AVMs were installed just upstream of the turbine scroll case to maximize the length of straight pipe upstream. Because of short penstock lengths and bends upstream, cross flows (flows with nonaxial velocity components) were anticipated. Crossed path AVMs are used in difficult installations to correct cross flow errors. The shortest of the five penstocks was fitted with a crossed path AVM system. However, ASME's PTC 18 requires installation of two, four-path measurement planes and the intersection of the two planes shall be in the plane of the upstream bend. The crossed path AVM installations at Davis Dam do not meet the above criteria.

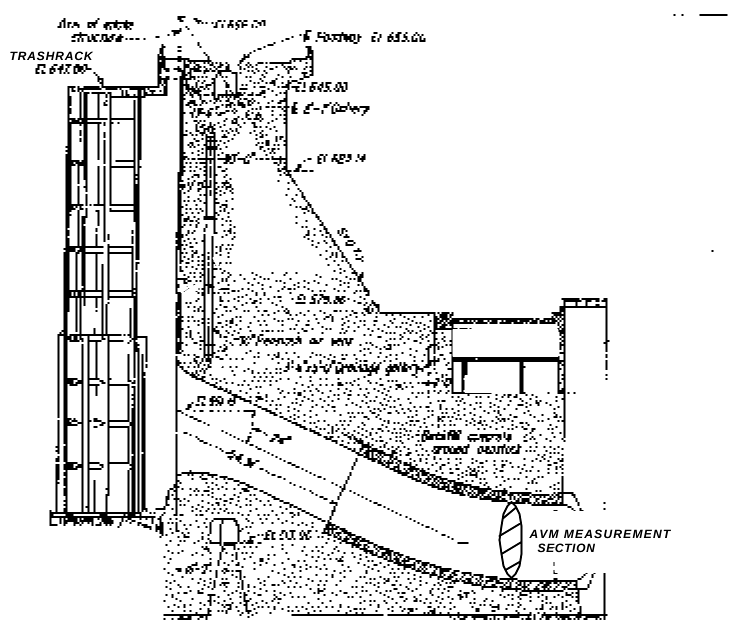
Parker Dam - Four AVMs were installed in 1989. A review of AVM equipment, system parameters, and as-built drawings at Parker Dam revealed that all four AVM installations were nonstandard because of an inadequate length of straight pipe upstream of the meter section. The length of straight pipe upstream from the meter section ranged from ½ to 6 pipe diameters, for each of the 6.7-m-diameter penstocks. However, these lengths could not be avoided because of short penstocks. Like Davis, all AVMs were installed just upstream of the turbine scroll cases to maximize the length of straight pipe upstream of the meter section. Therefore, two of the four penstocks were fitted with crossed path AVM systems, including the shortest penstock. The crossed path AVM installation at Parker does not meet ASME's PTC 18 requirement on acoustic path orientation with respect to the upstream bend.

In general, AVM system operators felt their systems were operating satisfactorily. However, our interviews indicated that there was a disparity in knowledge levels among system operators. There were varying degrees of expertise in system testing and troubleshooting depending on maintenance history. To alleviate this problem it was recommended that a training course be given to all system operators. It was also apparent that an experienced electronics technician is necessary to effectively operate and maintain an AVM system. We also recommended developing a database to log maintenance and repair data, as well as system parameters and error logs.

Some interesting equipment problems were identified during the surveys. At Hoover and Davis Dams, when acoustic transducers were removed for cleaning or when the penstock was dewatered, there was a large number of transducer failures. Transducer failures have been prevented by keeping transducers submerged during maintenance operations. Another common concern was with field survey accuracies of path angles and lengths, and cross-sectional areas of the penstocks. These parameters are very difficult to measure accurately, and must be determined to a high degree of accuracy. Therefore, operators should be comfortable with the survey accuracy prior to going on-line with an AVM system and should keep the original survey data in their files.



PLAN - POWER PENSTOCKS



SECTION - PENSTOCK NO. 5 WITH TRASHRACK

Figure 1. Plan and section of penstock No. 5 at Davis Dam. The AVM measurement section is shown at the end of the penstock. The combined bend has a 24E vertical and a 28Ehorizontal angle.

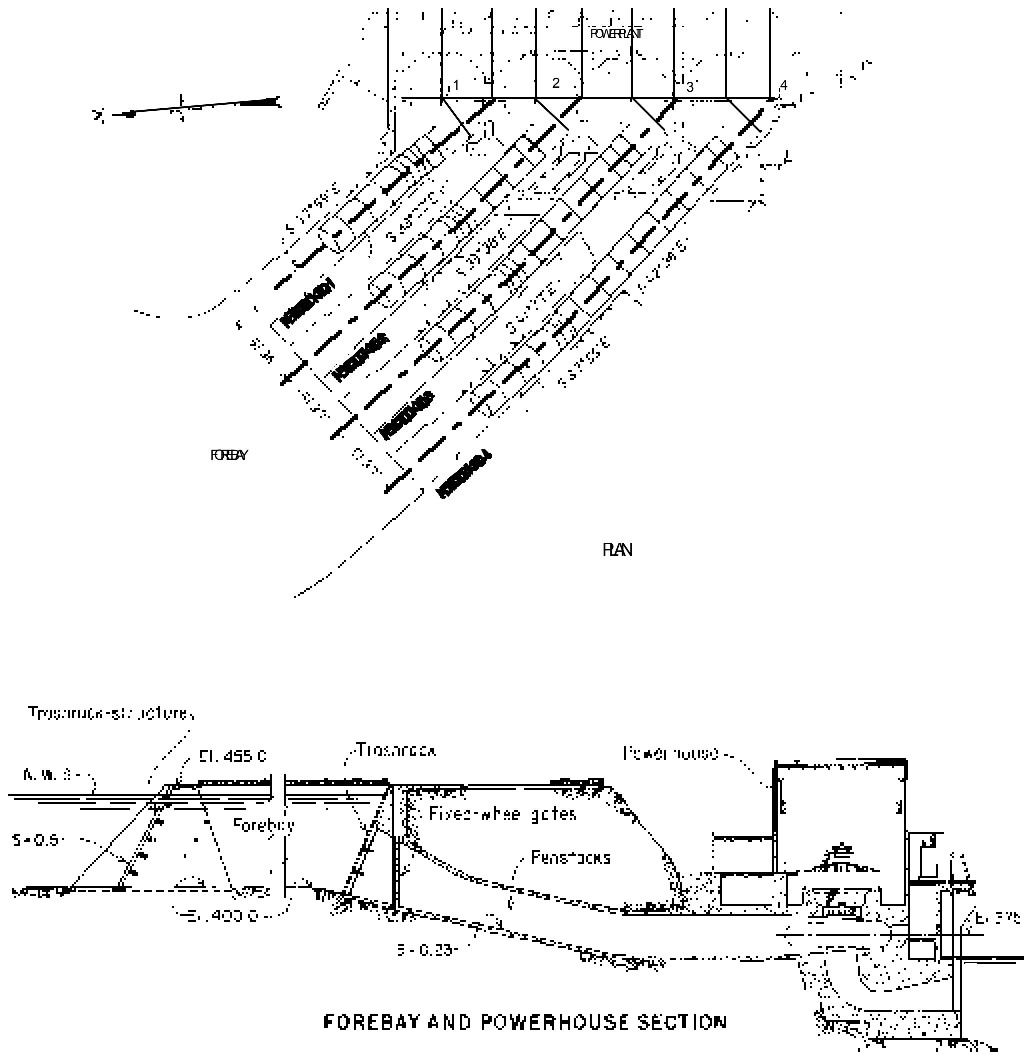


Figure 2. Plan and section of penstock and powerhouse at Parker dam. The combined bend is locted immediately upstream from the AVM transducers and consists of a 12.9E vertical bend and a 4.6E horizontal angle.

AVM Data Analysis - Individual path velocities and discharge values were collected for the crossed path AVMs at Parker and Davis Dams to determine the errors associated with cross flows. Figure 1a contains a typical sample (- 110 measurements taken over 2 minutes) of data collected from Parker penstock number 3 for a 50 percent wicket gate opening. This penstock is equipped with a crossed path AVM, so a total of eight path velocities and two discharges were measured. Paths 1 and 4 are the upper and lowermost acoustic paths, respectively. Paths 2 and 3 are located in between paths 1 and 4. Analysis of the path velocities indicated that there is very little cross flow component, because velocities measured on similar acoustic paths agreed very well (e.g, path 1, planes 1 and 2 in fig. 1a). Likewise, if there was a strong cross flow component, flow-1 and flow-2 would be substantially different, but figure 1b shows there was good agreement between flow-1 and flow-2. However, the four path velocities indicated that the profile is distorted toward the penstock's invert. This is evident from the difference between the velocities (0.7 m/s) measured along paths 1 and 4, as shown in figure 1c. This distorted profile is caused by a 30E vertical bend two pipe diameters upstream of the AVM measurement section.

A published error analysis by the AVM manufacturer (Lowell and Hirschfeld, 1979) does not adequately address the error related to the integration of an asymmetrical velocity distribution. The question remains, Can the integration method employed in the AVM discharge calculations accurately integrate an asymmetrical velocity distribution? To quantify the magnitude of the integration errors and to determine the velocity distributions a study was initiated which

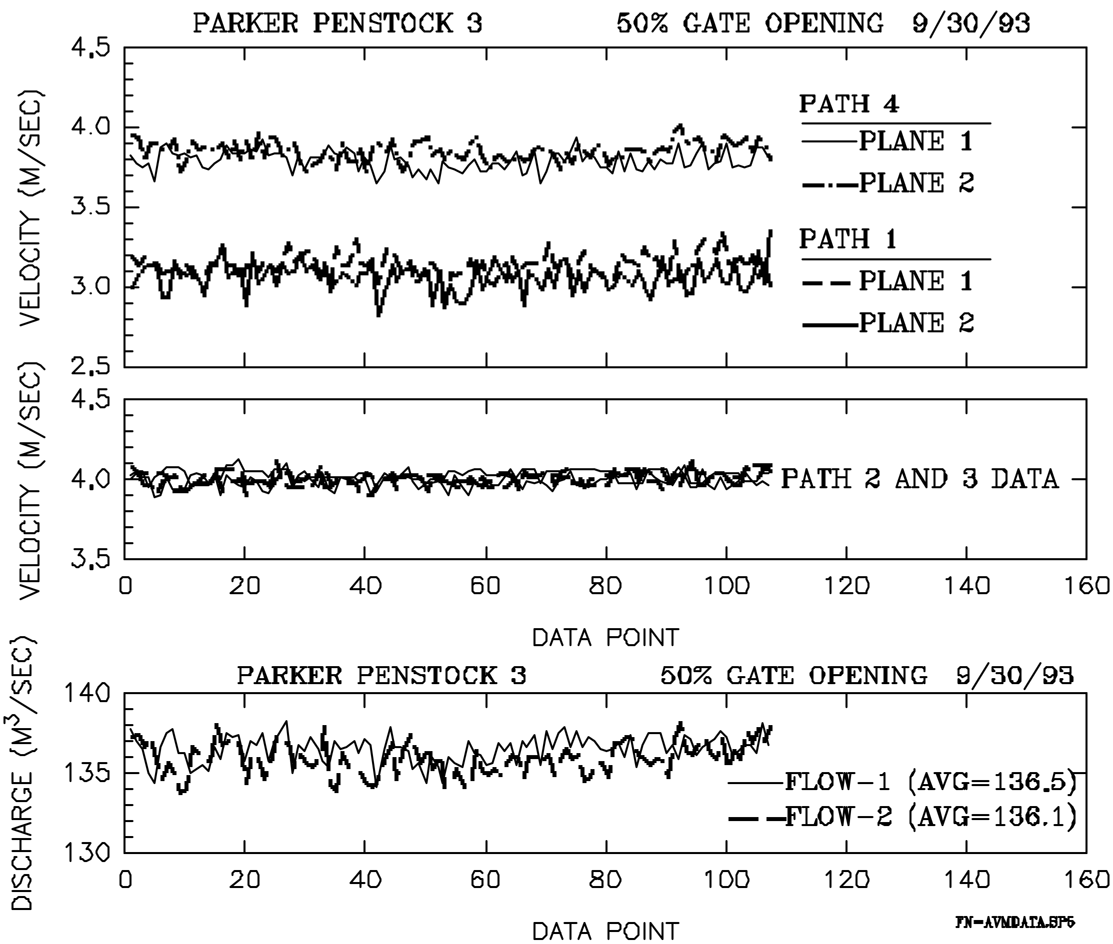


Figure 3. . Raw path velocity and flowrate data from the cross path AVM system installed on Parker Dam penstock no. 3.

included hydraulic model studies of penstocks at Parker and Davis Dams. Likewise, a field demonstration comparing strap-on acoustic flowmeters to four-path AVMs was performed at Davis Dam.

Strap-on Acoustic Flowmeter Comparison - At Davis Dam, AVM discharges were compared to discharges measured using a portable, strap-on acoustic flowmeter. The strap-on flowmeter installation consisted of one diametral path. This comparison was performed as a demonstration of a strap-on meter, it was not intended to be an evaluation of the four-path

AVMs. Accuracies for this uncalibrated discharge measurement application are normally expected to be within ±3 percent. However, discharges were measured for a full range of wicket gate openings and were consistently 6 percent lower than the four-path AVM measurements (see figure 3). This difference was likely attributed to the penstock's unknown coal-tar lining thickness, which affects the traveltime measurements, and the asymmetrical velocity distribution. While strap-on acoustic flowmeters cannot claim the installed accuracy of a four-path AVM, their cost is significantly less, and they are suitable for many discharge measurement applications. In addition, Taylor (1987) has suggested using strap-on flowmeters to determine the severity of asymmetric velocity distributions. Taylor's procedure may be useful in determining whether a crossed path AVM installation is warranted.

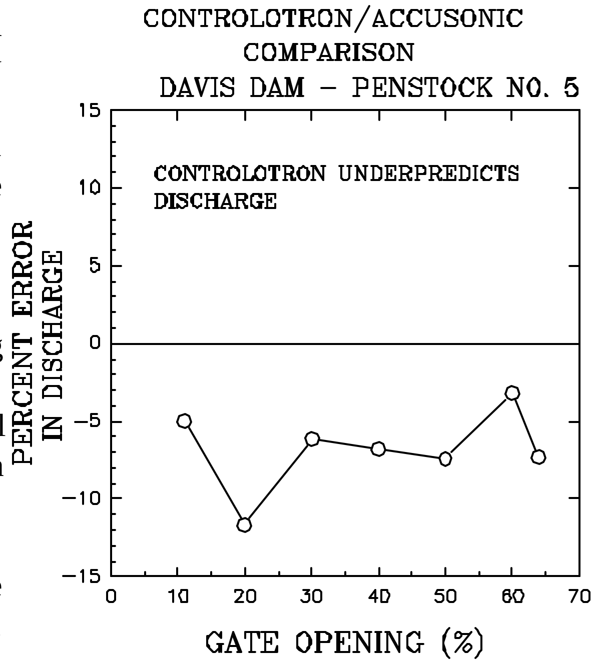


Figure 4. Percent error of Controlotron strap-on acoustic flowmeter and Accusonic AVM measured discharges for a range of wicket gate openings.

Field Study Conclusions

AVM installations at Davis and Parker Dams are nonstandard because they do not meet the ANSI/ASME standard concerning the required length of straight pipe upstream and downstream from the AVM measurement section.

AVM installations at Davis and Parker Dams do not meet the requirement in ASME's PTC 18 which states: "The intersection of crossed acoustic planes shall be in the same plane as the upstream bend to minimize the effects of the cross flow components on the accuracy of the measurement."

Cross flow errors were identified at Davis penstock No. 5 and Parker penstock No. 1 and were measured to be ±0.5 and ±1.8 percent, respectively. These errors are compensated for by using crossed acoustic planes. Therefore, all penstocks with single plane AVMs are likely to have similar cross flow errors.

Crossed plane AVMs are recommended on all penstocks at Davis and Parker Dams, except for Parker penstock No. 4. Analysis of path velocity data from Parker Penstock No. 3 indicate a minimal cross flow error. Parker penstock No. 4 has better flow conditions than penstock No. 3, so it is reasonable to conclude that crossed plane AVMs are not necessary for accurate discharge measurements.

Laboratory Studies

In order to establish error bounds on the AVMs discharge measurement, it was necessary to define the velocity distribution for penstocks with nonstandard AVM installations. A physical model was constructed in Reclamation's Water Resources Research Laboratory and was used to study representative penstocks at Parker and Davis Dams.

The Model - A 1:22.9 scale hydraulic model was used to determine the velocity distributions in penstocks at Davis and Parker Dams. The model included features from the trashrack and inlet transition down to, but not including, the turbine scroll case. Measured velocity distributions were analyzed to determine the deviation of the actual velocity distribution from a fully developed, turbulent velocity field. Model data were also be used to establish alternate measurement planes which minimize cross flow and integration errors. This model study was not intended to determine a calibration factor because of Reynolds number limitations. Its purpose was to determine the errors related to AVM integration techniques applied to asymmetrical velocity distributions.

Velocity Measurements - Point velocities were measured using a fiber-optic LDA (laser doppler anemometer) system mounted to an automated one-dimensional traversing system (fig. 4). An LDA measures fluid velocity by determining the oscillation frequency of light pulses reflected from particles in the fluid as they pass through the probe volume. The probe volume is created where the two laser beams cross. Velocity data were collected at 12 locations along a radial path, for 24 equally spaced radii on the pipe section. This resulted in 288 point velocity measurements. Normally, each LDA reading was taken as the mean of 500 or more instantaneous velocity measurements. Strict signal validation criteria are used to assure data quality.

Velocity measurement locations were determined by dividing the pipe area into a center circle and 11 annuli, all of equal area. Velocities were measured at the midpoint of each annulus. These velocity measurements were later used in a velocity-area integration method used to calculate discharge. This integration technique is commonly referred to as the tangential method.

Laser Mounting System - To efficiently collect velocity data on 24 different radii the LDA probe had to be easily rotated while keeping the laser beams in a plane perpendicular to the pipe's axis. This was done by machining a saddle-type mount with a slightly larger outside diameter than the model penstock. A plate and positioning table are attached at a 90E angle to the face of the saddle mount. A single-axis positioning table was used to accurately position the LDA probe at the 12 different measurement locations. The positioning table consisted of a stepper motor system to move the LDA probe (resolution is 0.1 mm per step). The stepper motor was controlled by a personal computer and manufacturer supplied software. For this application, a heavy duty stepper motor with adequate holding torque (1 N@m) was necessary to maintain position under the probes weight. The LDA's software combined with a positioning system was capable of automatically collecting velocity profile data. However, our data collection was done manually because the LDA system parameters had to be adjusted as the sampling position was changed.

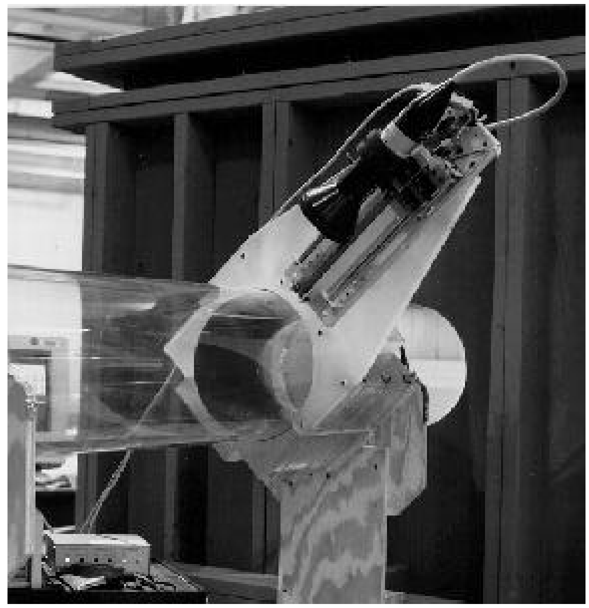


Figure 5. Photograph of the fiber-optic LDA probe, saddle mount, and single axis positioning table with stepper motor.

Discharge Measurements - Flows entering the model were measured using the laboratory's permanent bank of venturi meters. The venturi's are calibrated annually using a weigh tank; the calibrations for the 15-cm and 20-cm venturi meters used in this study were accurate to within ±0.35 and ±0.27 percent, respectively. Integration of the measured velocity distribution was used to verify the quality of the LDA velocity measurements. Two velocity-area methods were used to calculate the discharge, the tangential method and the log-linear method. A thorough discussion of both methods is presented in a paper by Winternitz and Fischl, 1957. A close agreement of both methods confirmed the quality of LDA measurements. An uncertainty analysis was performed on the computation of discharge using the tangential integration method. The two components analyzed were the LDA (velocity) measurements and the penstock cross sectional area. This analysis revealed that the uncertainty of discharge measurements for all tests was in the range of ± 0.5%. The primary component of the uncertainty was the systematic error associated with the LDA velocity measurements.

Davis Penstock No. 5

Four model tests were conducted to determine velocity distributions for a wide range of flows. All velocity profiles were collected at the same cross section in the center of the AVM measurement section.

Parker Penstock No. 1

Two model tests were conducted to determine the velocity distributions for two different discharges. All velocity profiles were collected at the same cross section, located in the center of the AVM measurement section.

Velocity Distribution Analysis

A computer software package (Amtec Engineeiing, 1988) was used to develop a numerical model of the velocity distribution which could be easily analyzed for several AVM path configurations. All velocity measurements were normalized using the average velocity calculated using all the LDA data. The pipe's average inside radius was used to normalize lengths. A right-handed coordinate system was used in collecting the data. The positive Z direction is upstream; the positive Y direction is upward; the positive X direction is to the right looking downstream.

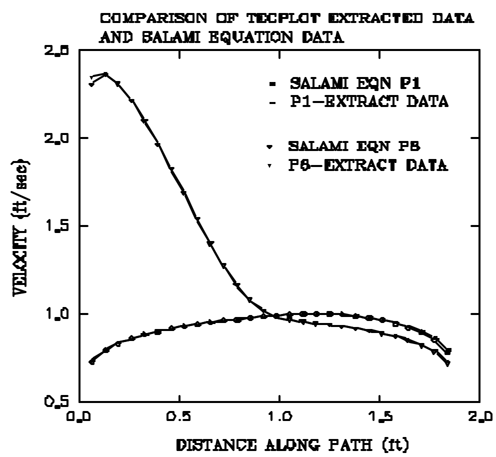


Figure 6. Comparison of interpolated and computed velocity profiles for velocity functions P1 and P8 as described by Salami (1972).

Velocity distribution numerical models were used to analyze the Chebyshev quadrature method used by the AVM (Accusonic, Model 7410) to compute discharge. The velocity distribution model was used to extract data required to compute discharges using the loglinear method described in ASME PTC 18-1992.

Data were extracted from the velocity distribution model and checked versus model data. Velocity interpolation uncertainties of 0.2 to 0.3% were typical. The small errors can be attributed to errors in interpolation methods used to predict velocities at intermediate locations between measured data points. These errors usually occurred in areas that had a large velocity gradient, like near the pipe wall. In addition, the software was also tested on mathematically derived velocity distributions as described by Salami (1972). This analysis resulted in errors of 0.26% and -0.09% for Salami velocity distribution profiles, equations Pl and P8, respectively. As illustrated on figure 5, the sound agreement between model velocity data and interpolated values indicated that computer models could be used to interpolate velocity profiles with confidence.

DAVIS PENSTOCK MODEL

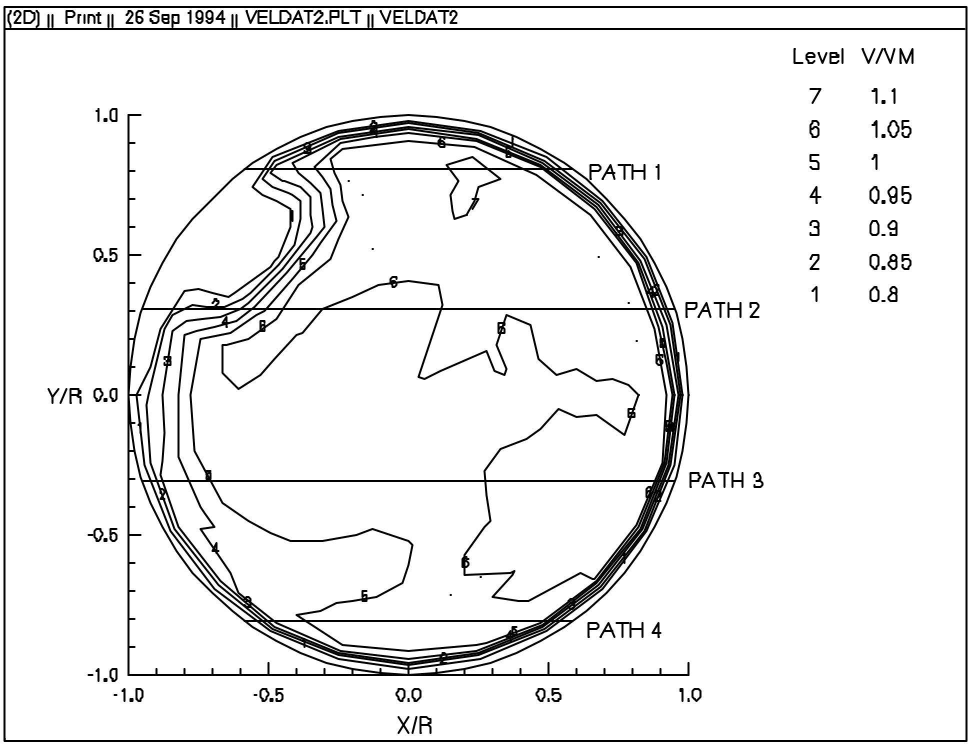


Figure 7. Non-dimensional velocity distribution (looking downstream) for prototype discharge of 154 m^3/sec. The AVM computed discharge was biased -0.31% from the actual flowrate.

Penstock No. 5 was selected for model testing because it is equipped with a crossed plane, eight-path AVM which provides information on severity of cross flow errors. Of the five penstocks at Davis Dam, only No. 5 has a crossed plane AVM. Penstock No. 5 was selected for crossed plane installation because it is the shortest penstock. Davis penstock No. 5 has 1.7 diameters of straight pipe upstream from the AVM measurement section. The combined bend in penstock No. 5 consisted of 24E vertical and 28E horizontal angles. However, penstock No. 5 also has the longest section of straight pipe upstream from the measurement section (fig. 6). Consequently, penstocks No. 1 through 4 may have velocity distributions which are worse than No. 5.

The Davis Dam penstock model included the following features: 1) trashrack, 2) intake transition, 3) combined bend, 4) penstock up to the turbine scroll case.

Hydraulic Model Study Results

A typical contour plot of non-dimensional isovels for tests Davis penstock tests is shown in figure 6. This figure shows four acoustic paths which represent a view looking downstream. Comparison of the plots shows a consistent region of low velocity in the upper left quadrant. These low velocities were caused by the combined (horizontal and vertical curves) bend just upstream from the measurement cross section. This bend caused a secondary current to form, which reduces velocity along the inside of the bend. Conversely, centrifugal forces cause higher velocities along the outside of the bend. These localized variations in velocity distribution make this AVM installation nonstandard. For nonstandard AVM installations, velocities measured along the four acoustic paths will differ depending on path orientation. Likewise, discharge measurements also depend on path orientation.

AVM Flow Measurement Simulation

To determine how an asymmetric velocity distribution affects the uncertainty, the flow measurement computations performed by the AVM had to be simulated. The Accusonic Model 7410 AVM uses the Chebyshev quadrature method of numerical integration. Simulated discharge computations were accomplished by using a software utility to extract (interpolate) data along each acoustic path from the velocity distribution model. The extracted velocity data were numerically integrated over the acoustic path length to determine the average path velocity. This average path velocity is the same parameter the AVM calculates using transit times and the path angle. Average path velocities were then used in the AVM discharge equation to compute discharge. The AVM discharge computation was then compared to the flow rate computed by integrating the LDA velocity data using the tangential method. The discharge computed using tangential integration was considered to be the standard for all comparisons. The error between the two discharges is an indication of the error associated with the Chebyshev quadrature method of integration for an asymmetric velocity distribution. This analysis was also carried out for the acoustic paths rotated by 15 degree increments through 90 degree clockwise and counterclockwise directions.

Model Study Conclusions - For this paper I will not go into the details of the model studies, but I will include the model study results. If further information is needed I can be contacted at (303) 445-2154 or my e-mail address is: *tvermeyen@do.usbr.gov*. A report for this study is available upon request.

Davis Penstock No. 5 - An asymmetrical velocity distribution was identified for Davis Penstock No. 5 for all discharges tested. A combined bend just upstream of the AVM measurement cross section creates a secondary current which results in a reduced velocity along the inside of the bend. Data analysis showed that, for this asymmetrical velocity distribution, velocities measured along the four acoustic paths are considerably different depending on acoustic path orientation. Discharge measurement errors as large as 2 percent were measured. An analysis to determine the optimum path orientation showed the existing condition, horizontal acoustic paths, is optimum. For the prototype path

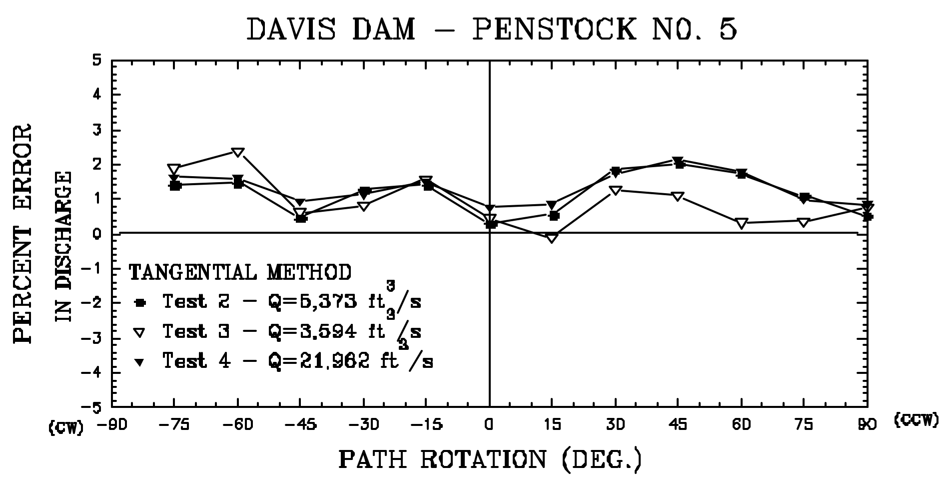


Figure 8. Percent error in discharge measurement as a function of path rotation. This plot indicates the best transducer configuration is the existing, horizontal acoustic paths.

orientation, errors in Gaussian quadrature integration of asymmetric velocity distributions for tests 2 through 4 were found to be -0.31, -0.44, and -0.75 percent, respectively (see figure 4).

Parker Penstock No. 1 - A nearly symmetrical velocity distribution was identified for Parker penstock No. 1 for all discharges tested. A combined bend upstream of the AVM measurement cross section creates a slightly skewed velocity distribution. Data analysis showed that for this particular velocity distribution, velocities measured along the four acoustic paths are very similar and path velocities are essentially independent of path orientation.

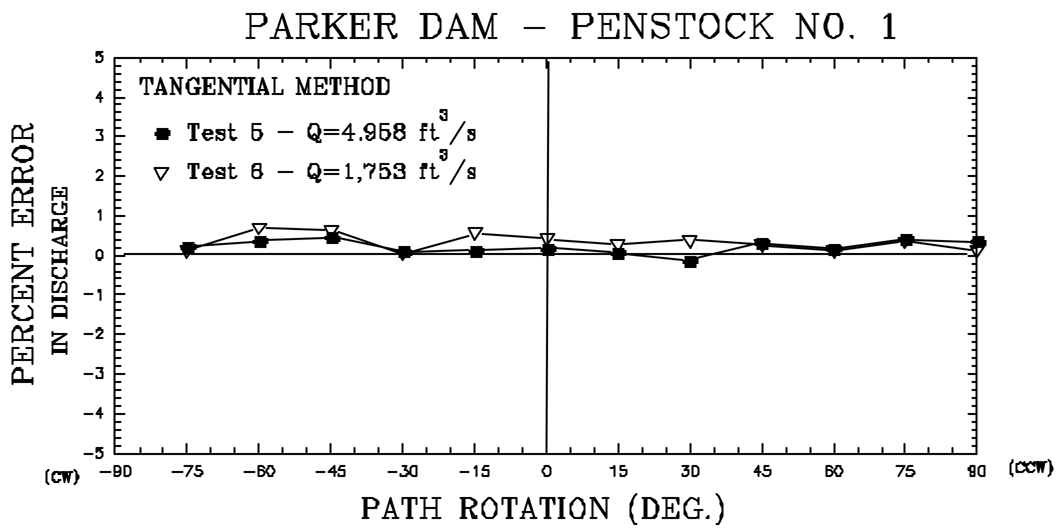


Figure 9. Percent error in discharge measurement as a function of path rotation. This plot indicates the best transducer configuration is for a 30E clockwise rotation, but the existing horizontal acoustic paths are also very accurate.

Errors in Gaussian quadrature integration of the velocity distributions for tests 5 and 6 were found to be +0.18 and +0.41 percent, respectively (see figure 5). Therefore, the prototype AVM installation on Parker penstock No. 1 should perform to the manufacturer's specified accuracy of ±0.50 percent, provided other errors related to AVM installation and setup are also within manufacturer's specifications.

Integration errors for penstocks No. 2 through No. 4 are probably smaller than penstock No. 1 because of there is more straight pipe downstream of the combined bend.

Conclusions

Field evaluations of AVM installations were valuable in identifying nonstandard installations and system parameter errors. A method for estimating integration errors associated with asymmetrical velocity distributions is needed to estimate the total uncertainty of an AVM discharge measurement.

Table #. As-built error summary for single plane and cross plane AVMs at Davis Penstock No. 5 and Parker Penstock No. 1. The total probable error was calculated as the square root of the sum of the individual errors squared.

Error Source	Typical Value	Typical Uncertainty	Worst Case Error (%) Davis No. 5	Worst Case Error (%) Parker No. 1
Path Length *	23 ft	±1/16 inch	0.02	0.02
Path angle *	45E	±20 sec	0.01	0.01
Area *	380 ft^2	±0.1%	0.11	0.09
Dimensional changes caused by temp./pressure**	-	unknown	-	-
Transducer installation **	-	±0.15%	0.15	0.15
Electronics and timing **	-	estimated	0.10	0.10
Cross flow*	-	varies	0.54	1.90
Velocity profile integr.#	-	varies	0.38	0.32
Total probable error for single plane AVM			0.69	1.94
Total probable error for cross plane AVM			0.44	0.38

* from field study
** based on manufacter's experience
\# from model study

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References

Durst, F., Melling, A., and Whitelaw, J.H., "Principles and Practice of Laser- Doppler Anemometry," *Academic Press*, 1976.
Fisher, S.G. and Spink, P.G., "Ultrasonics as a Standard for Volumetric Flow Measurement," Modern Developments in Flow Measurement, C.G. Clayton,

Proceedings of International Conference, September 1971 at Harwell U.K., London, *Peregrinus*, 1972.

Haecker, M.A., "Convergent Gridding: A new approach to surface reconstruction," *Geobyte*, June 1992.

Lowell, F.C., Jr. and Hirschfeld, F., "Acoustic Flowmeters for Pipelines," *Mechanical Engineering*, October 1979, pp 28-35.

Salami, L.A., "Errors in Velocity-Area Methods of Measuring Asymmetrical Flows in Circular Pipes," Modern Developments in Flow Measurement, C.G. Clayton, Proceedings of International Conference, September 1971 at Harwell U.K., London, *Peregrinus*, 1972.

Taylor, J.W., "Prototype Experience with Acoustic Flowmeters," American Society of Civil Engineers, *Proceedings of WATERPOWER '87*, 1987.

Winternitz, F.A.L., and Fischl, C.F., "A Simplified Integration Technique for Pipe Flow Measurement," *Water Power*, June 1957, P. 225.

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