FLOW CONDITIONER DESIGN FOR IMPROVING OPEN CHANNEL FLOW MEASUREMENT ACCURACY FROM A SONTEK ARGONAUT-SW

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ABSTRACT

Acoustic Doppler Velocity Meters (ADVMs) have become popular for open channel flow measurement. However, the methods used to calculate mean channel velocity from the ADVM sample (such as flow rate indexing procedure or theoretical computations such as depth-integrated power law) require significant investment in calibration time and channel improvements to provide reasonable calibration accuracy. This study utilized a Computational Fluid Dynamics model validated with the physical Cal Poly flume to design a device to condition the flow through the upward-looking ADVM sampling beams. It was found that a simple linear relationship exists between the mean sample velocity and the actual mean channel velocity when the conditioning device was used. A procedure has been developed to design a flow conditioner for applications in open channels where ADVM devices will be installed. The designed conditioner is shorter than expected and the ADVM requires minimal calibration, reducing the cost of construction and time required for calibration. Test results indicate that the flow rate measurement accuracy from the ADVM with the flow conditioner can be improved to within +/-2.2% under a range of typical flow rate and depth conditions.

INTRODUCTION

In the past decade there have been significant advances in new acoustic velocity measurement technologies. The Irrigation Training and Research Center (ITRC) has tested a variety of acoustic Doppler, magnetic, and transient-time devices in the laboratory and in irrigation districts for pipelines and canals.

Commercial Acoustic Doppler Velocity Meters (ADVMs) sometimes provide considerable advantages over traditional techniques such as current metering, stage-discharge relationships, flumes and weirs because they require no headloss, provide real-time data, are more accurate than stage rating, and are less expensive than the alternatives. However, for the canals and drainage ditches in irrigation districts, ADVMs still have significant problems including the time required for, and the uncertainties related to, accurate calibration of the device.

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In some cases, this problem is approached by integrating the one-sixth Power Law over the depth of the ADVM measurement region to relate the ADVM average sample velocity to the cross-sectional average velocity (Huhta and Ward 2003). However, this method shows poor accuracy in field applications and is not recommended (Styles et al. 2006). Likely reasons that the depth integrated Power Law does not perform adequately in field installations are that the method does not directly account for either channel geometry or roughness when relating sample velocities to the cross-sectional average velocity.

The alternative to the depth-integrated Power Law or other theoretical procedures is to calibrate the device for each installation. The recommended ADVM calibration procedure is termed the “Flow Rate Indexing Procedure” (QIP). The QIP relates the ADVM velocity to the cross-sectional average velocity measured using a “standard” device such as a current meter (Morlock et al. 2002; Styles et al. 2006) at numerous points in a cross section. At least 10 calibration points over the full range of flow rates and channel depths are recommended. In an agricultural installation it could take several months of calendar time to obtain readings over the full range of flows because low flow rates may only be available during the spring and fall. If sedimentation or vegetative growth is prevalent, this procedure may have to be completed every several years. The cost advantage of the ADVM installation degrades once the cost of labor for calibration is included.

In order to maintain accurate ADVM flow rate measurement post-calibration, a well-maintained cross section is necessary. Concrete lining of a flow measurement section 5 to 10 times the channel width typically provides the most stable cross section and is generally recommended for ADVM installations where accurate flow data is desired (Styles et al. 2006).

In recent years numerous ADVM designs have been developed for open channel and closed conduit flow measurement. Most common designs utilized in open channels are either horizontal profiling where the device is mounted on the side of a channel or bridge pier, or vertical profiling where the device is mounted on the channel bottom and velocities are sampled vertically. This paper will discuss an ADVM that is bottom-mounted in the center of the channel and uses two acoustic beams: one pointed in the upstream direction at an angle of 45˚ from vertical and the second pointed in the downstream direction at an angle of 45˚ from vertical (termed “upward-looking” ADVM). A third vertical transducer is used to provide flow depth measurements. A SonTek/YSI Argonaut-SW (SonTek-SW) with these characteristics was utilized for the physical measurements in this study.

As with most ADVM devices, the first velocity reading must be taken with a recommended “blanking distance” away from the device. The SonTek-SW is approximately 6 cm high and has a recommended blanking distance of 7-8 cm. Assuming a mounting bracket is used that adds 1-2 cm, the distance between the channel bottom and the first velocity measurement is typically 15-16 cm.

This paper will present a velocity conditioner design consisting of a relatively short contraction, which can be used in conjunction with the SonTek-SW to improve flow measurement accuracy with minimal calibration. The design parameters for the contraction were developed using a 3-D computation fluid dynamics software. The design was validated by taking physical measurements in the Cal Poly ITRC flume.

The conditioner is recommended to replace the concrete lined flow measurement section because it not only provides a constant cross section but also, as will be seen in the results presented in this paper, the required calibration can be minimized or eliminated completely while maintaining a high degree of accuracy. The conditioner presented here will likely be shorter than a concrete lined section that has a similar shape as the existing channel, which could result in a reduced installation cost.

CONDITIONER DESIGN

A computational fluid dynamics (CFD) software called Flow 3D™ was used to design a velocity profile conditioning device that could be used in open channels in conjunction with an upward-looking ADVM. Flow 3D™ was selected because it handles free surface flows well and has been field tested under a number of hydraulic conditions (Cook and Richmond 2001). Flow 3D solves the Reynolds-Averaged Navier-Stokes (RANS) equations by finite volume method, three-dimensionally using a Cartesian grid system and resolving free surface flow using a volume-of-fluid (VOF) model.

Prior to designing the conditioner, the CFD model accuracy was verified against physical measurements. A model was constructed with the same dimensions as the actual large rectangular flume at the Irrigation Training and Research Center, California Polytechnic State University, San Luis Obispo (Cal Poly flume). Velocity measurements were taken in the Cal Poly flume under a variety of flow rate and depth scenarios. CFD simulations were conducted under the same flow rate and depth scenarios and the velocities from the model were compared to the actual flume measurements.

Once model accuracy was verified, differing conditioner designs were simulated. It was found that subcritical side contractions with a smooth inlet transition provided a reliable velocity distribution in the measurement section. With the velocity measurements taken near the start of the contraction throat, the ADVM average sample velocity was shown to have a direct linear relationship with the channels cross-sectional average velocity. Figure 1 shows a plan view of the proposed contraction with the basic design parameters.

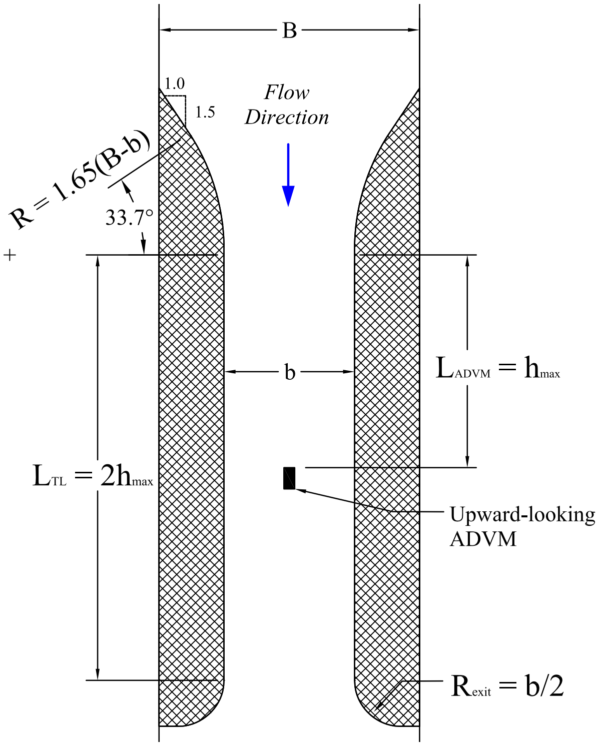

Figure 1. Plan view of the contraction used for velocity conditioning with a SonTek-SW.

The contraction ratio is commonly calculated as b/B, where b is the contraction opening width and B is the upstream channel width measured at 50% of the maximum flow depth. The contraction entrance is a combination of straight section at a ratio of 1:1.5 (perpendicular:parallel to channel side) and a rounded section with radius, R, which leads into the contraction throat. This entrance design was first published by Smith (1967) and was selected because it provides a smooth transition with minimal flow separation at the throat entrance. It was also felt that this entrance would be easier to construct, making it less costly than alternative designs with similar hydraulic characteristics.

The contraction throat length and location of the upward-looking ADVM are functions of the ADVM beam angle. SonTek-SW utilizes a 45˚ beam angle from vertical for the upstream and downstream beams for a total of 90˚ between the two velocity sampling beams. In order to maintain sampling within the contraction throat (straight section) the contraction throat length (L_{TL}) must be 2 times the maximum expected water level (h_{max}). The ADVM must be located (L_{ADVM}) at a distance equal to h_{max} from the start of the contraction throat. The exit transition is not as critical as the entrance since downstream conditions have not been shown to impact the velocity readings. Figure 1 shows a simple rounded exit with a radius (R_{exit}) equal to $b/2$.

Importantly, the flow within the contraction must remain subcritical. The contraction ratio (CR=b/B) selected for the design should not exceed a maximum (CR_{max}) of 0.75. The minimum CR should be selected so that the Froude number (F) within the contracted section does not significantly exceed 0.45 to minimize wave formation within the measurement section. The minimum CR (CR_{min}) and contraction opening (b_{min}) can be calculated as:

$$CR_{\min} = \frac{Q_{\max}}{0.45 B h_{\min *}^{3/2} g^{1/2}} \tag{1}$$

$$b_{\min} = \frac{Q_{\max}}{0.45 h_{\min *}^{3/2} g^{1/2}} \tag{2}$$

where Q_{max} = maximum expected flow rate in the channel, h_{min*} is the minimum flow depth expected in the channel at the maximum flow rate, B is the upstream channel width measured from bank to bank at 50% of the maximum depth, and g is gravitational acceleration. Actual h_{min*} will be lower in the contraction as velocity is accelerated in the contraction due to the change from potential energy to kinetic energy. This will cause the post-design Froude number to be slightly greater than 0.45 if b_{min} is selected as the contraction width design. Ideally, the design CR should be selected somewhere between CR_{max} and CR_{min} to maintain the maximum F between 0.2 and 0.3.

The height of the conditioner should provide sufficient freeboard so that water does not pass over the top of the contracted sides. The bottom of the contraction should be at the same elevation as the existing channel.

The conditioner shown in Figure 1 was modeled under the four flow rate scenarios and three depth scenarios shown in Table 1. Contraction ratios (CR) of 0.5 and 0.75 were simulated at most of the flow and depth scenarios. However, scenarios that resulted in critical or supercritical flow within the contraction were not analyzed.

Table 1. Contraction ratios (CR) simulated at each depth and flow rate scenario.

Flow Rate	Nominal Depth		
(cms)	1 m	0.65 m	0.35 m
0.283	0.5, 0.75	0.5, 0.75	0.75
0.425	0.5, 0.75	0.5, 0.75	none
0.566	0.5, 0.75	0.75	none
0.708	0.5, 0.75	0.75	none

Data was extracted from each simulation along the same beam paths as a SonTek-SW would sample (45° beam angles from vertical). Data was extracted at and above a buffer distance of 0.15 m from the channel floor (assuming a blanking distance of 0.08 m above the sensor and assuming the sensor and mounting bracket height is 0.07 m) at intervals of 0.034 m up to the water surface. This simulates the dynamic boundary setting of the SonTek-SW where the SonTek averages velocities from the buffer distance to the water surface. Velocity data from the upstream and downstream beams was averaged to develop the average ADVM velocity (V_{ADVM}). The cross-sectional average velocity (V) was computed using the known flow rate divided by cross-sectional wetted area calculated using the contraction opening (*b*) and water depth (*h*) at the simulated SonTek-SW location.

Figure 2 shows the simulated SonTek-SW average sample velocity (V_{ADVM}) compared to the cross-sectional average velocity (V) from the simulations. The linear regression on the data from Figure 2 generates the following equation with an $r^2 = 0.9995$:

$$V_{calc} = C_{sc} V_{ADVM} \tag{3}$$

where V_{calc} = calculated cross-sectional average velocity and C_{sc} is the subcritical contraction coefficient which is equal to 0.9498 for a buffer distance of approximately 0.15 m.

Equation 3 is only valid for SonTek-SW using 45° beam angles, within a conditioner designed using parameters from Figure 1, with a buffer distance of 0.15 m to 0.16 m, and where V_{ADVM} is obtained as the raw depth averaged velocity using the dynamic boundary condition.

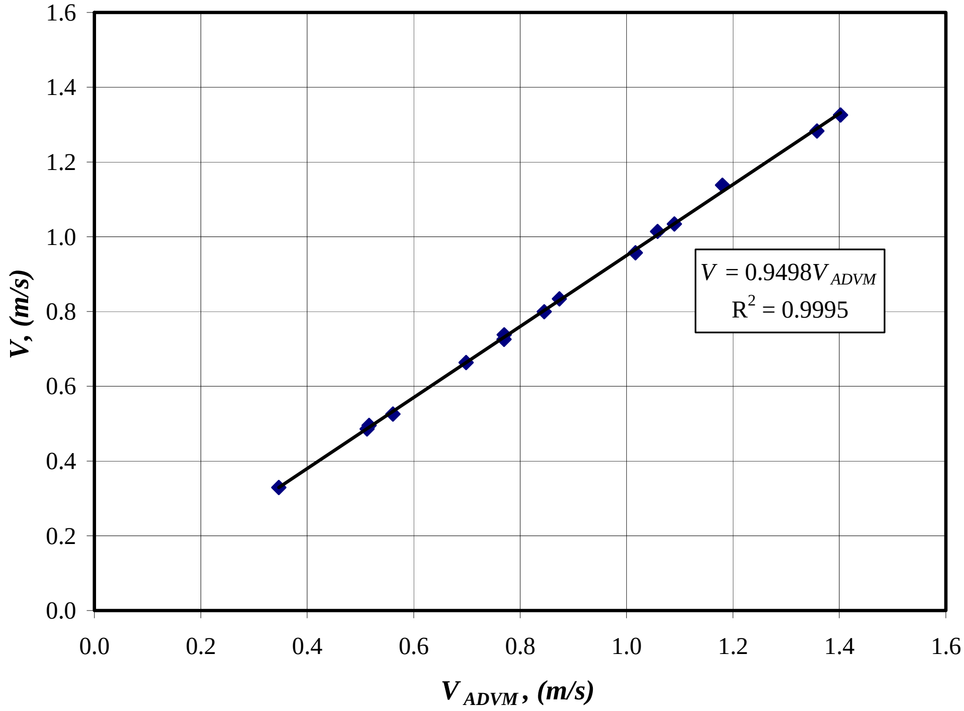

Figure 2. Comparison of ADVM sample velocity (V_{ADVM}) to cross-sectional average velocity (V) at the ADVM within the conditioner from CFD simulation results used to derive the linear relationship between the values

Evaluation of Accuracy of Equation 3 using CFD Results

The CFD data extracted from simulations in Table 1 were used to calculate the cross sectional average velocity (V_{calc}) using Equation 3. Table 2 shows the percent error between V_{calc} and the actual cross-sectional average velocity (V) from the simulations.

Table 2. Comparison of V_{calc} and V from the CFD simulations

Flow Rate (cms)	Nominal Depth (m)	Contraction Ratio (CR)	V_{ADVM} (m/s)	V_{calc} (m/s)	V (m/s)	Percent Error
0.283	1.00	0.50	0.516	0.490	0.495	-0.95%
0.283	1.00	0.75	0.347	0.329	0.329	0.06%
0.425	1.00	0.50	0.770	0.732	0.738	-0.84%
0.425	1.00	0.75	0.512	0.487	0.486	0.18%
0.566	1.00	0.50	1.059	1.005	1.014	-0.86%
0.566	1.00	0.75	0.698	0.663	0.663	0.02%
0.708	1.00	0.50	1.358	1.289	1.283	0.51%
0.708	1.00	0.75	0.874	0.830	0.834	-0.44%
0.283	0.35	0.75	1.017	0.966	0.957	0.89%
0.283	0.65	0.50	0.845	0.803	0.800	0.44%
0.283	0.65	0.75	0.561	0.533	0.526	1.33%
0.425	0.65	0.50	1.180	1.121	1.138	-1.48%
0.425	0.65	0.75	0.770	0.731	0.726	0.75%
0.566	0.65	0.75	1.090	1.035	1.034	0.10%
0.708	0.65	0.75	1.402	1.332	1.326	0.45%

The results in Table 2 show errors between -1.48% and 1.33% using Equation 3 to relate V_{ADVM} to V. The range of percent error is considered excellent and confirms the accuracy of Equation 3 for simulated flows.

PHYSICAL TESTING OF THE CONDITIONER

Experimental Setup

The contraction design parameters from Figure 1 were used to construct a contraction for testing in the Cal Poly flume. The Cal Poly flume is 1.215 m wide by 1.215 m deep by 86 m long (Figure 3). The bottom slope of the painted steel flume is 0.002. Flume components are capable of handling flow rates up to 0.85 cubic meters per second (cms). The testing region of the flume is approximately 54 meters long. The starting point of the testing region was just downstream of a flow conditioner consisting of a honeycomb of 3 inch diameter PVC pipes approximately 1 meter in length (Figure 3). The water level in the testing region is regulated by a vertical weir at the downstream end of the flume.

Figure 3. Cal Poly flume, looking downstream (left) and honeycomb flow conditioner (right)

The Cal Poly ITRC flume uses a recirculation facility to achieve high flow rates in the flume. The flow rate into the flume is regulated through a valve at the flume entrance and is measured in real-time by a calibrated 0.76 m diameter McCrometer Magmeter.

The conditioner design parameters for the CR of 0.5 included a L_{TL} of 2 m, an entrance radius (R) of 1 m, and an R_{exit} of 0.3 m. The subcritical contraction design was installed in the Cal Poly flume 30 m downstream of the flow measurement section entrance.

A SonTek-SW, an upward-looking ADVM with a beam angle of 45˚, was installed within the contraction at a distance of 1.0 m (L_{ADVM}) downstream of the start of the throat. The SonTek-SW's average velocity samples were developed using the SonTek's dynamic boundary setting whereby the SonTek takes a depth-averaged velocity above a buffer distance of 0.15 m from the channel bottom to just below the water surface. The SonTek automatically adjusts the top velocity boundary depending on the real-time water level. The V_{ADVM} sampling interval was 5 to 10 minutes and the number of samples for each scenario ranged from 20 to 50.

Figure 4. Subcritical contraction and SonTek-SW installed in the Cal Poly ITRC flume.

Physical tests analyzed nominal flow rates of 0.283, 0.425, and 0.566 cms at nominal depths of 0.7 and 1.0 m maintaining F below 0.45. The actual flow rates and depths varied somewhat from nominal because of hydraulic conditions related to the conditioner and the inability to match the nominal values exactly with the VFD and downstream weir.

Actual cross-sectional average velocity (V_{actual}) was developed using flow rate values from the Magmeter and a cross-sectional area calculated using the SonTek-SW measured water levels at the SonTek location and the contraction opening width.

Equation 3 was used to calculate V_{calc}, which is an estimate of V_{actual}. The C_{sc} used for Equation 3 was .9498 with V_{calc} calculated as:

$$V_{calc} = 0.9498 V_{ADVM} \tag{4}$$

The percent error between the calculated (V_{calc}) and V_{actual} was computed as:

$$Error = \frac{(V_{calc} - V_{actual})}{V_{actual}} * 100\% \tag{5}$$

Results and Discussion

The results of the physical tests are shown in Table 3. The percent error between calculated cross-sectional average velocity (V_{calc}) and actual cross-sectional velocity (V_{actual}) on average over all of the samples was less than +/-1%. The results indicate that using the conditioner with Equation 3 has a range of errors within +/-2.2% without any calibration.

Table 3. Results of the subcritical contraction with the SonTek-SW from physical measurements in the Cal Poly ITRC flume.

Actual Flow (cms)	Number of Samples	Average				Error of V_{calc}		
		Depth (m)	V_{ADVM} m/s	V_{calc} m/s	V_{actual} m/s	Average %	Minimum %	Maximum %
0.292	30	0.926	0.543	0.516	0.518	-0.35%	-2.15%	1.32%
0.440	50	1.000	0.767	0.728	0.722	0.86%	0.03%	1.74%
0.571	20	1.053	0.939	0.891	0.889	0.32%	-0.21%	1.22%
0.293	30	0.739	0.682	0.648	0.651	-0.39%	-2.09%	1.33%
0.440	50	0.731	1.046	0.993	0.987	0.69%	-0.73%	1.69%

The results show successful validation of the conditioner design. The ranges of errors from the physical test are considered excellent for open channel flow measurement.

SUMMARY

A concrete cross section with a special velocity profile conditioning design was presented that can be used in conjunction with a SonTek-SW or similar upward-looking ADVM to provide accurate out-of-the-box calibration. Initial CFD simulation results were validated using physical measurements taken at the Cal Poly ITRC flume. Results indicate that the conditioner used in conjunction with the SonTek-SW will provide accurate flow rate measurement within a +/-2.2% error without calibration.

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