Evaluation of ADCP Streamflow Measurements in Open Channel

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Abstract

The purpose of this paper is to explore the potential of calibration of ADCP discharge measurement in open channel, which conclusion can improve the traceability of ADCP. In this paper, the current velocity and discharge synthesis and other important issues are taken into consideration, and establishes a set of rectangular open channel standard discharge facility, and conducts experimental research on the flow measurement by using Workhorse. The moving boat ADCP measurement uncertainty source is analyzed, and the error situation introduced by the approximate solution is analyzed. By estimating the back scattering intensity, a new type of acoustic reflector is designed, so that the signal quality of ADCP can be kept in the best state in the process of towing calibration, so as to ensure the reliability of the WT measurement results. An experimental device for WT, BT, depth measurement is established to evaluate the basic performance of the instrument. At last an ultrasonic transit time flow-meter(UFM) is taken as reference in field situation, to calibrate the discharge directly, the results are close to laboratory calibration.

1. Introduction

ADCP is widely used in the river and open channel, and the measurement principle of discharge is velocity area method. The most commonly measurement moving-boat approach is to carry the ADCP on the ship and move cross the river section, so that the velocity field can be depicted, and the discharge can be calculated by integrating. Considering the complexity of the on-site situation, the previous evaluation method is mainly carrying out a variety of repeated measurements on the premise that the discharge does not have a sudden change, which is a variance analysis. The uncertainty of the discharge measurement also includes the fluctuation on the time axis and cross-section selection. Some studies still take the vertical mean velocity measured by current meter point by point as reference standard, which makes the site work heavy.

The uncertainty sources of discharge measurements are mainly including instrument performance, integration method, cross-sectional effect, operators, etc[1]. The most important performance of the instrument is water tracking (WT), bottom tracking (BT), depth, temperature and compass[2]. The WT and BT is the most widely calibrated in laboratory, but the WT calibration is related by the testing environment, when scattering solid particles or air bubbles in still water as acoustic reflector, to simulate the natural water of the site conditions[3,4]. The concentration of acoustic reflectors gradually decreases with time, which make the SNR of ADCP variation and increases the error of WT velocity measurement[5]. The errors introduced by integration are mainly including the discharge synthesis method, the estimation of the boundary area, and the error introduced by sailing path[6,7]. Due to the driving effect of the river, the moving path is adjusted constantly, and is not a straight line perpendicular to the flow direction, which needs to be compensated by compass or GPS[8]. In addition, the stability of the flow field distribution, the measurement time across the section and the number of cross sections are also important uncertainty sources of the measurement results. Therefore, the evaluation through each component of uncertainty source is complex.

Although the measurement procedures may present differences between ADCP companies, the moving-boat measurement results are commonly the average of elemental discharges based on a number of transects, which is crossings of the stream, under approximately steady flow conditions. Ideally, the average includes pairs of reciprocal transects to minimize directional biases in measured discharges, due to asymmetrical deployment, compass, or heading errors[9,10]. Given the use of ADCP measurements as inputs to flow monitoring and decision-making activities related to water resources[11,12], the uncertainty has to be estimated carefully in addition to a quality assurance and quality control process[13,14]. Uncertainty analysis aims at providing relevant information for decision making and whenever possible for refining the measurement process to reduce the uncertainty.

In this paper, the flow integration used in the experiment is established, based on the analysis of the flow velocity distribution model and boundary effect in the typical open channel. An experimental device for WT, BT, depth measurement is established to evaluate the basic performance of the instrument. At last, an on-site calibration method in open channel is established.

2. Principle

The moving-boat ADCP method can be used for cross-sectional flow measurement with flexible and high-precision. Compared with the natural river, the boundary of the regular open channel is much simpler, and the error of the measurement result using the velocity area method can be smaller. Taking the RiverPro as an example, 4 symmetrical spatial ultrasonic sensors are settled, and the measured velocity data can be converted into a 3D pointing current velocity under the ship. According to the boat's track, the river cross-section can be divided into *m* sub-sections, and then the vertical sub-section can be divided into *n* sub unit area, the discharge of open channel can be taken as the integral of the velocity of m×n units. According to the velocity in each sub-area unit, boat entry depth, sailing speed, and attitude declination, the flow-rate in edge area can be estimated.

The calculation of flow discharge is quite complex, which can be simplified in Figure 1. Considering the uniformity of the distribution of sound reflectors in water and the attenuation of ultrasonic waves, which affect the measurement results of the velocity original data quantity, the gross velocity errors in the stratified data set can be removed by the built-in algorithm of ADCP, and these missing points has to be interpolated or fitted approximate to fill the velocity field in section. The direction of effective data is rotated by real-time compass modification to obtain the beam velocities, and then the current velocity and average depth in each layer under instrumental coordinate can be transformed according to boat track.

According to the moving-boat ADCP synthetic calculation, the discharge in cross section can be divided by 5 parts, as shown in Figure 2, the total discharge of cross section can be expressed by

$$Q_s = (Q_m + Q_{em}) + Q_{et} + Q_{eb} + Q_{el} + Q_{er} \tag{1}$$

Where, Q_m is the discharge obtained by quantities measurement through coordinate transformation and direction compensation, Q_{em} is the estimation through effective current velocity distribution by the ADCP post-processing for the missing subsection data, Q_{et} and Q_{eb} is the discharge estimated by the current velocity distribution near free surface and bottom, Q_{el} and Q_{er} is the discharge estimated in the unmeasured area near left and right edge.

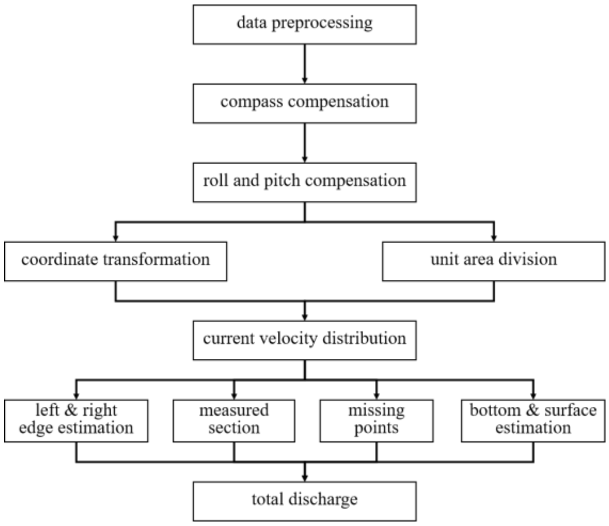

Figure 1: Data processing of moving-boat ADCP discharge measurement.

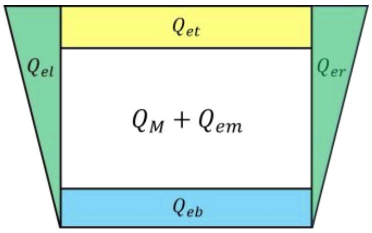

Figure 2: Schematic of discharge estimation in open channel cross section by moving-boat ADCP.

2.1 Measured discharge and velocity distribution

The discharge in the middle of channel can be measured, the Q_m can be defined by Velocity area method as

$$Q_m = \int u_f nds \tag{2}$$

Where, u_f is water velocity vector, *n* is unit vector normal outward to the differential area *ds*. In open channel flow, *s* is total white section in Figure 2. Constraints of the ADCPs architecture and operating principles, renders them unable to measure near solid boundaries or the free surface. The section area can be measured when the boat moving cross the channel, as

$$ds = |v_b|_d \cos(\theta) dt \tag{3}$$

Where, v_b is the moving velocity of boat, which can be measured by bottom track or GPS, θ is the angle between track and section. And the discharge Q_m measured by ADCP can be illustrated as

$$Q_m = \int_0^T \int_{Z_l(t)}^{Z_u(t)} (u_f \cdot (v_b \times b)) dzdt = \int_0^T \int_{Z_l(t)}^{Z_u(t)} ((u_f \times v_b) \cdot b) dzdt \quad (4)$$

Where, b is the roll and pitch angles measured by compass, $Z_L(t)$ and $Z_U(t)$ is the lower and upper limit of the water column at time t during the transect where the water velocity is measured.

Because of the data of ADCP measurements is quite intensive, some missing data can be replaced by extrapolation method, such as power law for the lower part of the velocity or constant velocity for the upper part of the profile.

2.3 Edge estimation

The discharge in edge area cannot be measured directly in sharp slop situation. Considering a thin layer of the open channel as a rectangular open channel, the simulation result shows that the velocity distribution in the horizontal direction is in the form of a power function regardless of the influence of wind on the surface.

$$U = a(1-2z)^b \quad (5)$$

Where, z is the relative position to the boundary of channel. The ideal distribution is shown in Figure 3. As is shown, the velocity gradient is the largest, in the thin layer near the boundary on edge, and U drops below 0.85 when the thickness of the boundary layer is 1%.

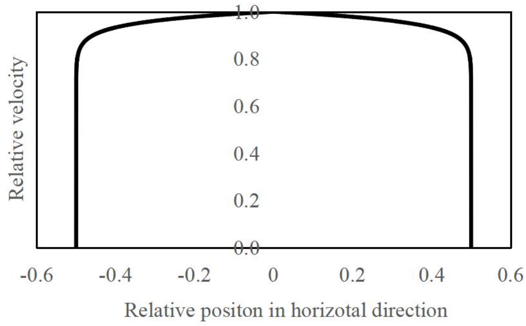

Figure 3: Current velocity distribution in horizontal direction.

The left and right edge discharge can be estimated by triangular or square approximate model, for symmetrical regular open channel, it can be simplified as

$$\frac{Q_{el}}{Q_s} = \frac{Q_{er}}{Q_s} = K\overline{U}\,\overline{y} z_e \quad (6)$$

Where, K is a coefficient set to 0.35 for triangular and 0.91 for square case, respectively, $\overline{U}$ is the estimated average relative velocity in edge, $\overline{y}$ is the average relative height in edge, z_e is the width of edge area.

The average velocity $\overline{U}$ is hardly be measured by ADCP, but can be estimated by interpolation. In one way, the velocity in each layer can be estimated by power function, and integration is used to obtain discharge by using (5). In another way, the edge velocity can be linearity interpolated by few units close to edge, by using "no-slip" method, the discharge is estimated by (6).

2.4 Surface and bottom estimation

Assumptions of distribution in surface and bottom are usually made by fitting, and the parameters are estimated by measured velocity in the lowest good bins, which is using "no-slip" method. Use the dimensionless relative velocity U and relative water depth to characterize the velocity distribution in vertical direction, the logarithmic function is mostly used, in binary open channels, based on the Prandtl theory.

$$U = 1 - \frac{U^*}{U_{\max} k} \ln\left(\frac{1}{y}\right) \quad (7)$$

Where, U_{max} is the maximum vertical velocity, U^* is the friction velocity, k is the Karman constant, y is the ratio of the distance from the survey point to the bottom to the water depth.

In order to obtain more accurate measurement results, a segmental fitting function can be used. The CFD simulation in rectangular open channel shows that, it is close to the logarithmic distribution in the range close to the bottom, and is closer to the parabolic mode in the half-deep and the free surface region. The current velocity distribution can be express by

$$\begin{cases} U = a_1 + b_1 \ln(y) & 0 < y \leqslant 0.2 \\ U = a_2 + b_2 y + c_2 y^2 & 0.2 < y \leqslant 0.6 \\ U = a_3 + b_3 y + c_3 y^2 & 0.6 < y \leqslant 1 \end{cases} \quad (8)$$

Where, a_1, b_1, c_1 is the linearity function of z, and a_2~c_3 is the second-order polynomial of z, which z is the relative position of the vertical line to the boundary. The fitting of piece-wise function and logarithmic function is quite close, but separated in surface area, which is shown in Figure 4.

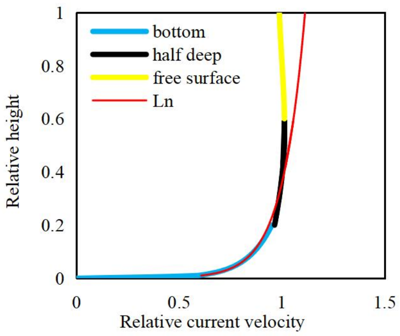

Figure 4: Current velocity distribution in vertical direction.

3. Calibration method in laboratory

According to the Q_m expressed in formula (4), the items that can be calibrated in the laboratory are current velocity and depth. The ADCP measured water track velocity is hard to calibrate in limit tank, which is mainly due to the difficulty of simulating an ideal acoustic reflector in field. And Multiple reflections near the smooth tank wall are also affecting the acoustic Doppler measurement.

In order to improve the testing environment in the water tank as much as possible, rough surfaces are laid on the side wall and bottom of a 8m length glass water tank, and there are certain intervals inside the water body. In case of bottom track, the indication error is about 0.7%, which illustrate the ability of velocity measurement, and the repeatability is about 0.5%. The BT calibration represented the relative displacement between ADCP and rough bottom of tank.

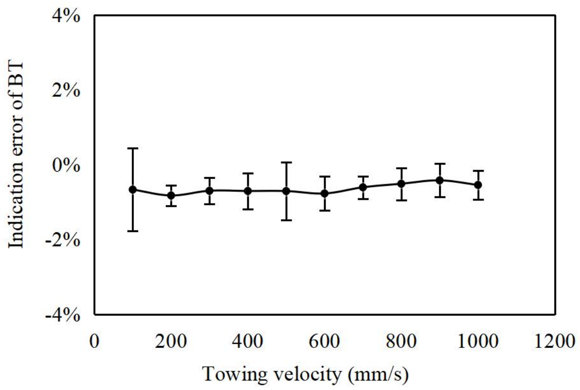

Figure 5: Indication error of BT calibration in towing tank.

The ability of WT measurement depends on the reflected acoustic signal quality. The 50μm diameter solid reflectors are settle in the tank and without movement, the indicating value of current velocity represented the relative movement between ADCP and reflector, the blockage effect isn't affect the testing results in this situation. The indication error shows periodic fluctuation in velocity scale, average error is about 0.13%, with the max deviation is lower than 2%, and the repeatability is about 2%.

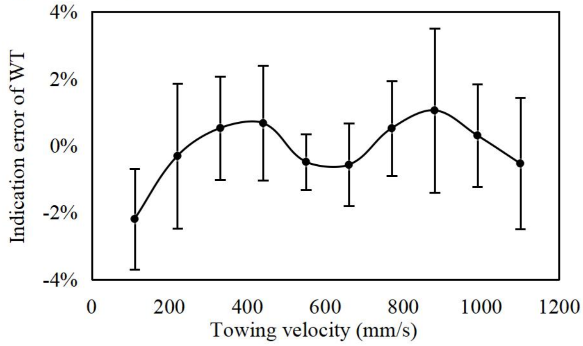

Figure 6: Indication error of WT calibration in towing tank.

4. On-site flow rate calibration

Although laboratory calibration results are not precision enough, the ADCP can obtain a plenty of WT with BT in the same time, which the sample size of the data was increased, and the statistics results of discharge measurement may even better. We take a trapezoidal open channel as example, with a high precision ultrasonic transit time flow meter(UFM) as reference, to analyse its on-site measurement ability. The measured velocity distribution in open channel is shown in Figure 7, as the flow rate increasing, the distribution near bottom changes.

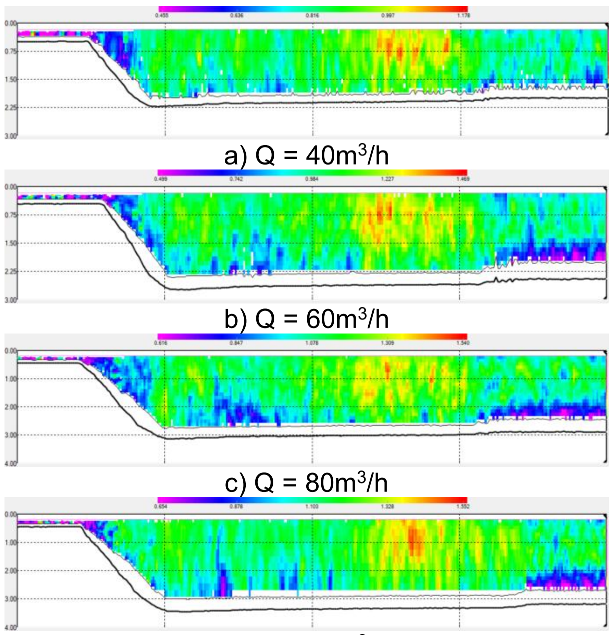

Figure 7: Flow velocity sections of open channels measured by RiverPro ADCP.

The measurement results of ADCP and reference UFM can be shown in Table1, all experiments are held in same section, and each discharge point is repeated 12 times, and the average value is record. The Q_m takes about 80% of total discharge, and average relative error is smaller than 2.8% with better than 1% repeatability, which means the on-site statistical testing results of cross section are close to that of current meter in laboratory flow velocity. The Q_{et} almost has nothing to do with total discharge, and may influenced by wind.

Table 1: Measurement results in open channel.

Q	Q_s	Q_{et}	Q_m/Q_s	Q_{eb}/Q_s	MRE
40.679	40.151	4.315	77.0%	12.0%	2.8%
60.495	60.439	4.552	78.1%	11.5%	0.3%
77.647	77.613	4.972	79.2%	11.5%	1.0%
90.491	88.877	5.769	76.0%	13.8%	-0.1%

7. Conclusion

The method of ADCP measurement in open channel is studied, and the influencing factors of synthesis formula are discussed. The calibration results in on-site situation is even better than towing in still water in laboratory. In the future, more component such as compass and boat track will be test in on-site situation.

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