Design of Acoustic Doppler Current Profiler Calibration System

HuiXie¹, YichengLiu² and MingminZhang²

¹School of Precision Instrument & Opto-Electronics Engineering, Tianjin University, Tianjin, 300072, China
²Tianjin Research Institute of Water Transport Engineering, Tianjin, 300456, China

Abstract. In order to trace and transmit the velocity value of acoustic Doppler current profiler (ADCP), an ADCP velocity measurement method based on deep water channel and unmanned ship is proposed. An unmanned ship carrying ADCP moves at a uniform speed along the planned route. High-speed camera and total station are used as the main standard for time and length measurement. The average velocity of ADCP in the measurement section is measured as a reference value for velocity. Compared with ADCP velocity indication, the error of velocity indication is calculated. Real-time kinematic positioning technology (GPS-RTK) is used to map the trajectory and yaw error of unmanned ship and verify the instantaneous velocity stability. The test results show that, under the condition of unmanned ship setting speed of 1 m/s, the error of ADCP velocity indicated by inspection is -0.029 m/s, and the extended uncertainty of this test system is evaluated as \( U=0.071 \text{m/s} \), \( k=2 \).

1. Introduction

ADCP is an instrument which uses acoustic Doppler shift to measure vector velocity[1]. At present, it is widely used in water transportation engineering construction, hydrologic environment monitoring, ocean and estuary field structure investigation, port channel velocity and flow test, etc.[2] At present, ADCP velocity measurement or calibration is mainly in indoor tank and outdoor rivers, lakes or seas. These two measurement environments have their own advantages and disadvantages. Due to the limitation of construction size, it is difficult to measure low-frequency ADCP and carry out stratified velocity measurement in indoor tank. Boundary reverberation noise influences test results. And the water in the tank is too pure, requiring artificial addition of a certain concentration of scattered particles, such as lime and bubbles[3]. How to add particles and ensure the uniform distribution of them are difficult issues. The outdoor rivers, lakes and seas are wide, and contain natural and uniform scattered particles. However, due to the influence of natural factors such as wind waves, turbulence, tide and sound velocity profile, many uncertain components are introduced into the measurement results[4-6]. This paper relies on the Tianjin lock channel (180m long × 25m wide × 10m deep), which is broad, deep with no waves, and a carrier unmanned ship. The water has the advantages of suspended matter, controllable stratified flow field and other environmental favorable conditions for ADCP calibration. The unmanned ship has the advantages of lightweight, high stability and strong carrying compatibility. The traceability chain of measuring instruments and measurement standards is established to ensure the accuracy and reliability of ADCP velocity measurement.
2. Design of calibration test system

2.1. System hardware design
Traditional ADCP calibration using trailer as carrier, the overall device is complex and the trailer speed is limited. The unmanned ship is used as the carrier to carry test instruments; its speed can reach the highest 3m/s. And the unmanned ship is smaller in size, more flexible and freer, and can sail according to the prescribed route, which is more ideal. In this paper, a customized automatic unmanned ship is adopted. The ship adopts high-molecular polyester carbon fiber material to reduce the influence of magnetic metal on the detection equipment, and carries the absolute straight-line technology. The calibration system installs ADCP transducer to the bottom of the unmanned ship through the connecting flange, and connects the ADCP communication cable to the electronic watertight tank of the ship. The ADCP of different models can be adapted by means of flange switch. The GPS-RTK is installed on the top of the unmanned ship and the axes of the two are in the same line as far as possible, as shown in figure 1, to ensure that the measured velocity measured by ADCP and GPS-RTK is the same position velocity value of the ship.

![Figure 1. Construction of unmanned ship.](image)

1-test tank; 2-velocity calibration device; 3-transfer bracket; 4-GPS-RTK; 5-switch flange; 6-ADCP transducer.

2.2. Test method
The ADCP transducer is installed on the bottom of the unmanned ship through the connecting flange, and the GPS-RTK is installed on the top of the unmanned ship. The two axes shall coincide, and the sampling frequency is 1Hz. Total station electronic tachometer (total station for short) is adopted to lay out two virtual equal length and parallel straight lines of 180m. One straight line is parallel to the long side of the pool and passes through the midpoint of the short side of the pool. The other line is located near shore and serves as a standard line for measurement. The lock is divided into three sections of 15m+80m+15m. The first 15m is the unmanned ship acceleration section, the middle 80m is the uniform measurement section, and the last 15m is the deceleration section. Coordinate information of starting point and ending point of track line is determined and input into the software of unmanned ship for route editing.

High-speed optical induction camera and motion analysis system are installed at the beginning and end of the measurement section, to collect the motion images of the unmanned ship entering and leaving the measuring section. Then analyze the time of the unmanned ship characteristic points frame by frame. The total station is used to accurately measure the horizontal distance of measurement section. The schematic diagram of test method is shown in figure 2.
Figure 2. The schematic diagram of test method.

1-unmanned vessel; 2-high-speed camera (A); 3-high-speed camera (B); 4-starting line of measurement section; 5-track line; 6-long side of pool; 7-short side of pool; 8-termination line of measurement section; 9-measuring section; 10-acceleration section; 11-deceleration section; 12-total station.

After entering the route to the unmanned ship, the ship is sailed autonomously on the water, while the ADCP collected velocity data. According to the horizontal distance of the measurement section and the running time of unmanned ship in the measurement section, the average velocity is calculated as the reference value of velocity. Compare it to the velocity value measured by ADCP, the error of velocity indication is calculated.

At the same time, GPS-RTK measurement data of unmanned ship are collected. The original data measured by GPS-RTK are coordinate data, which can be converted into the real-time speed value $V_G$ of the ship by using equation (1). Compared with ship speed measured by ADCP, the instantaneous velocity stability of unmanned ship can be verified by calculation.

$$V_G = \frac{\sqrt{\Delta x^2 + \Delta y^2}}{t}$$  \hspace{1cm} (1)

Where, $\Delta x$ is the coordinate difference between two adjacent points along x-axis; $\Delta y$ is the coordinate difference between two adjacent points along y-axis; $T$ is the measurement interval between two points.

3. Test results

The length of velocity measurement section measured by total station is $L=79.771\text{m}$. The running time of unmanned ship in the measurement section is $t=78\text{s}$. The moment when the unmanned ship enters the measurement section (triggering the early-warning line) is 15:10:12, and the moment when the unmanned ship leaves the measurement section (triggering the early-warning line) is 15:11:30. The reference value of average velocity $V_0=1.02\text{m/s}$. The measured data of ADCP within the same time are shown in figure 3.

Figure 3. The measured data of ADCP.
During the test, the comparison between the measured results of GPS-RTK and the flow velocity data of ADCP is shown in figure 4.

![Comparison of velocity data](a)

![Comparison of velocity data](b)

Figure 4. Comparison of velocity data

120 groups of velocity data are recorded in the uniform measurement section. The measurement results and indication errors are shown in table 1. Only the data with an interval of 10 seconds are listed in the table.

| Time   | GPS-RTK measured velocity $V_g$ (ms$^{-1}$) | ADCP measured velocity $V$ (ms$^{-1}$) | Indication error (ms$^{-1}$) |
|--------|---------------------------------------------|----------------------------------------|-----------------------------|
| 17:04:07 | 0.98                                        | 0.96                                    | -0.02                       |
| 17:04:17 | 0.97                                        | 0.95                                    | -0.02                       |
| 17:04:27 | 1.01                                        | 1.00                                    | -0.01                       |
| 17:04:37 | 1.00                                        | 0.97                                    | -0.03                       |
| 17:04:47 | 1.00                                        | 1.02                                    | 0.02                        |
| 17:05:07 | 1.00                                        | 0.97                                    | -0.03                       |
| 17:05:17 | 1.01                                        | 1.01                                    | 0                           |
| 17:05:27 | 1.01                                        | 1.01                                    | 0                           |
| 17:05:37 | 1.01                                        | 0.98                                    | -0.03                       |
| 17:05:47 | 1.00                                        | 1.00                                    | 0                           |
| 17:05:57 | 0.99                                        | 0.98                                    | -0.01                       |

According to the data processing method described in HY/T 102-2007. The gross errors in the data are eliminated by using $3\sigma$ criteria, and the remaining 101 groups of data, which are more than 100 groups, meet the requirements. The average value of the GPS-RTK measurement is calculated as...
\( \bar{V}_G = 0.997 \text{m/s} \) and the average value of the measured ADCP measurement is \( \bar{V} = 0.982 \text{m/s} \).
Comparison diagram of 101 groups of data after gross errors are eliminated is shown in figure 5.

![Comparison diagram of 101 groups of data.](image)

**4. Uncertainty analysis**

4.1. *Mathematical model and sensitivity coefficient*

The mathematical model of the ADCP calibration system designed in this paper is shown in equation (2).

\[
\Delta V = V - \left( \frac{L}{t} + \Delta V_0 \right)
\]

Where, \( \Delta V \) is the error of ADCP measurement, and \( \Delta V_0 \) is the error introduced by the instantaneous velocity stability of unmanned ship. According to the propagation law of measurement uncertainty, the uncertainty of the measured ADCP indication error can be calculated according to equation (3).

\[
u(\Delta V) = \sqrt{c^2(V)c^2(V) + c^2(L)c^2(L) + c^2(t)c^2(t) + c^2(\Delta V_0)c^2(\Delta V_0)}
\]

Velocity point is chosen as 1m/s, and length point as 80 m. Then the sensitivity coefficient in equation (3) can be calculated.

\[
c(V) = \frac{\partial(\Delta V)}{\partial V} = 1; \; c(L) = \frac{\partial(\Delta V)}{\partial L} = -\frac{1}{80}; \; c(t) = \frac{\partial(\Delta V)}{\partial t} = -\frac{L}{2t^2} = -\frac{1}{160}; \; c(V_0) = \frac{\partial(\Delta V)}{\partial V_0} = -1
\]

4.2. *Calculation of uncertainty components*

4.2.1. **Uncertainty introduced by measured ADCP results.** The measured average velocity of the ADCP in measurement section contains 79 flow velocity data, and 79 of them are left after gross errors are eliminated by using the \(3\sigma\) criterion. The type A uncertainty is the sample standard deviation, which can be calculated by Bessel formula

\[
u_a(V) = s(V) = \left( \frac{\sum_{i=1}^{n}(V_i - \bar{V})^2}{n-1} \right)^{1/2} = 0.0204 \text{m/s}.
\]

The standard velocity point is taken as 1m/s, the maximum permissible error of ADCP velocity measurement is calculated as 0.0045m/s, it is estimated as uniform distribution, then the type B uncertainty introduced by ADCP is

\[
u_B(V) = \frac{0.0045}{\sqrt{3}} = 0.0026 \text{m/s}.
\]

4.2.2. **Uncertainty introduced by distance measurement.** The measurement uncertainty brought by the total station adopts the type B uncertainty. The maximum permissible error of distance measured by
the second-level total station is $\pm (3 + 2 \times 10^{-6} D)$ mm. The standard distance is selected at 80m and it is estimated as uniform distribution. The uncertainty is $u(L) = \frac{3.16}{\sqrt{3}} = 1.824$ mm.

The ADCP calibration device is in outdoor environment, so the influence of environmental factors on measurement results should be considered. The environmental conditions of Tianjin lock are relatively stable and there is no strong electric or magnetic field to influence the measurement results of total station. Therefore, the temperature is the maximum quantity that affects the measurement results. At the measuring distance of 400m, the total station instrument can produce 0.41 mm on the ranging accuracy with each temperature change of 1°C. Therefore, at the measurement point of 80m, the uncertainty brought by temperature change to the system is $u(L) = \frac{0.82}{\sqrt{3}} = 0.473$ mm.

These two components are not related, so the standard uncertainty introduced by distance measurement is $u(L) = \sqrt{u_1^2(L) + u_2^2(L)} = 1.884$ mm.

4.2.3. **Uncertainty introduced by time measurement.** In this experiment, two high-speed cameras are used to record the time interval between the unmanned ship entering and leaving of the trigger line. And time measurement deviation was mainly introduced by two high-speed cameras. A high-speed camera can display 120 frames per second. Its timing value interval half width $a = 0.0042$ s, which is estimated as uniform distribution. The measurement uncertainty introduced by high-speed cameras adopts type B uncertainty evaluation method, which is $u(t) = \frac{a}{\sqrt{3}} = 0.0024$ s.

4.2.4. **Measurement uncertainty introduced by instantaneous velocity stability of unmanned ship.** The velocity error introduced by unmanned ship is shown as equation (4):

$$\Delta V_0 = V - V_G$$

According to the 101 groups of velocity data, the type A uncertainty introduced by ADCP can be calculated by Bessel formula as $u_a(V) = s(V) = \left( \frac{\sum_{i=1}^{n} (V_i - \bar{V})^2}{n-1} \right)^{1/2} = 0.0156$ m/s. And it is known that the type B uncertainty introduced by ADCP is 0.0026 m/s, so the uncertainty of ADCP measuring results is $u(V) = \sqrt{u_a^2(V) + u_B^2(V)} = 0.0157$ m/s.

The type A uncertainty introduced by GPS-RTK is calculated by Bessel formula

$$u_a(V_G) = s(V_G) = \left( \frac{\sum_{i=1}^{n} (V_{G_i} - \bar{V}_G)^2}{n-1} \right)^{1/2} = 0.0161$$ m/s. The data measured by GPS-RTK is the coordinate data of the current point, which is converted into velocity value through calculation. The measurement frequency is 1Hz, the positioning accuracy is $\pm (8 + 1 \times 10^{-6} D)$ mm, and the standard interval distance $D = 1$ m. It is estimated as uniform distribution. Therefore, the class B uncertainty of GPS-RTK is $u_B(V_G) = \frac{0.009}{\sqrt{3}} = 0.0052$ m/s. The measurement uncertainty component introduced by GPS-RTK is $u(V_G) = \sqrt{u_a^2(V_G) + u_B^2(V_G)} = 0.0166$ m/s. According to equation (5), the correlation coefficient of measurement results of GPS-RTK and ADCP is calculated as 0.623.

$$r(V, V_G) = \frac{s(V, V_G)}{s(V)s(V_G)}$$

(5)
\[ s(V, V_G) = \sum_{i=1}^{n} \frac{(V_G - \bar{V})}{n-1} \]. Significance level is selected as \( a = 0.01 \). Significance table is looked up to get the critical correlation coefficient \( r_0 = 0.2540 \), \( r(V, V_G) > r_0 \), which means measurement results of GPS-RTK and ADCP is related. Then, the measurement uncertainty introduced by the instantaneous velocity stability is \( u(\Delta V_G) = \sqrt{u^2(V) + u^2(V_G) + 2r(V, V_G)u(V)u(V_G)} = 0.0291 \text{m/s} \).

4.2.5. Composite uncertainty. During this test, \( L, t, V \) and \( V_0 \) components in the mathematical model are not related to each other. According to equation (3), the composite standard uncertainty of this measurement system can be calculated as \( u(\Delta V) = 0.0355 \text{m/s} \). Take the coverage factor \( k = 2 \), the measurement uncertainty of the test results is \( U = k \times u(\Delta V) = 0.071 \text{m/s} \), \( k = 2 \).

5. Conclusion
The ADCP has the characteristics of measuring section velocity profile directly, not disturbing flow field, short test duration and large velocity range. Therefore, it is widely used in the velocity and flow detection of ports and waterways, water structure analysis in sea areas, and large-scale search and rescue work in sea areas. The ADCP calibration system designed with unmanned ship as the carrier in this paper has the advantages of small size and easy operation. When the speed of unmanned ship is set at 1 m/s, the error of ADCP velocity indicated by inspection is -0.029 m/s, and the extended uncertainty of this test system is evaluated as \( U = 0.071 \text{m/s}, k = 2 \).

References
[1] Yong, Q. Yusahng, W. Keke, Z. ect. (2016) Classification and Research Progress of ADCP. J. Meteorological, Hydrological and Marine Instruments, 33(1):110-114.
[2] Zhanqiao, L. Zhiguang, T. Baoqin, W. ect. (2012) Analysis on Velocity Measuring Accuracy of RDI ADCP. J. Hydrographic Surveying and Charting, 32(6):57-59.
[3] Zhengming, Q. Xiaoming, G. Shaoping, S. ect. (2018) The Study on Physical Size of Test Pool for ADCP Calibration. J. Hydrographic Surveying and Charting, 38(5):75-78.
[4] Simpson, M. R. . (2001). Discharge measurements using a broad-band acoustic doppler current profiler. U. S. Geological Survey, Open-File Rep.
[5] Oberg, K. Mueller, D. S. (2007) Validation of streamflow measurements made with acoustic doppler current profilers.Journal of Hydraulic Engineering, 133(12): 1421-1432.
[6] Bingzhao, W. Zhanqiao, L. Hui, S. (2010) The Statistical Analysis of a Comparisons Test of ADCP. Hydrographic Surveying and Charting, 30(6), 74-76.