Uncertainty Evaluation Method of Rotating Element Current Meters

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Abstract

The main expression of the calibration results of rotating element current meter is based on the approximate linear relationship between rotation rate and velocity, and the uncertainty evaluation method is not perfect. A technical scheme with hydraulic pitch as the result of calibration is studied, and the uncertainty can be devided to standard current velocity, rotation rate and hydraulic pitch. The measurement and uncertainty evaluation method of unit velocity and background velocity are studied based on the water velocity calibration platform. The calculation method of unit rotation rate for synchronous equidistant trigger speed measurement is proposed, and the uncertainty evaluation of unit rotation rate is realized through the self-developed standard rotation rate experimental platform. The uncertainty evaluation method for the laboratory calibration and on-site measurement results of current meter is proposed, based on the analysis of the calibration results of hydraulic screw pitch and the relationship between the calibration results and environmental factors. The results show that, the uncertainty of water flow velocity standard device is 0.04%v+2mm/s, the background velocity is the main uncertainty source in laboratory calibration results. After reasonable correcting the environmental impact of positive hydraulic pitch, the change of mechanical properties caused by long-term use is the main source of uncertainty.

1. Introduction

Current velocity is the basic index of hydrological monitoring. As a traditional on-site measuring instrument, rotor element current meter has the advantage of environmental requirements, simple structure and long service life. It is widely used in hydrological environments such as rivers, lakes and reservoirs. The uncertainty is of great significance to evaluate the reliability of the measurement result of the current meter.

At present, the most commonly used laboratory test method is the towing through still water method[1-5], and the linear formula is used to approximate the relationship between the rotor rotation rate n and the flow velocity v. Although the linear function is convenient, the error in the low velocity range is larger due to the effect of internal friction. Hubbard[6] evaluate the measurement error of priceAA and PricePygmy current meter is less than ± 1% above 0.5m/s, which can reach up to ± 6% below 0.1m/s, in the USGS report . Although this error can be reduced by using piecewise linear method, but it is still difficult to establish a quantitative relationship with environmental conditions[4]. Therefore, the current standard specification has not given a clear uncertainty evaluation method.

The stable and accurate standard current velocity is the key factor for the reliability of test results in the laboratory test. The results published by the METAS on the basis of its internationally recognized calibration measurement capability (CMCs) device show that the sources of uncertainty of the standard current velocity include the standard speed and the residual velocity fields. Among them, the fluctuation of residual velocity fields is quite complex. It decays exponentially on the horizontal two-dimensional plane[7], and its influence on the detection results can be reduced by increasing the waiting time. In the work of METAS, after the current meter is dragged and waiting for 5 minutes and 25 minutes, respectively, the difference in the reproducibility level of velocity is 0.5%[8]. In addition, the towing through still water method do not give the standard value of the rotation rate, and the uncertainty evaluation of the rotation rate measurement is not considered.

The sources of error and uncertainty in field are more diversified than those in laboratory testing. Among them, some environmental conditions can be modified. For example, Staubli[9] proposed a velocity correction method for the displacement effect in small cross-section water. Johnson[10] researched the law that water temperature affects, and Daniel[11] further proposed a current velocity calculation method with temperature correction. However, most of the environmental conditions can be hardly directly corrected, and the complex correction process also increases the difficulty of field work. Sauer[12] shows that the uncertainty sources of the current meter mainly include the depth inserted into the water, the horizontal installation angle deflection, and the mechanical performance of the instruments, but the evaluation method needs to be further discussed, in USGS report. It is of great significance to study the uncertainty sources brought by laboratory calibration and field environment to ensure the transmission of current velocity.

The uncertainty evaluation methods of the laboratory and field measurement results of the rotation element current meter are studied. Based on the towing current velocity calibration platform, the basic characteristics and uncertainty synthesis method of standard velocity are studied. A high-precision calculation method of laboratory rotation rate is analyzed, and the uncertainty evaluation method is studied based on the a calibration platform. Aiming at the technical scheme that takes the instrument characteristic parameter hydraulic pitch as the calibration results. The influence of laboratory calibration and field environmental variables are analyzed, and a sub item evaluation for the uncertainty of laboratory and field measurement results is proposed.

2. Measurement and calibration of rotating element current meter

2.1 Measuring Principle

The rotor current meter is a hydrological instrument that calculates the velocity by recording rotation rate. The basic structure is shown in Figure 1, which is composed of mechanical sensors and measuring instruments. The measurement process mainly includes 3 basic steps:

1) Signal generation. The water drives the mechanical sensor to generate contact pulse signal.

2) Rotation rate measurement. By recording the time interval and numbers of pulse signal, the measuring instrument can obtain the number of turns N and the experienced time t, and rotation rate of the rotor can be obtain according to the relationship $n = N / T$. The LS1206B current meter outputs 2 pulse signals per revolution.

3) Velocity calculation. The average velocity during measurement can be calculated according to the N-V relationship through calibration.

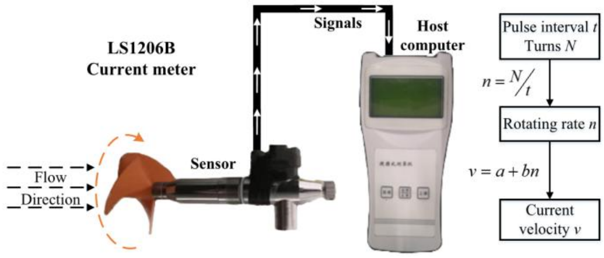


Figure 1: Picture and working principle of rotating element current meter.

2.2 Uncertainty Source

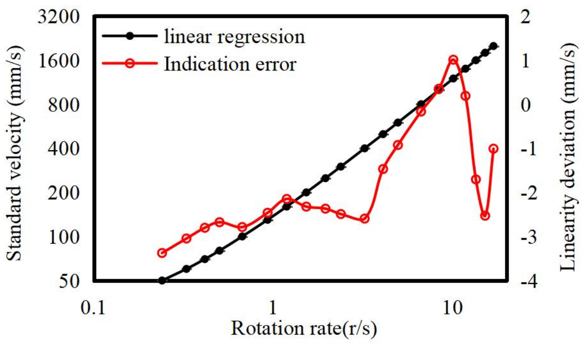
The calibration of current meter mainly adopts the method of towing. The current meter is drived by trailer to make uniform motion along a straight line in still water. The towing speed is taken as the standard value of v. The main advantage of this method is that it can provide a very stable relative flow field. The uncertainty of calibration results mainly comes from 3 aspects:

1) Mapping relationship. The mapping relationship between rotation rate and current velocity can be expressed as $v = bn$, where b is the hydraulic pitch that means the moving distance of water per revolution, $b = l / n$. Linear or piecewise linear simplified relations $v = a_0 + b_0 n$ are often used, where b_0 is the approximate value of hydraulic pitch at high speed. The calculation results of this method in the low speed range are usually not ideal due to the internal friction[6,13]. In addition, the measurement conditions such as depth and installation deflection angle also affect the results, and the relationship between the influence law and linear formula is quite complex[10].

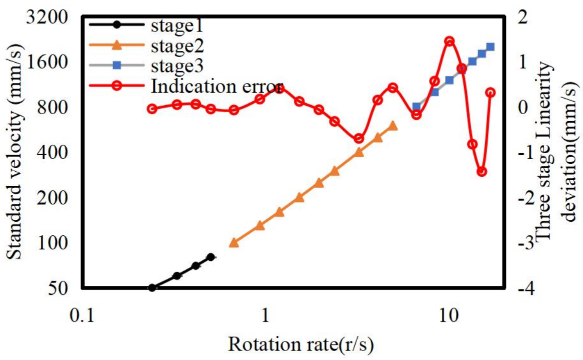
2) Rotation rate measurement. The working mode of most current meters is to record the integer revolutions of the rotor in a fixed time period, and the incomplete cycle close to the start and end of recording is the main error source of the rotation rate measurement. During on-site flow measurement, this error can be restrained by a long time measurement. But it is limited in laboratory testing process, the uncertainty of measurement results caused by the asynchronous timing and counting becomes more significant.

3) Standard current velocity. In order to improve the calibration by keeping the timing and counting synchronization, and decrease the uncertainty of rotation rate and towing speed fluctuation, the calibration facility is usually designed very long [10,14-15]. The uncertainty of standard velocity comes from towing speed and the background velocity in water after towing.

Take the LS1206B current meter as an example to carry out the experiments from low to high speed in the range of 50mm/s~2000mm/s, after each towing, the water will reach enough static through sufficient waiting time, and after the completion of the last experiments, it will be keeping waiting for more than 8h until the water in tank reaches the initial state before first towing, and the same experiments will be repeated for 6 times. The linear regression is established for all testing points of experiment No.1, the average current velocity of other 5 experiments can be calculated and the indication error is shown in Figure2a). The linear deviation is smaller than 4.5mm/s which is more pronounced below 500mm/s. This deviation in the low-speed range is caused by mapping relationship. In order to decrease the approximate deviation in the low speed range, a three-stage linear formula is established with the rotation rate of 0.5r/s and 5r/s as the boundary. The calculation results of current velocity are shown in Figure2b). The measurement deviation of piecewise linearity is reduced to 3mm/s.



a) Linear method



b) Piecewise linear method

Figure 2: Measurement results and indication error of linear regression.

Although the linear expression can illustrate the mapping between the rotation rate and the velocity as the result of calibration, it is still difficult to be take the influence of environmental factors such as the depth of water entering, deflection angle into consideration. Therefore, the uncertainty evaluation of rotor current meter is not yet perfect.

The instrument characteristic parameter hydraulic pitch *b* represents the ability of the rotor to overcome internal friction and is more sensitive to the change of velocity. The laboratory measurement results are shown in Figure3. The *n*-*b* relationship can be approximated as an exponential function $b = 20.75n^{-1.037} + 117.305$ that the goodness of fit can reach 0.999.

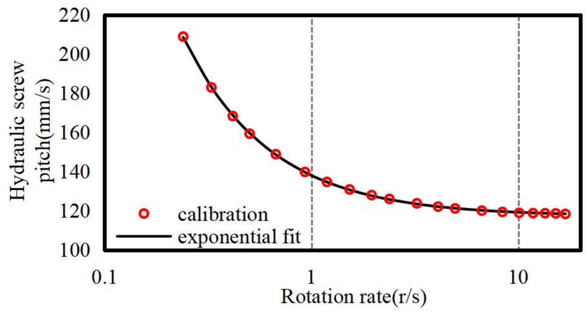


Figure 3: The relationship between hydraulic screw pitch and rotation rate.

In this paper, we mainly study to take the hydraulic screw pitch as form of laboratory calibration results, which is convenient to evaluate the uncertainty introduced by environmental factors. The uncertainty can be expressed as

$$u = \sqrt{u_v^2 + u_n^2 + u_b^2} \quad (1)$$

Where, u_v is the uncertainty of standard current velocity.

u_n is the uncertainty of rotation rate measurement.

u_b is the uncertainty of hydraulic screw pitch .

3. Standard current velocity

3.1 Standard current velocity

Ensure the towing velocity accurate and stable is the fundamental problem for the reliable calibration. Using equidistant trigger speed measurement method to obtain the average towing speed. When the trailer passes through the fixed triggers, the average speed in each unit can be calculated by time difference and length. The accuracy of measurement results depends on the dynamic time and length measurement ability. The standard towing tank facility in NIM is shown in Figure 4. A light trailer and traction mode is adopt to provide the speed range from 1mm/s to 2000mm/s. The trigger is evenly arranged every 200mm within the length of about 7000mm to make 34 measurement units. The time interval in each unit can be measured by a high-precision continuous pulse interval recorder. In order to simplify the measurement system, the unit lengths are calibrated by laser interferometer before tests.

The time measure ability is mainly influenced by waveform of the trigger switch and performance of crystal oscillator, and it is calibrated,and the uncertainty shown in the certificate is 0.0013% (k=2).

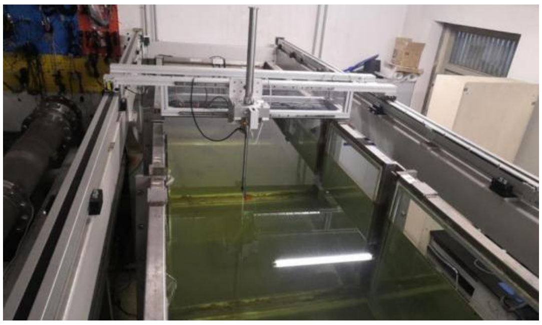


Figure 4: Towing calibration platform of rotating element current meter.

Due to the fluctuation during the towing process, the trailer and trigger will have small vibration that will affect the unit length measurements. The length of each unit is repeatedly measured by laser interferometer in the speed range of 1mm/s ~ 2000mm/s to evaluate the uncertainty. When the change of temperature in air is lower than 5℃, the maximum expansion is no more than 70μm, then the uncertainty of length is U_L=70μm / 200mm = 0.04%(k=2). Then the uncertainty of towing speed U_{vs} can be expressed as

$$U_{vs}=\sqrt{U_L^2+U_t^2}=0.04\% \tag{2}$$

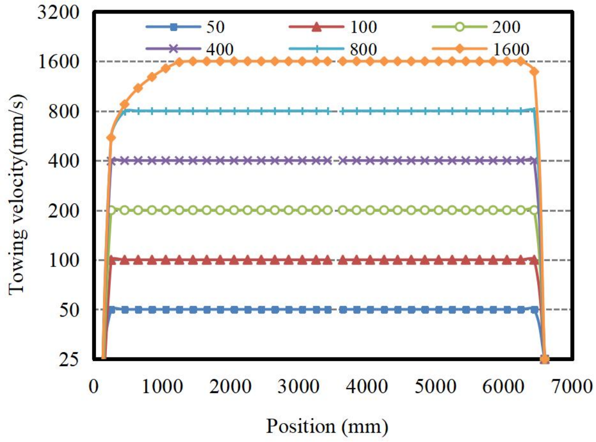
Among them, U_t and U_L are the uncertainty of time and length, respectively. The measurement results obtained by equidistant trigger speed measurement method are shown in Figure 5. The relative fluctuation under different speeds can be maintained in the range of ± 0.05%.

3.2 Background current velocity

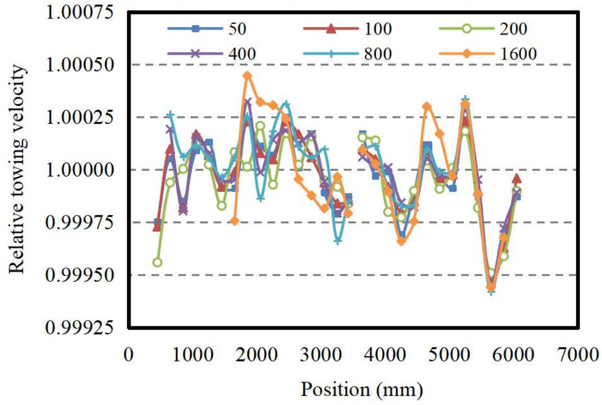
The background velocity is the main factor to break hydrostatic hypothesis, and its attenuation is related to the friction, water viscosity, relative velocity, tank size and other factors [16]. People usually reduce its effect on the calibration results by extending waiting time after towing. The formation and attenuation process of the background velocity is complex. At present, the relationship between the waiting time and the calibration results is not clear[5]. It is hard to evaluate the influence of the background velocity on current meters directly.

Although the influence evaluation is complicated, there is a certain rule of water movement, especially the periodic fluctuation related to the size of the flume [8]. The frequency is

$$\nu=\frac{\sqrt{gk\tanh(kH)}}{2\pi} \tag{3}$$



a) Towing speed during the calibration process



b) Relative towing speed in stable stage

Figure 5: Tow cart speed during towing calibration.

Where g is the gravitational acceleration, h is the depth of the water, and k is the wave number. In the case of low speed and long time towing, the background current velocity can be restrained based on the periodicity of fluctuation, but don't work in high speed situation. Adding waiting time is the only way to decrease the background velocity influence. A ultrasonic time difference flow measurement device with 50 ° angle and 5 path is used to observe the attenuation process of background velocity, which has 0.5mm/s resolution. The sound path covers the whole width direction of the flume. The measured background velocity after towing at the speed of 2000mm/s is shown in Figure 6. It can be easily seen from the figure that the envelope of the background current velocity decreases with an exponential trend of $28e^{-0.002t}$, and the fluctuation frequency is about 0.19Hz, which is close to the theoretical calculation. Therefore, the reasonable assumption can be made according to the waiting time for the peak value of background velocity to decay to a certain threshold.

It takes time for the envelope to deceasing to threshold, which means the maximum background current velocity after waiting, and regarded as the uncertainty U_{bk} (k=2)of the background current velocity. Taking the condition in Figure 6 as an example, the uncertainty of background current velocity is set to 2mm/s, and it is predicted that it needs 20min waiting time after towing at the speed of 2000mm/s. The expanded uncertainty of the standard current velocity can be expressed as

$$U_v = U_{vs} + U_{bk} = 0.04\%v + 2mm/s \tag{4}$$

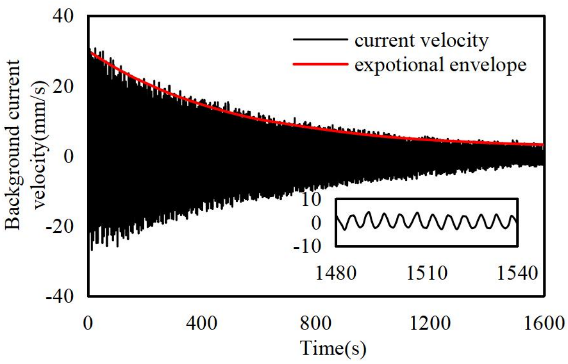


Figure 6: background current velocity after towing with 1000mm/s.

4. Rotation rate calibration

The rotation rate is the direct measurement value of current meter, and the non-synchronization of time and count recording is the main source of uncertainty.

4.1 Unit rotation rate

In case of on site situation, a long fix recording time is set to simplify the measuring process, the number of pulse is counted. However, the measurement time is limited by the length of tank in laboratory testing, and the deviation caused by non -synchronization measurement is amplified. In order to reduce such kind of measurement deviation, a non integer revolution estimation method is adopted to obtain the revolution rate corresponding to the standard velocity measurement directly. The revolution measurement is shown in Figure 7. Between the beginning and end pulse of the towing speed measurement unit, the fractional revolutions corresponding to the incomplete cycle times T_1 and T_2 are estimated according to the average period T of the complete rotation cycle in the unit, and added the integer revolutions N_0 to obtain the non integer revolutions in the unit as shown in . This method improves the synchronization of pulse interval and towing speed measurement, and is helpful to reduce the length of tank.

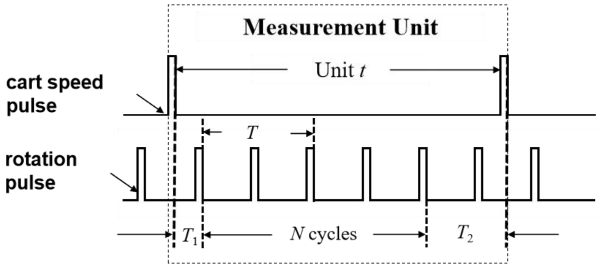
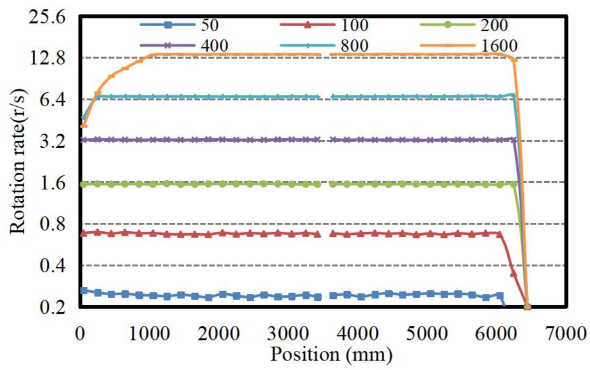
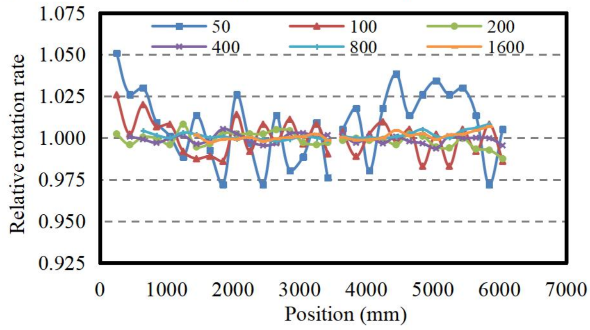


Figure 7: Non-integer turns number in a measuring element.

Using the precision unit measurement method, the segmented average rotation rate corresponding to the towing speed in Figure 5 can be obtained, as shown in Figure 8. The fluctuation of rotation is higher in low velocity, but tend to be relatively stable as the velocity increasing, and better than 0.15% at 500mm/s. Therefore, this unit rotation rate calculation method has better accuracy than long time recording, and lays a foundation for improving the calibration ability of current meter.



a) Rotation rate during the calibration process



b) Relative rotation rate in stable stage

Figure 8: Rotation rate fluctuation during towing

4.2 The uncertainty of rotation rate measurement

Although the unit rotation rate calculation method has a better corresponding relationship with the towing speed and rotation rate, and the deviation is smaller, a efficient evaluation method is still needed for uncertainty.

An additional standard rotation rate testing platform is designed to deal with calibration problem, as shown in Figure 9. The mechanical rotor is driven by the motor to rotate at a constant speed or simulated fluctuation process of towing. The non integer number of the actual rotation is measured by a 16 bit precision encoder , which provides the standard rotation rate in calibration. Corresponding to the towing speed measurements, the rotation rate in a single unit is taken as the conservative estimation of the uncertainty. Each rate is measured m times, the uncertainty u_n of the rotation rate can be expressed as

$$u_n = \sqrt{\frac{1}{(m-1)} \sum_{i=1}^{m} (n_i - n_{standard})^2} \quad (6)$$

Where, n_i is the *i*th measured value time counter, and N is the mean value of the m-th testing point.

A high-precision continuous pulse interval measuring instrument is used in the rotation rate calibration. The length of the measuring unit is 200mm, and the revolutions number of LS1206B in the unit is about 2. Assuming the roration is stable enough, the revolution is set to *N*=2.5, so that the rotor can be measured at the speed of 0.2r/s~16.9r/s, corresponding to the current velocity of 50mm/s~2000mm/s, each speed point is measured 5 times, and the relative uncertainty of the measurement results is better than 0.2%.

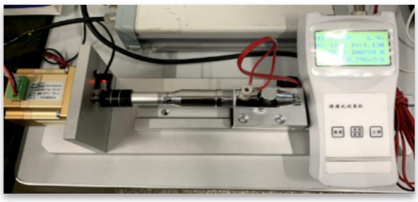


Figure 9: Rotation rate calibration platform.

5. Characteristic of hydraulic screw pitch

Hydraulic pitch is a characteristic parameter of rotor current meter performance, and can be taken as a form of expression of calibration results. The relationship between the hydraulic pitch and the environmental conditions is easier to quantify, compared with the linear regression.

Through the analysis of the characteristics of the hydraulic pitch, it is of great significance for on site uncertainty evaluation of current meter.

5.1 The uncertainty of calibration results

The hydraulic pitch can be obtained directly by length *L* and non integral revolution number *N* measurement, in laboratory, which uncertainty are already evaluated respectively, so the uncertainty of unit hydraulic pitch does not need to be calculated repeatedly. The hydraulic pitch obtained by towing through still water in calibration refers to the average value in the stable speed range. The fluctuation of towing process is taken as the uncertainty source of the hydraulic pitch calibration results. For m times repeated measurements with *k* stable sections. The hydraulic pitch measurement uncertainty u_b can be expressed as

$$u_b = \sqrt{\frac{1}{k(m-1)} \sum_{i=1}^{m} (b_i - b_{均})^2} \quad (7)$$

Where, b_i is the average hydraulic pitch of *k* units in the stability section of the *i*th repeating test, and *b* is the average value of m times of testing.

According to the non integer revolutions and length of measurement unit, the hydraulic pitch in stable calibration range is obtained. As shown inFigure 5, the whole length of trailer motion at each speed is the same, the number of measurement units in the stable section varies from 31 to 19, excluding the acceleration and deceleration processes. The relative uncertainty of hydraulic pitch measurement results is shown in Figure 10.

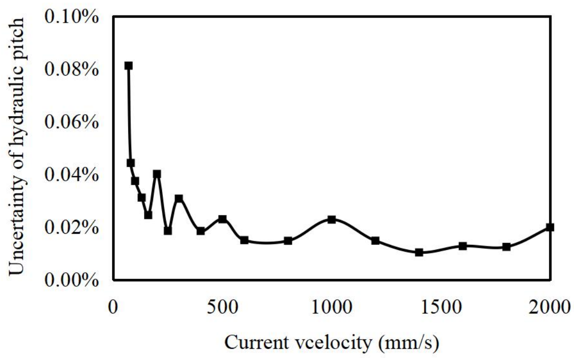


Figure 10: The uncertainty of hydraulic screw pitch calibration results.

5.2 On-site influence

Environmental conditions can be measured and controlled by instruments in the laboratory, but not easy to realize in on-site situation. For example, the insertion depth of current meter can be control and measured in still water, but much harder in river. And the angle between the meter axial and flow direction can be adjust by high precision encoder, but in on-site situation, the current meter is swayed under the action of unstable flow filed, the angle is hardly be ensured. In addition, after a period using, the mechanical properties of the current meter drift gradually, which is also an important reason to affect the measurement results.

Therefore, the the depth and installation angle and the drift of the mechanical properties after long-term use are the important uncertainty sources of the current meter on-site measurement.

1) Insertion depth

The depth is not only affects the static pressure, but also the blocking effect of connecting rod, which affects the mechanical characteristics of current meter.

The quantitative relationship between the mechanical characteristics and the depth of entering water is analyzed. Taking the speed of 1000mm/s and 1500mm/s as an example, the experiments are carried out in the range of 200mm ~ 600mm depth of the rotor axis, each depth point is repeated for 3 times at each depth point. The measurement results of hydraulic pitch at different depths are shown in Figure 11. As the increasing of insertion depth, the measured average hydraulic pitch show an approximate linear downward trend. The hydraulic screw pitch reduce 0.6% with 40mm depth increment, the maximum deviation of measurement results is about 0.1mm/r.

The results show that the deeper the current meter is inserted, the smaller the hydraulic screw pitch is, then the hydraulic pitch can be predicted according to this trend. Therefore, the hydraulic pitch can be properly estimated by depth, the uncertainty can be expressed by the linear deviation of the measurement results in Figure 11. It should be noted that if the linear relationship above is used to modify the current meter on-site, further experimental results need to be accumulated.

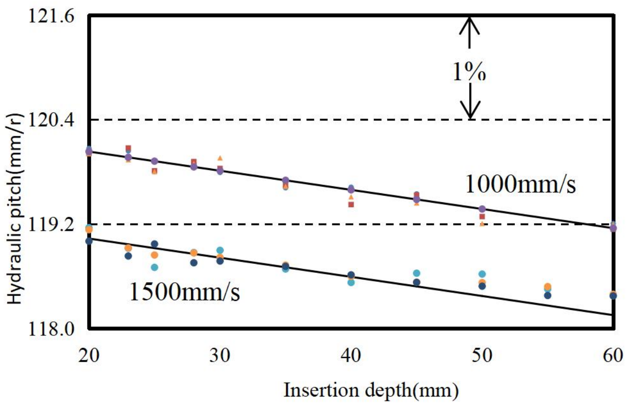


Figure 11: Hydraulic screw pitch under different penetration depth.

2) angle deflection

Considering the instability of the flow field and the accuracy of installation, there is a certain angle between the flow direction and the axial direction of current meter.

Explore the relationship between installation angle and hydraulic pitch. Taking 1000mm/s and 1500mm/s as examples, the experiment is carried out in increments of 0.5 ° within the range of ± 10 °. The hydraulic pitch under each installation deflection angle is shown in Figure 12. The red line in figure is the fitting curve of hydraulic pitch and installation angle, which meets the parabolic relationship with same opening.

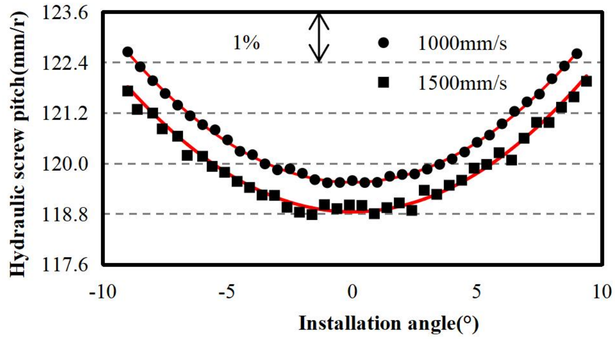


Figure 12: Hydraulic screw pitch under different angle of installation.

It is difficult to measure the installation angle in field. The simple way is to take the maximum installation angle into the parabola function to calculate the linear deviation of the hydraulic pitch, which can be used to estimate its uncertainty. As shown in the figure, when the installation angle is 1 °, the hydraulic pitch changes about 0.04mm/r; which changes about 0.34mm/r at 3 ° situation.

3) Long term reproducibility

In order to ensure the reliability of calibration results, generally speaking, it is required to maintain and recalibrate for one year or no more than 300 hours.

To explore the general rule that the mechanical properties change by using. In order to evaluate the stability, the experiments are repeated at high frequency for a period of time, to simulate long-term use. The test within the range of 50 mm/s~2000mm/s, and the water is still enough before towing. The uncertainty of long term stability is evaluated by indication error cross 1 month, the results are shown in Figure 13. After a period of use, the uncertainty of hydraulic pitch in high velocity section above 500mm/s changes about 0.4% ~ 0.6%.

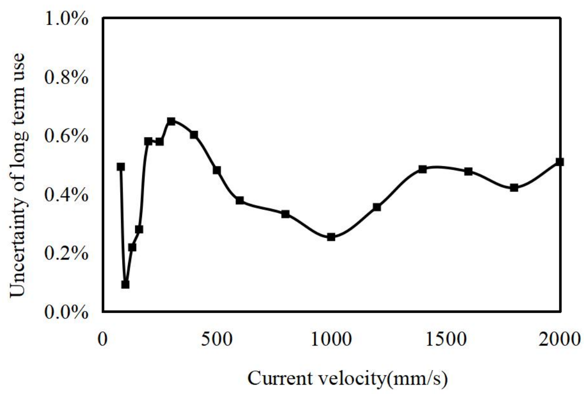


Figure 13: Reducibility of hydraulic screw pitch after long term use.

6. Uncertainty

6.1 uncertainty of laboratory calibration

According to and the results of the analysis above, the uncertainty of the laboratory calibration results are shown in Table 1. On the premise that the towing speed and rotation rate can be measured with high precision, the background velocity is the main uncertainty source of laboratory calibration. Therefore, sufficient waiting time is an important premise to ensure the reliability of calibration results.

Table1: Uncertainty of hydraulic screw pitch in laboratory.

Source		Velocity (mm/s) 100	300	500	1000	1500	2000
u_v	u_{vs}	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%
	u_{bk}	1.00%	0.33%	0.20%	0.10%	0.07%	0.05%
u_n		0.13%	0.10%	0.08%	0.07%	0.00%	0.00%
u_b		0.04%	0.03%	0.02%	0.02%	0.01%	0.02%
uncertainty U_{95} (k=2)		1.97%	0.68%	0.42%	0.24%	0.14%	0.11%

6.2 uncertainty of on-site situation

In order to evaluate the on-site measurement results, a method is proposed to evaluate the uncertainty of the influence of the field factors on the hydraulic pitch. The main assessment is the depth, the installation angle, and the contribution of the change of the mechanical properties after long-term use. The on-site uncertainty can be expressed as:

$$u_o = \sqrt{u^2 + u_d^2 + u_\theta^2 + u_e^2} \quad (8)$$

Where, u_d is the uncertainty of depth.
u_θ is the uncertainty of installation angle.
u_e is the uncertainty of long term reproductivity.

The maximum linear deviation of 40mm depth is 0.1mm/r, the change of hydraulic screw pitch with 3° installation angle is 0.34mm/r, and reproductivity results in Figure13, are taken into consideration to evaluate the uncertainty, as shown in Table 2. The uncertainty in on-site situation is significantly higher than that in laboratory, especially in high speed range, which is about 1%. It can be found that the change of mechanical properties after long-term use is the main source of on-site uncertainty under the premise of reasonable correction of the influence of entry depth, and the current meter and flow direction do not produce excessive deflection

Therefore, the uncertainty of laboratory calibration results plays a guiding role for on-site measurement. In order to improve the evaluation, we should also master the role of typical on-site factors, and make reasonable correction to the measurement results.

Table2: Uncertainty of on-site measurement results of rotation element current meter.

Source		Velocity (mm/s) 100	300	500	1000	1500	2000
on-site factor	u_d	0.03%	0.04%	0.04%	0.04%	0.04%	0.04%
	u_θ	0.23%	0.27%	0.28%	0.29%	0.27%	0.29%
	u_e	0.53%	0.65%	0.61%	0.39%	0.45%	0.51%
uncertainty U_o(k=2)		2.28%	1.53%	1.38%	0.97%	1.04%	1.16%

7. Conclusion

In this paper, the towing through still water method is used to study the uncertainty evaluation of the rotor current meter in the laboratory and field situation. Based on the experimental platform of towing tank and standard rotation rate facility, a evaluation method that take the hydraulic screw pitch as calibration result is put forward. The standard current velocity and rotation rate is evaluated respectively, and a laboratory and on-site uncertainty is proposed. The main conclusions are as follows

1) The uncertainty sources of standard velocity can be divided into towing speed and background velocity. The method of equidistant triggering is used to measure the towing speed, which has good traceability. The uncertainty of single measuring unit can reach 0.04%. The influence of the background velocity on the calibration results is complex, and the maximum amplitude of its fluctuation is used for conservative estimation in this paper.

2) The main uncertainty source of rotation rate measurement is the non synchronization of timing and counting, which is difficult to be directly evaluated by towing. A calculation method of unit rotation rate is proposed, which can improve the accuracy of measurement as much as possible, and a standard experimental platform is developed to evaluate the unit rotation rate uncertainty.

3) Using hydraulic pitch as the result of calibration, the influence of depth, deflection angle, and the change of mechanical properties after long-term use can be evaluated much easier. The results show that the background velocity is the main uncertainty source in the laboratory calibration. After proper correction, the reproductivity after long term use is the main uncertainty source.

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