Traceability of ultrasonic transit time based on relative displacement method

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Abstract

The increasing demand for ultrasonic flow meter (UFM) is due to the absence of moving, protruding parts projecting into the measured flow, transient response, high accuracy and wide range, so that it becomes important in flow measurement. By analyzing the error sources and magnitude of measurements in water, considering the uncertainty caused by sound speed profile and standard length, comprehensively. This research proposes a method to trace the transit time to standard length. Firstly, based on the servo driving and automatic displacement control, a facility which can provide displacement with a minimum displacement step of 10μm, is designed, and has been precisely calibration by laser interferometer. The error function of water temperature uniformity on transit time measurement is evaluated by theoretical model. A high-precision constant system is developed to control the temperature gradient in water better than 5mK, and the Anton Paar MKT50 platinum wire resistance thermometer is being used as the temperature standard. Assuming that the ultrasonic waveform does not change during propagation in water. The transit time for multiple reflections between fixed stainless steel protective layer and movable reflector is measured. The time difference between two different reflections of same wave can be obtained by high-precision cross-correlation algorithm, and the center frequency of the first five cycles are calculated through Hilbert transform. Through the linear increasing experiments, the effects of reflection times, path length and test temperature to the measurement of transit time are compared.

1. Introduction

With the rapid development of electronic technology and industrial flow, more and more flowmeters based on the ultrasonic transit time method have been introduced into the water conservancy, environmental protection, electric power, and other industries. The accuracy of their measurement evaluation is becoming increasingly important. The calibration of large diameter ultrasonic flowmeters, in particular, is a matter of current importance in the field of flow measurement.

More energy is consumed in case of real flow calibration for large diameter ultrasonic flowmeters[1]. And it is difficult to stop the water flow in large diameter pipes in field situation, and pipe disassembly and calibration can be time-consuming and laborious. Therefore, Dry calibration methods[2], in which the flow is decomposed into geometric quantities, integral models, and ultrasonic transit time, are most commonly used. This method has the advantage of being simple to set up and take down. Because the pipe cannot be disassembled, the external clamping ultrasonic measuring device's sources of error are primarily pipe size, pipe thickness, lining material thickness, and wall roughness[3]. Geometric quantities can be calibrated by high-precision length instruments such as measuring arms, total stations, and laser trackers. The flow velocity distribution in the pipe is related to flow velocity, Reynolds number, and pipe length, and varies somewhat from the single channel approximation[4]. The quality of the signal and the location of the installation are also important factors that influence measurement results. Deviations in the installation position, in particular, can affect the sound path, resulting in unpredictable effects[5] on transit time. External clamp flowmeters are typically accurate to within 5%[6]. External clamp ultrasonic measurement is currently the most widely used method of field calibration, but its calibration capabilities are clearly in need of improvement, given the cost of calibration and the difficulty of implementation. Observing the zero offset and calibrating the speed of sound is a common way to assess the ability to measure the transit time and time difference. However, it is not possible to take direct measurements of the transit time using real fluids to give standard values. As a result, the evaluation of transit time measurement is the most difficult part in dry calibration.

An idea is proposed to trace the time measurement capability of ultrasonic transducers on a path-by-path basis to traceable relative displacement and sound velocity to address the problem of traceability of transit time in the dry calibration of large diameter pipes. To provide a feasible solution for the traceability of the ultrasonic transit time, the relative displacement method thermostatic experimental platform is established, and the error sources of ultrasonic shape measurement, the displacement experimental platform, and the error situation introduced by the temperature gradient of the water body are each analyzed.

2. Measurement principles and sources of error

Establishing a correspondence with the path length of ultrasound propagation, which can then be used as an intermediate quantity for the traceability of the time volume by means of an accurate measurable length, is a more intuitive way of equivalently replacing the ultrasonic transit time.

It is necessary to provide a suitable length range and the ability to calibrate the displacement when using length as an intermediate quantity for the traceability of time quantities. The corresponding displacement change must be on the μm scale in order for the ultrasonic transit time to be accurate to the ns scale. The length and speed of sound affect the accuracy of the ultrasonic transit time measurement. To trace individual ultrasound transducers, a smooth reflector plate is arranged in the direction directly opposite the transducer, and the transit time of the ultrasound waves between the transducer surface and the reflector plate is measured, where the time difference can be expressed as the interval between the reception of the adjacent two reflected signals by the transducer, that is, the amount of ultrasonic transit time t can be expressed as

$$\boldsymbol{t = \frac{2H}{c}} \quad \textbf{(1)}$$

where H is the distance between the transducer and the reflector plate and c is sound path's average speed.

The ability of the measurement system to calculate the time is the main source of error in the amount of ultrasonic transit time. For time difference measurements, a comparison of the errors introduced by the cross-correlation algorithm and propagation time algorithms. The transit time were analyzed using Hilbert's algorithm[7] and the classical over-0 method, taking into account the small range of variation in time differences within the ultrasonic flowmeter, so that random errors introduced by cycle calculations misalignment were not taken into account. The centre frequency of the ultrasound transducer is 1 MHz, which means the width of each cycle is approximately 1 μs. Assume the ultrasonic shape is

$$\begin{cases} y(t) = (1-e^{-t})\, sin(\omega t) & (t < 3T) \\ y(t) = (1-e^{-t})e^{\left(1-\frac{t}{T}\right)} sin(\omega t) & (t \geq 3T) \end{cases} \quad \textbf{(2)}$$

where ω is the angular frequency, T is the period and t is the time.

The impact of sampling rates ranging from 8MHz to 256MHz is investigated. The algorithm creates an analytic function that is similar to the experimental waveform, adds a minor fixed time shift to the time series of the analytic function so that the shifted waveform has a known time deviation directly from the theoretical waveform, and then compares the deviation of the calculated time difference to the theoretical value to evaluate the algorithm's accuracy. The waveform is sequentially shifted, resulting in a series of shifted signals with a theoretical time increment of 1ps. 8MHz sampling yields 125,000 time-shifted waveforms in a single sample step.

Figure 1 depicts the average error introduced by the various waveform algorithms. The Hilbert transform method of fitting a phase straight line is insensitive to sampling rate. The waveform method has the largest error level and is most susceptible to interference from noise. The measurement capability of the cross-correlation method is monotonically affected by the sampling rate only and has the highest theoretical measurement capability, so the inter-correlation algorithm is used in this paper.

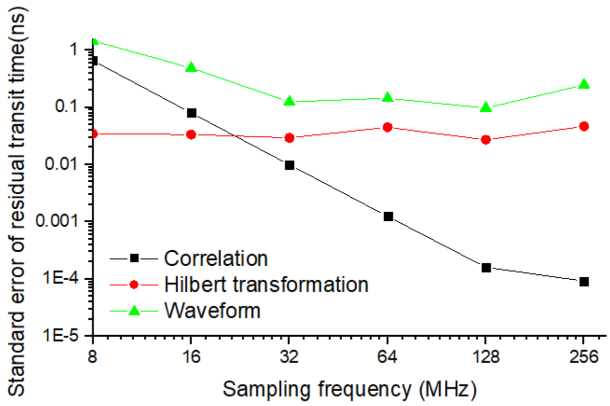


Figure 1: Response of the time difference algorithm to sampling rate.

3. Relative displacement experimental device introduces errors

A vertically moving precision displacement device has been designed to provide stable, reliable, and accurate displacements as well as a reference standard for the amount of ultrasonic transit time. The ultrasound transducer is housed in a water tank that is both closed and thermally insulated. A movable experimental platform is connected to a polished metal reflector plate facing the surface of the ultrasound transducer, platform is driven in a uniform linear motion by a servo motor, thus regulating the length of the ultrasound propagation path. The sealed insulated water tank measures 240mm × 140mm × 80mm, with the outer wall wrapped in insulating material to minimize the temperature gradient inside the vessel and ensure the representativeness of the sound velocity probe measurement results. A laser interferometer provides a standard length and records the speed of sound in the water column to provide a standard value for the ultrasonic transit time. The experimental device is depicted in Figure 2.

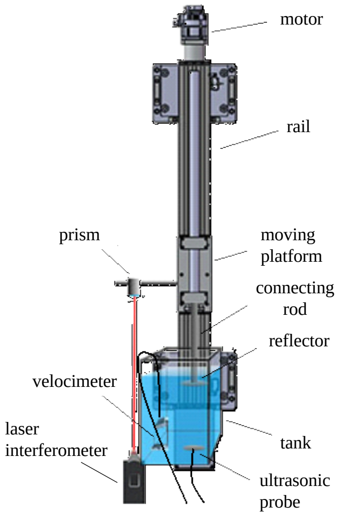


Figure 2: Schematic diagram of the experimental platform.

The experimental platform can deliver a minimum displacement step of 10 μm over a wide range, which is equivalent to 14 ns ultrasound time increments in water. The experimental platform can perform reciprocating step motion with any length of steps within a certain range during the experiment, and stay at each height for a sufficient time until each measuring instrument reaches a stable state, thanks to the motion control programme. At steady state, the traceability of the transit time is tested.

3.1 Displacement experimental platform

The ability to control the motion displacement of the experimental devices has a direct impact on the tow length accuracy. The movement path of the reflective surface is parallel to the direction of ultrasound transducer emission to ensure consistency of ultrasonic transit time with mechanical displacement. The displacement experimental platform was calibrated with a laser tracker, and the deviation of the step size from the standard value in the direction of the guideway movement was investigated. In the calibration process, the displacement experimental platform starts from the same starting point and moves from top to bottom, with a displacement step of 20mm to do step movement, each step is stationary for 20s, the displacement value of the experimental platform and the average value of the spatial coordinates of the laser tracker in the stationary time range are recorded, and the error of indication of the segmental movement of the guide rail is analyzed during the calibration process.

The data obtained from the laser tracker measurement is in 3-dimensional spatial coordinates. Assuming that the guide makes a one-dimensional movement, the three-dimensional coordinates need to be converted to the direction of movement. Using the spatial coordinate rotation method, the coordinates recorded in the three directions are u、v、w. The direction vector of the normalized motion is noted as

$$\begin{gathered} \boldsymbol{p}=(\boldsymbol{u}(\boldsymbol{n})-\boldsymbol{u}(\boldsymbol{m}),\boldsymbol{v}(\boldsymbol{n})-\boldsymbol{v}(\boldsymbol{m}),\boldsymbol{w}(\boldsymbol{n})-\boldsymbol{w}(\boldsymbol{m})) \\ \boldsymbol{p}=(\boldsymbol{p_1},\mathbf{1},\boldsymbol{p_3}) \end{gathered} \tag{3}$$

The angle between the direction of motion and the Y-axis in the instrument coordinate system is

$$\boldsymbol{\theta} = \boldsymbol{tan^{-1}}\left(\frac{\mathbf{1}}{\sqrt{\mathbf{1}+\boldsymbol{p_1}^2+\boldsymbol{p_3}^2}}\right) \tag{4}$$

The 3D transformation matrix of the coordinates is expressed as

$$\boldsymbol{M} = \begin{bmatrix} \boldsymbol{p_1}^2+\boldsymbol{cos\,\theta}\cdot(\mathbf{1}-\boldsymbol{p_1}^2) & \boldsymbol{sin\,\theta}\cdot\boldsymbol{p_3} & (\mathbf{1}-\boldsymbol{cos\,\theta})\cdot\boldsymbol{p_1}\cdot\boldsymbol{p_3} \\ -\boldsymbol{sin\,\theta}\cdot\boldsymbol{p_3} & \boldsymbol{cos\,\theta} & \boldsymbol{sin\,\theta}\cdot\boldsymbol{p_1} \\ (\mathbf{1}-\boldsymbol{cos\,\theta})\cdot\boldsymbol{p_1}\cdot\boldsymbol{p_3} & -\boldsymbol{sin\,\theta}\cdot\boldsymbol{p_1} & \boldsymbol{p_3}^2+\boldsymbol{cos\,\theta}\cdot(\mathbf{1}-\boldsymbol{p_3}^2) \end{bmatrix} \tag{5}$$

By means of a three-dimensional rotation matrix, the coordinates of the translation space are obtained with the direction of motion as the Y-axis.

Figure 3 depicts the indicated error of the segmental motion of the displacement experimental platform, with the grey line segments representing the indicated error's upper and lower limits. The measured values for each stable segment after coordinate conversion have a repeatability of about 0.01 percent, and the indicated error of the displacement step of the experimental platform is about ±5μm, as shown. During the experiment, the displacement value of the experimental platform is measured with a laser interferometer to obtain the amount of change in the standard length.

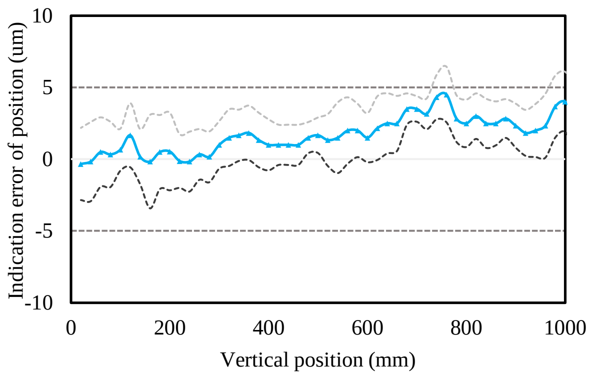


Figure 3: Displacement experimental platform with equal step motion.

3.2 Temperature gradient of water

Natural convection causes height-dependent temperature stratification in the water column during the vertical movement of the displacement experimental platform. The water tank's airtight insulation reduces the temperature gradient to some extent, making the sound velocity measurements as representative of the temperature gradient as possible.

In a static or slowly changing body of water, the speed of sound C in water is an increasing function of temperature T, salinity S and depth Z (static pressure), the simplified Del Grosso equation[8] for the speed of sound is as follows.

$$C = 1449.2 + 4.6T - 0.055T^2 + 0.000029T^3 + (1.34 - 0.01T) \times (S - 35) + 0.016Z \quad (6)$$

To evaluate the effect of temperature gradients on ultrasonic transit time measurements, a high-precision platinum wire thermometer was used to measure the temperature along the path, and the average sound velocity on the sound path was obtained by integration. To measure the temperature distribution in the tank, the displacement experimental platform was fitted with a platinum wire thermometer and an ultrasonic sound velocity metre. Move in steps of 0.1mm from top to bottom in the range of 50mm~100mm from the ultrasonic transducer, taking into account the platinum resistor's response speed. Each position is measured long enough for the measured value to stabilize. The platform moves at a speed of 1mm/s to avoid causing a violent heat exchange in the water. The sound velocity over the entire sound path is shown in Figure 4.

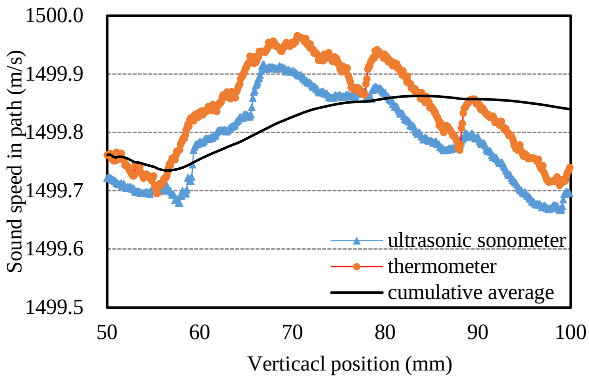


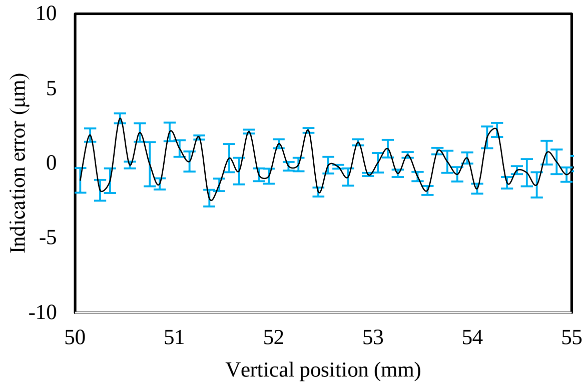
Figure 4: Sound velocity gradients in water tanks.

When the reflector is located at different heights, the average sound velocity on the sound path is obtained by integrating the sound velocity at different height positions. In the 50mm range, the maximum variation in sound velocity is approximately 0.3m/s, and the average sound velocity trend is approximately 0.1m/s. As a result, when the ultrasonic tachometer's measurement segment is able to cover the displacement path, the measurements differ by less than 0.01 percent from the sound velocity measurements introduced by the true temperature gradient. A micro-peristaltic pump was added to the bottom of the tank to allow the water to flow slowly and the water was agitated before the experiment began to improve the temperature gradient conditions. The temperature gradient inside the tank was less than 10 mK before the experiments, and the maximum change in sound velocity was about 0.003 percent.

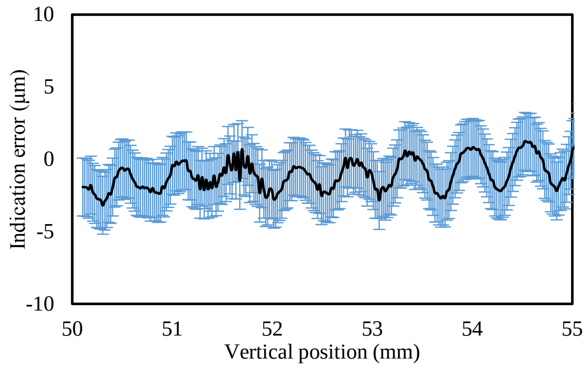
4. Experimental result

The traceability results of the ultrasonic transit time were experimentally analyzed using the above method. The ultrasonic measurement device's sampling frequency is 32MHz, and the measured time difference represents the time interval between the first and second reflections back to the transducer, with a measurement range of 50mm to 55mm between the probe and the reflector plate. Each displacement platform is left to stand for 20 seconds, and the average value of the stable segment of data is used as the measurement result, with each working condition being tested 5 times.

The displacement experiments were carried out in steps of 100 µm and the results of the ultrasonic transit time measurements were expressed in terms of the indicated error of the displacement variation, with the error bars indicating the standard deviation of the five measurements, as shown in Figure 5a). The range of variation of the indicated error of the ultrasonic transit time difference measurement results is less than ±3µm, which corresponds to a time difference measurement error range of approximately ±4ns. In addition to this, the fluctuations in the indicated error also show a certain periodicity. To further observe the pattern of the indicated error, the step size was reduced to 20 µm and the indicated error of the ultrasonic transit time difference measurements is shown in Figure 5b). The trend towards periodicity became more apparent after densening the motion step size and the period width was 0.75 µs.



a) The step length is 100µm



b) The step length is 20µm

Figure 5: Schematic error of ultrasonic transit time difference measurement results.

The measurement instrument's performance should be related to the periodicity of this measurement result. The Hilbert transform is used to calculate the centre frequency within each cycle after the experimental procedure in Fig. 5a) is repeated. The amplitude of the first cycle is usually small, resulting in unreliable frequency measurements. Figure 6 depicts the relationship between the centre frequency difference and position during the second to fourth cycles of a pair of ultrasonic shapes. A periodic fluctuation of approximately 0.75 μs can also be seen in the frequency difference. As a result, the main source of error in the transit time difference measurement results is periodic variation in the frequency of the measured waveform.

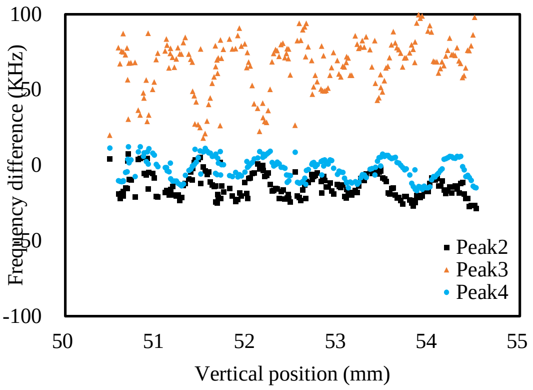


Figure 6: The course of the central frequency change in cycles 2 - 4.

5. Conclusion

A vertical displacement measurement system was constructed and the transit time and time difference were traced to length quantity by means of an ideal reflective surface, with the displacement device providing a minimum 10 μm displacement step. The results show that there is a certain periodicity in the transit time and time difference of the ultrasonic measurements with length, which is reflected in the measurement of time and the variation of frequency, and that the width of this period is slightly less than the inherent fluctuation period of the transducer, giving a measurement deviation of approximately ±4ns to the measurement of the time difference corresponding to the displacement. Temperature gradients, on the other hand, are a source of measurement error.

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