

Design and capability analysis of pure water calibrated TOF for ultrasonic level meter

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Abstract

We will investigate the measuring principle of time-of-flight (TOF) ultrasonic level meter, related analysis and comparison of performance and modification method. Higher measuring precision of height at 0.1mm order of magnitude, and algorithm robustness in the case of weak surface movement, are expected. When using absolute transit time algorithm, the head of wave should be clear, by eliminate echo faster than that through main wave path. And in second trace echo case, ensure there are parts of two echo waves, can be located by theoretical arithmetic and waveform algorithm, have higher relevancy than 98%. In order to enhance the precision of ultrasonic level meter, a proper transit time algorithm will be selected and optimized. The systematic time deviation and delay, transit time in protective containment, cable delay and circuit running time, will be estimated, then adjusted in stable water. The speed of sound, to modify level results with high precision TOF, in objective experimental environment can be calibrated by manometer and thermometer, in pure water media, fluctuation of sound speed measured by ultrasonic apparatus and transfer from temperature is smaller than 0.01%. Finally, micrometer and pressure meter will be used, to compare and evaluate the precision, stability and linearity of level meter, in stable and moving water.

1. Introduction

Research of the water level with high accuracy and precision is fundamental to the application of acoustic systems and technologies in the flow rate measurement in open channel. Water level is can be illustrated by a variety of principles, including mechanical, optical, electromagnetic and ultrasonic methods, that have achieved certain progress on the water level measurement. The mechanical method mainly uses a buoy floater on the water to measure the distance between surface and a proper height. This distance can be obtained by sliding resistance, radar, digital camera or ruler, which is usually easily to implement, but limited by posture of the buoy. The ultrasonic time-of-flight method is physically related to speed of sound, much easier to use in complex situation and higher cost performance, that can be compared with manometer measurement^[1]. There are several significant point to improve the capacity of ultrasonic water level measurement, including transmit signal optimization, chosen and utilization of echo, time-of-flight estimation, and received signal processing algorithm. Attenuation and reflection of ultrasonic wave can influence the signal quality used in measure apparatus^[2], thus

sensor and echo method used in different situation has to be chosen^[3]. The lamb wave travel along the wall can be detected by ultrasonic sensor in water level bucket^[4]. In case of principle of water level detection is essentially a kind of transit time sensing, most of method in ultrasonic time-of flight estimation can be applied to improve the resolution^[5]. Digital filter can be used to remove the noise and interference in ultrasonic wave, many a time algorithm, such as Hilbert transformation and cross-correlation, is effective in different measuring apparatus^[6-8].

We discuss our results with respect to potential of ultrasonic time-of-flight sensor in length and water level measuring to produce stable and high precision apparatus. Then compare with length and manometer value, to analyze the linearity of it, the results present are restricted to NPT(normal pressure and temperature).

2. Apparatus and Principle

2.1 Stable water level

In order to illustrate the ability of ultrasonic level meter, assume it is used in still water. This apparatus was similar as the time-of-flight (TOF) speed meter, for laboratory use. Ultrasonic wave pulses are emitted from one side into water over a

distance of a few centimeters by a transducer and detected by the same element after reflection. The travel distance is then calculated from the measured travel times and sound speed of the pulses along the unknown sound path.

An extensive second trace echo technique approach is used, where sound pulses are emitted by the same transducer simultaneously in same directions into the liquid along paths of different length. Most system time delay source from waveform and processing circuit will be eliminate during additive operation of two transit time, in the case of two echo have nice correlations. A simple cross-correlation method is used to get the time difference, the range is fixed 1024 sample points at 16MHz sample rate, automatically, ultrasonic waveform is simplified to capture by threshold value method. The sensor need to be designed to make only one pure wave pack without long trail, reflection echo in the sensor has to be separated. The center frequency of the forced vibration is 1MHz, and thickness of protective layer is 1.47mm, stainless steel, shown in Fig 1. In this measuring application, a single transducer and a stainless steel reflector are used to generate and capture echo, take the place of water surface. Connecting structures are several pairs of stainless steel single end studs with different length from 50mm to 500mm, instead of water level. The length connection can't neither be too short, or the first echo may overlap with the other echo and noise, nor too long, or the connecting structures may be easily twisted a small angle, which make the reflection not straight enough to represent the water level. The environment are NPT, about 19°C in water. The total offset in experimental period is about 1°C, and expansion by heat and contraction by cold during this range is about 25nm~250nm, far less than water level accuracy requirement, and will not be taken consideration in this case.



Fig 1: Time of flight sensor with changeable echo path length

The sound speed we used is dependent on the real-time condition of liquid media. In this case, the liquid media is tap-water, it's assumed to pure water to simplify the process. Two thermometers with high-precision was set nearby the center of connecting structure's outer edge. Anton Paar MKT50 platinum wire resistance thermometer are used to record real-time temperature, with 0.001°C resolution. We will use IAPWS-95 polynomial

formulation^[1] to transfer temperature to sound speed, which means resolution of temperature takes 3mm/s to sound speed, about 2 ppm deviation in theory, also enough for this apparatus. The temperature is between 18.9°C~19.9°C, its gradient characteristics can be described by the difference between two sensors, shown in Fig 2, in the range of [-0.0138,0.0259] ° C, about 39.7mK width.

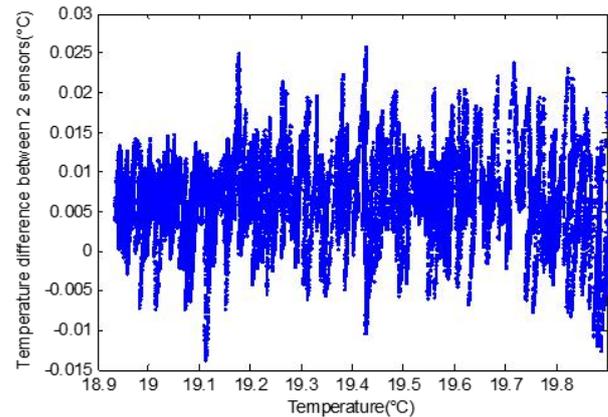


Fig 2: Temperature homogeneity between two thermometers in about 40 hours

The length between center of ultrasonic and reflector is the average observed value from a micrometer, which is enough resolution in water level measurement.

2.2 Unstable water level

Based on the illustration of ultrasonic sensor ability in stable length measurement, the unstable water level with small fluctuation will be taken into consideration. In this case, a liquid level measuring bucket with 150mm inner diameter, PVC hollow containment structure. The basic principle of this apparatus is to drive a series of ultrasonic waves to measure the transit time between sensor and almost static water level, depend on the real-time sound speed. Then the average distance between center of sensor and geometric center of water in bucket can be estimate by transit time and sound speed in same liquid environment.

Because of fluctuation of water level, each reflection path during short time will alterable in a certain extent. This may bring more uncontrollable factors if we choose second trace echo method. Ultrasonic echo from the water surface may not straight from sensor and water face, the second echo may meet the shell of pipe wall because of a certain beam width, which will change the transit path and received waveform. The time difference will contain more information on the reflection path, and distorted waveform will take more deviation to correlation method. So a single pulse echo method is used in this water level measurement, and an

easy waveform algorithm method is use to find a zero-crossing fitting point on the proper edge of waveform. In this case, system time delay from wave propagation in protect layer and measuring circuit will be counted in transit time, so a correction is necessary to calibrated by standard instruments.

A Yokohama MT210 digital manometer is used to record the pressure of water, with $\pm 0.01\%$ accuracy declared. The results can be considered directly to represent height of water level, if there is a communicating vessels to connect liquid level measuring bucket and the manometer. A plastic hose is used as a connector on the bottom of bucket and manometer, and we tried different heights of manometer, in case of responds characteristics to measuring range. During the experiments, water level could be quantitative changed by add or draw off water in a proper short time, the results of manometer continuous record once in 1s through serial port. We observed that the gauge reading need a long time to reach steady state if we try to draw off water by steps, which may caused by water environment disturbance near the connector and influence the responds character of sensor in manometer. When we try to add water to bucket, there will be water droplets on the wall of pipe and slide down gradually, which will cause smaller than 0.1mm magnitude changes in few minutes, the display of manometer barely be disturbed during this process, so it is chose to make sure pressure as accurate as possible.

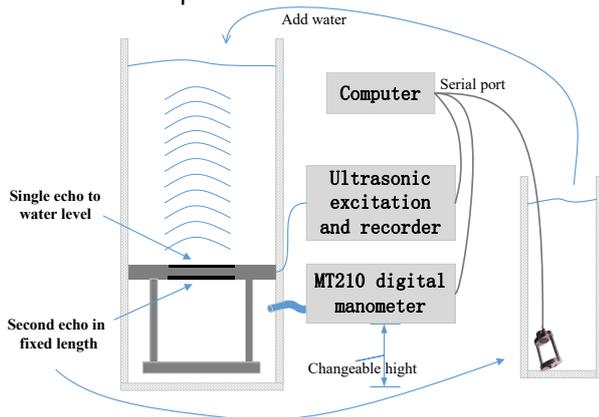


Fig 3: Measurement setup of ultrasonic level meter

We use a sound speed measuring application by second trace echo method, similar to the sensor used in stable water, see as Fig 1. The fluctuation and accuracy of ultrasonic speed meter will be illustrated by the experiments in section 2.1. The sound speed application is in the extra water bucket, where the water added to liquid level bucket from, all of this measuring process is happened in 1 hour, enclosed environment, so that,

the sound speed in two bucket can be considered the same, record synchronously with water level sensor and manometer. The measurement setup of water level, sound speed and manometer is shown in Fig 3.

3. Measurement results

3.1 Ability of the sensor in steady state

We start the water level measurement in solution with fixed length reflection, between 50mm and 500mm, instead of still water surface, in section 2.1. Solution is measured in 2 days, with at least half hour in each length step. The thermometer on the both sides of ultrasonic measuring application can record the real-time temperature around sound path, and then transfer to sound speed. To account for variety and fluctuation of temperature and transit time, 30 continuous 60s data are chosen from each measuring step, randomly. The fluctuation of sound speed in each half hour is less than 0.01%, transfer from temperature, during 40 hours, is shown in Fig 4, the total offset of temperature is 1° C, much less than expectant of water level, can be considered as a steady state. The fluctuation of measured length is shown in Table 1, which is smaller than 0.01%, the trend is not monotonically with length, and get largest undulation at 200mm, about 15 μ m. The precision deviation measured from thermometer can be ignored.

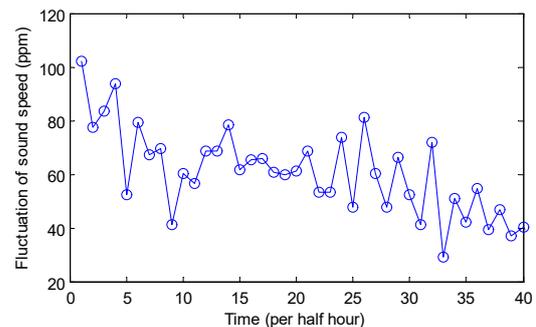


Fig 4: Fluctuation of sound speed calculated from thermometer by IAPWS-95 (average value in each continuous 30mins during 40hours)

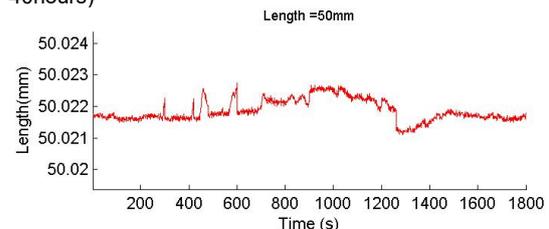


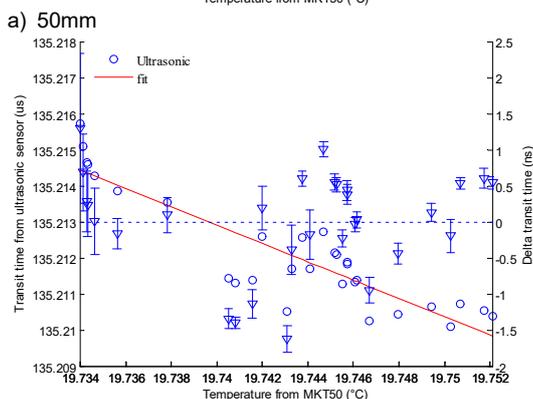
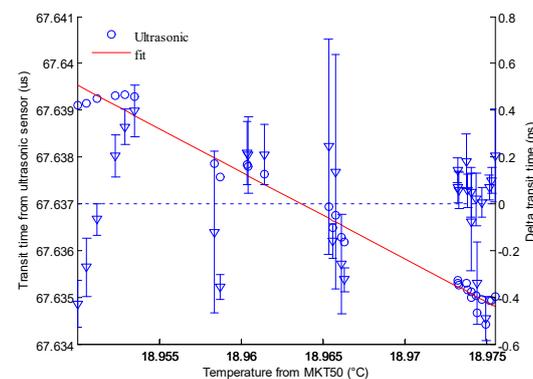
Fig 5: Length measured by ultrasonic sensor in random 30mins (when length is 50mm, display width is about 0.05% of nominal length)

Using tap water instead of pure water in a quite and close environment, we still relied on the

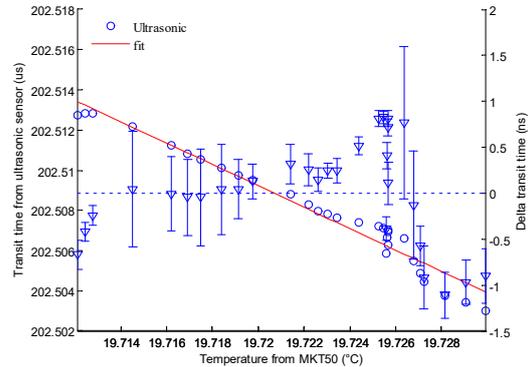
temperature to calculate the sound speed by IAPWS-95 polynomial formulation, which may make a unidirectional offset during 1 ° C variation range. Transit time is the direct measured value of ultrasonic sensor in 2.1 and 2.2 section, thus its characteristics is significant in water level measurement. The linearity and fluctuation of transit time in each 60s, measured by ultrasonic sensor and length, measured by micrometer, divided by real-time sound speed, is shown in Fig 6. The red straight full line is fitted curve of average temperature of each 60s and divided transit time in random 1800s, variation range of transit time is from 5ns to 50ns, increase with travel length of wave monotonically, approximately. The triangle shows the difference between measured ultrasonic transit time and fitted value, which means the linearity, and its whisker show the standard error of ultrasonic transit time in each 60s. Abscissa axis is average temperature of two thermometer in 60s. These will display the influence and changing rule of minor environmental differences.

Table 1: Fluctuation of ultrasonic sensor measurement in each length.

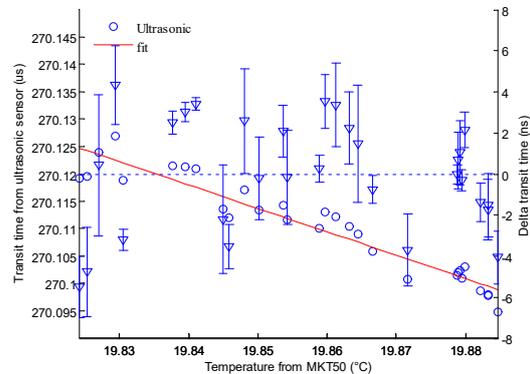
Nominal length (mm)	50	100	150	200	300	400	500
Fluctuation in 30mins(μm)	1.657	3.939	2.707	15.073	9.177	8.320	9.777
Relative fluctuation(ppm)	33.14	39.39	18.05	75.37	30.59	20.80	19.56



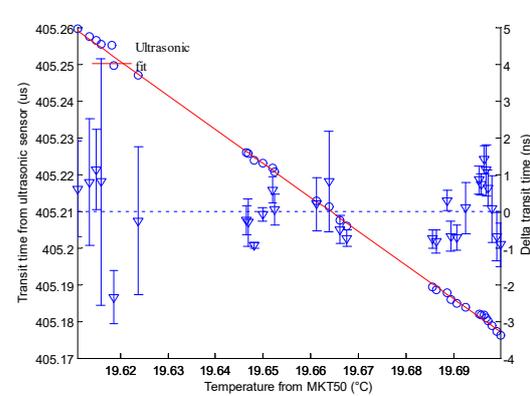
b) 100mm



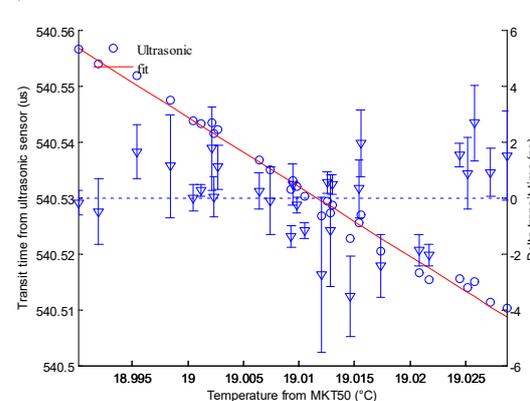
c) 150mm



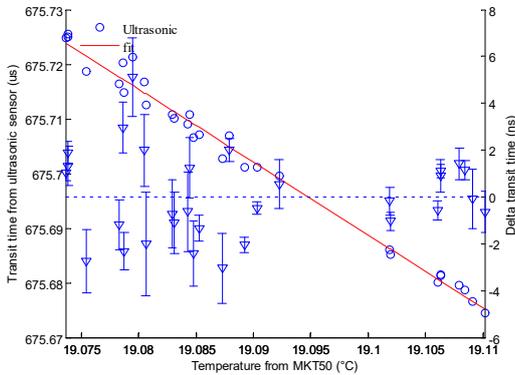
d) 200mm



e) 300mm



f) 400mm



g) 500mm

Fig 6: Linearity and fluctuation of ultrasonic time of flight sensor (each sample set contain 1min calculation, 30 sample sets are selected random)

The standard error shows similar law to fluctuation in Table 1, which means stability of transit time measurement is not monotonic to travel length of wave. Indication and linearity deviation of travel length can be seen in Table 2, the results measured by ultrasonic sensor is transit time multiplied real time sound speed. There is always about 0.5mm offset between two measured value, which may caused by steel protective layer. If the average offset is ignored or counted in system delay, the linearity between micrometer and ultrasonic sensor is smaller than 0.05mm. This can easier be seen in Fig 7, tendency of difference shows no obvious relationship with length, and the standard error of length is smaller than 5µm.

Table 2: Comparison of length between ultrasonic sensor and micrometer.

Nominal length (mm)	Average value by ultrasonic (mm)	Average value by micrometer (mm)	Indication error (mm)	Linearity deviation (µm)
50	50.022	49.432	0.590	26.644
100	100.163	99.652	0.511	-53.024
150	150.008	149.412	0.596	31.525
200	200.141	199.598	0.543	-22.037
300	300.123	299.546	0.577	10.903
400	399.798	399.205	0.593	25.980
500	499.860	499.312	0.548	-19.992

3.2 Liquid level measuring bucket

With the conclusion in section 3.1, water level can be measured in bucket. Where the sound speed application use the same setup as that for section 3.1, 50mm length, characteristics can be shown in Fig 6a, standard error of transit time is less than 0.5ns, about 7ppm in 60s.

Water level measurement is usually prospected in short period, thus we wait 5 to 10 min after adding water to the bucket for each step, till most water drop fall down to water surface and water calm FLOMEKO 2019, Lisbon, Portugal

enough, 1min in each steady state is chosen. Experiments are repeated 3 times, with 3days and 1month interval to ensure the repeatability in a proper period. We record the sound speed in 100min, and rotate a proper angle, which is the gradient of temperature change, then the fluctuation is about 60ppm in the whole range (still lower than 0.01%).

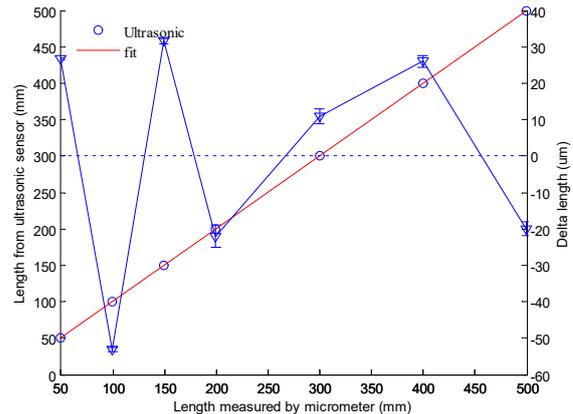


Fig 7: Linearity and standard error of ultrasonic time of flight sensor in random 1800s

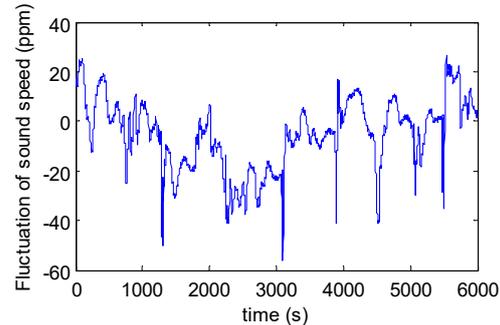
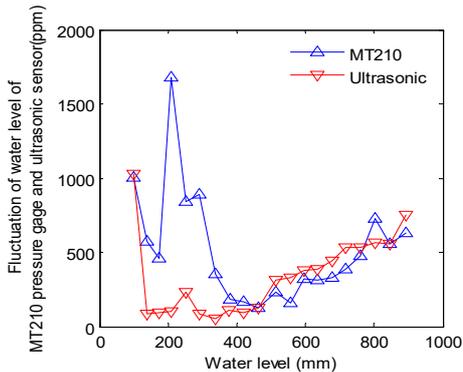


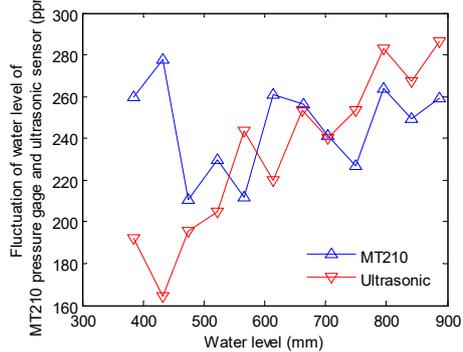
Fig 8: Fluctuation of sound speed without circumstantial change by rotation in the first experiment

In the first experiment, the manometer is set the close level with ultrasonic water level sensor, and second higher, the third lower, which will change the linear range of it. The fluctuation of manometer and ultrasonic sensor in each measuring step can be shown in Fig 9. Each of ultrasonic measured length need to add a system offset, including the altitude intercept of manometer and system time delay of ultrasonic sensor, the manometer results can be taken as standard value. The offset of each experiment is average difference in same setup. The fluctuation of manometer results increase slowly when water level is higher than 400mm, and lower than 0.05% in most situation, however undulate strenuous in low water level. The ultrasonic results shows monotonous increasing trend with waver level when higher than 20mm, and show a repeatability better than 0.01% in overlapping range (400mm~600mm).

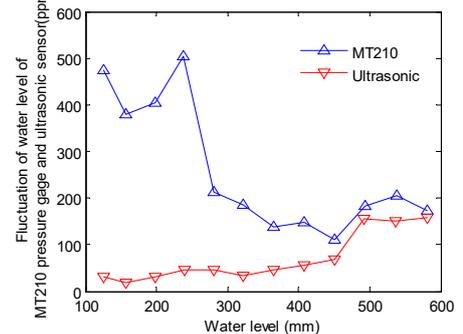
Fig 10 summarizes the ultrasonic measurement linearity which are also listed as an indication error relative to manometer in Table 3. Most linearity deviation is lower than 0.5mm, and most indication error is in ± 0.5 mm range, increasing with water level when height is higher than 100mm.



a) Exp.1



b) Exp.2



c) Exp.3

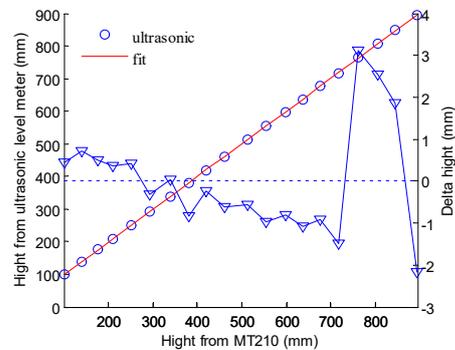
Fig 9: Fluctuation of water level measured by manometer and ultrasonic sensor

5. Conclusions

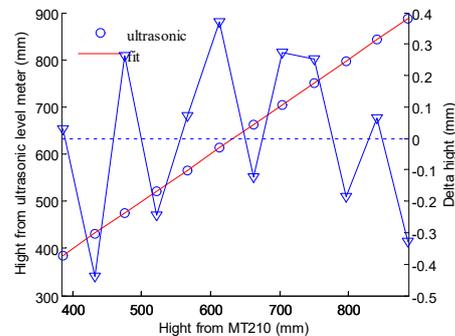
The primary intention of our analysis is to ensure the capabilities of the time-of-flight ultrasonic sensors as instruments for routine practice of in situ water level measurements. We make the results in this paper as the first step of a thorough application that demonstrates and substantiates the potential of time-of-flight sensors in flow research. With the fluctuation, linearity FLOMEKO 2019, Lisbon, Portugal

deviation and indication error of each component to obtain water level in still reflect surface and water surface, we can obviously find the fluctuation of ultrasonic time-of-flight sensor about 0.01%, increase monotonously in a effective measuring range larger than 20mm, and the linearity depends on the stability of contrastive standard apparatus. However, as the contrastive apparatus, such as manometer, show not stable enough responds in test, the indication error and linearity will be abnormal in part of range, yet still tendency toward monotony.

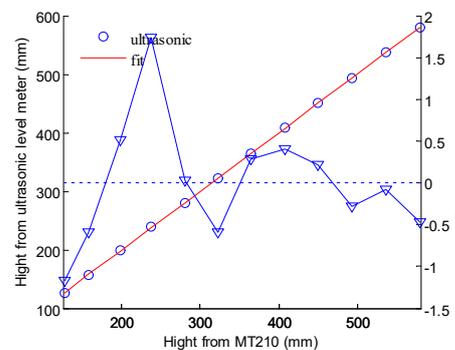
In the follow exploration, we will transfer the water level directly to length, then more precise measuring instrument can be used to evaluate the capacity of ultrasonic time-of-flight sensor



a) Exp.1



b) Exp.2



c) Exp.3

Fig 10: Linearity of water level measured by manometer and ultrasonic sensor

Table 3: Comparison of length between ultrasonic sensor and manometer from 3 repeating experiments.

Experiment time & No.	Average value by ultrasonic (mm)	Average value by manometer (mm)	Indication error (mm)	Linearity deviation (μm)
2019/1/29 1	99.668	98.874	-0.794	-185.402
	139.769	139.414	-0.355	190.910
	175.519	175.136	-0.383	107.305
	208.477	208.104	-0.373	65.673
	250.159	250.042	-0.117	255.707
	292.911	292.329	-0.582	-275.819
	338.750	338.660	-0.090	143.987
	379.617	378.872	-0.745	-574.835
	420.104	420.131	0.028	134.372
	461.754	461.601	-0.153	-111.944
	512.543	512.692	0.149	111.224
	554.878	554.806	-0.072	-176.398
	596.873	597.178	0.306	135.413
	635.435	635.659	0.224	-7.065
	676.400	676.961	0.561	266.127
	717.624	717.834	0.210	-149.021
760.489	761.122	0.634	206.926	
803.964	804.346	0.382	-112.846	
844.744	845.560	0.816	257.700	
893.881	894.234	0.354	-282.012	
2019/1/31 2	385.285	385.174	-0.111	30.231
	432.468	431.913	-0.555	-439.908
	475.066	475.237	0.172	262.282
	522.378	522.068	-0.310	-245.847
	566.034	566.064	0.031	70.132
	613.482	613.839	0.357	370.127
	662.837	662.730	-0.108	-122.585
	703.896	704.206	0.310	271.721
	749.915	750.231	0.316	251.736
	795.878	795.782	-0.097	-186.533
841.984	842.165	0.181	65.000	
886.768	886.583	-0.185	-326.357	
2019/3/4 3	126.297	125.184	-1.113	-1172.013
	157.708	157.168	-0.540	-590.613
	197.871	198.430	0.559	519.167
	237.584	239.351	1.768	1738.692
	280.661	280.708	0.047	29.803
	322.475	321.891	-0.583	-589.825
	364.851	365.127	0.277	281.714
	407.697	408.084	0.387	403.113
	450.151	450.338	0.187	215.206
	492.862	492.540	-0.321	-282.031
537.425	537.293	-0.132	-80.906	
580.832	580.297	-0.535	-472.307	

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