Experimental Investigations of Boundary Layer Thickness Using Ultrasonic Transit Time Method

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Abstract

The widely used investigation method of fluid boundary layer is to record or simulate the current profile distributions near boundary, and then the loss of velocity can be estimate by integration. A directly measuring method of boundary layer displacement thickness by using ultrasonic transit time instrument is proposed. The problem of boundary layer measurement can be simplified to a easier measurement process of current velocity calibration, and the verification experiments are carried out by taking smooth plate as an example. An experimental platform of towing tank facility is established, the towing velocity is taken as the standard value of the outflow speed. The device for flat plate boundary layer measurement is regarded as an ultrasonic current meter. The inner side of the pair of plates equipped with ultrasonic probes can be considered as smooth surface, when the concave at the end of probes, installed by path axial angle, is filled with the material, which acoustic impedance is approximately equal to water. The measured value of ultrasonic current meter is equivalent to the difference between the outflow velocity and the loss caused by boundary layer. The accuracy of measurement result is ensured through high-precision geometric measurement, time delay calibration and sufficient zero-offset correction. In order to improve the time measurement resolution of the current meter, the range of flow velocity is set higher than 100mm/s. By changing the towing velocity and the characteristic position of ultrasonic probe installation, the Reynolds number range is 5e4 to 5e5. By analyzing the principle of ultrasonic current meter and towing tank facility, the uncertainty of displacement thickness measurement results can be properly evaluated. The measurement results of these experiments are close to the integration of flow field record by LDA.

1. Introduction

Boundary layer is a typical flow patterns, which is closely related to a large number of fluid motion problems, such as stall, drag reduction, etc. The accurate measurement of boundary layer flow parameters is the basis of studying its action mechanism in engineering. In particular, the velocity loss caused by the the boundary layer thickness has a great impact on the flow measurement.

The plate shape is the basic form to observe the shape and development of the boundary layer. Based on the thin layer assumption, the theoretical N-S equation can be simplified to the boundary layer equation, and the characteristics of the velocity field can be obtained by calculation. However, when the Reynolds number is high or the disturbance in the flow field is large enough, the laminar transition becomes turbulent, which is more complex. With the development of measurement, hot wire anemometer (HWA), laser anemometer (LDA) and particle image velocimetry (PIV) have been applied to boundary layer observation. Dekou[1] characterized the structure, including size, strength and life time, and focusing on the spatiotemporal organization of coherent structures and their energy contribution to flow. There is heat conduction effect between the HWA and the plate wall, which is more suitable for the gas medium measurement[2]. LDA doesn’t have such problem of HWA method, and has the advantages of high measurement accuracy and fast dynamic response, which is widely used to scanning the flow field distribution. Niederschulte[3] used LDA to measure the velocity profile data from the near wall zone to the viscous bottom layer. On the basis that the LDA measurement frequency is much higher than the turbulence frequency, the normal and flow velocity field components at low Reynolds number are obtained. David[4] used LDA to study the normal stress scale under high Reynolds number but low velocity condition, however, disputes of boundary layer distribution assumption function still exist. PIV technology can collect a large number of sample points at the same time, and has a good ability to observe the transient flow field, comparing with the method of HWA and LDA. Manovski[5] studied the long-distance and high-power turbulent boundary layer along the slender body by PIV, and the measured surface friction coefficient is in good agreement with the Preston tube measurement. The shape of complex flow field can be comprehensively observed, by increasing the number of synchronous optical cameras[6-7]. However, the random motion of particles will introduce noise to PIV measurement, which makes resolution is lower than LDA[8]. In addition, the measurement of LDA and PIV depends on the particles in the water, and the uniformity of particle distribution is also affecting factors.

In order to directly evaluate the velocity loss in the flow field, a ultrasonic transit time method is used to measure the displacement thickness of the plate boundary layer. A new boundary layer thickness measurement method based on towing tank facility is proposed. The error source of measurement method, standard velocity and measurement device are analyzed, and the results are compared with the flow field integral measured by LDA method.

2. Boundary layer thickness measurement model

2.1 Displacement in flow field

It is assumed that the plate is placed in an infinite uniform flow with velocity U along its direction, and the theoretical velocity u near the plate is 0, according to the assumption of viscous fluid. The flow away from the plate surface is inviscid, and the theoretical velocity is close to the outflow velocity U, that forms a gradient perpendicular to the plate surface. The development process of the boundary layer near the plate is shown in Figure 1. It is considered that when the velocity u reaches 99% of U, the velocity gradient can be ignored, and the vertical distance from here to the plate surface is defined as δ or δ_{99}. The displacement thickness is used to represent the integral of the flow velocity loss caused by this velocity gradient, which is defined as

$$\delta^* = \int_0^\infty \left(1 - \frac{u}{U}\right) dy \tag{1}$$

The displacement thickness δ^* is approximately 1/3 of the boundary layer thickness δ, which is related to the Reynolds number Re and the boundary layer development distance x along the velocity direction. Its theoretical solution is usually expressed as

$$\delta^*_{Theory} = \frac{1.721x}{\sqrt{\mathrm{Re}}} \tag{2}$$

The Reynolds number of fluid is a function of fluid density ρ, dynamic viscosity coefficient μ, outflow velocity U, and characteristic length x.

$$\mathrm{Re} = \frac{\rho U x}{\mu} \tag{3}$$

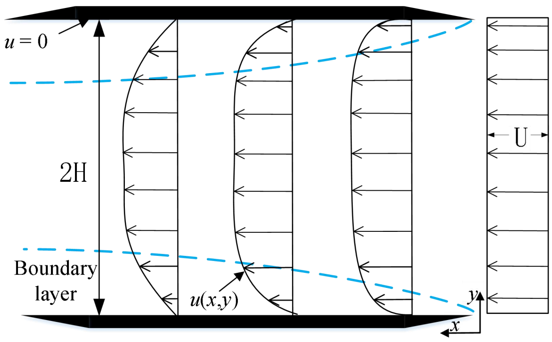


Figure 1: Boundary layer flow field development.

2.2 Ultrasonic transit time method

Ultrasonic transit time method is a easier way for average velocity measurement. A pair of opposite ultrasonic transducers send waves to each other to measure the transit time and time difference in water. By using the relationship between the velocity difference formed by fluid motion and propagating time, the average velocity between the transducers can be expressed as

$$\overline{v_a} = \frac{L}{2\cos\theta} \frac{\Delta t}{t_{ud} \cdot t_{du}} \tag{4}$$

Where, the path length L and the path angle θ, can be combined as geometric parameter. t_{ud} and t_{du} are the transit time of upstream and downstream , respectively, and Δt is the time difference between t_{ud} and t_{du}, which is the real-time measurement results of ultrasonic measurement system. Due to the characteristics of time delay estimation and the algorithm, the cross-correlation algorithm is usually more accurate in time difference measurement. In order to reduce the system measurement error, the downstream transit time measurement can usually be expressed as

$$t_{du} = t_{ud} + \Delta t \tag{5}$$

According to the ultrasonic transit time principle, a pair of ultrasonic transducers are clamped on parallel plates. The loss of the flow velocity can be obtained, and then the displacement thickness can be estimated, through the measurement of the average value between the plates and standard velocity.

A plate type flow measuring device is designed, which path length can be adjusted along the sound path. The sketch is shown in Figure 2. Since the angle between propagation direction of ultrasonic wave and the fluid movement, the sound path cannot be arranged in an axisymmetric manner as shown in Figure 1. In order to make the upstream and downstream boundary layers have similar development patterns, the sound path and the boundary layer intersect at the same position, the end of the plates and sound path parallel. Assuming that the characteristic length x is the distance from the front of plate to the center of transducer, boundary layer thicknesses of upstream and downstream can be written as δ_u and δ_d, respectively. When the flow boundary of the two plates does not intersect when x is small enough and shows a monotonic development trend, the boundary layer thickness at x is approximated as follows

$$\delta \approx \frac{\delta_u + \delta_d}{2} \tag{6}$$

The displacement thickness δ^* at x can be taken as the average loss of upstream and downstream flow velocity. Then the average velocity between the plates with $2H$ vertical spacing can be approximately expressed as the relationship between δ^* and U.

$$\overline{v_t} = \left(1 - \frac{\delta^*}{H}\right)U = \left(1 - \frac{2\delta^*}{L\sin\theta}\right)U \tag{7}$$

The idea adopted in this paper is the equivalence of equations (4) and (7), i.e

$$\overline{v_a} = \overline{v_t} \tag{8}$$

When the standard value of the outflow velocity is obtained by towing tank water facility, and the displacement thickness at x from the plate end can be calculated according to equation (8)

$$\delta^* = \frac{L\sin\theta}{2}\left(1 - \frac{L\Delta t}{U \cdot \cos\theta \cdot t_{ud} \cdot (t_{ud} + \Delta t)}\right) \tag{9}$$

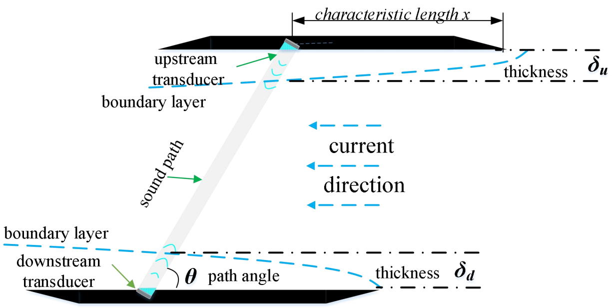


Figure 2: Sketch diagram boundary layer measurement by ultrasonic transit time method.

The boundary layer thickness can be obtained by the ultrasonic transit time method. In addition, it is also affected by the approximation of the boundary layer shape in equation (6), except capacity of the measuring device. The average thicknesses of the upstream and downstream corresponding positions is different from that perpendicular to the plate surface in Figure1.

3. The experimental platform

The experimental platform includes a towing tank water facility and a plate type ultrasonic flow measuring device, which can be used to obtain the outflow velocity and the ultrasonic transit time, respectively.

3.1 Towing tank facility

The principle of the towing tank is based on the assumption that the trailer and current meter to move together at a uniform speed in still water. The facility is mainly composed of a towing system and a water pool, the measurement period is when the vehicle speed is stable enough. The water in front of current meter being test is in a static state when testing, and the moving flow field can be considered as uniform. The facility is 8m length, and can provide standard speed in the range of 1mm/s~2000mm/s.

The vehicle speed is measured by the equidistant trigger method. Triggers are arranged every 0.2m along the trailer motion path, and there are 34 measuring units. On the premise of calibrating the length of each unit, the unit cart speed can be obtained by recording the time interval passing through adjacent triggers. Its accuracy is determined by the unit length calibration and the time interval measurement. The outflow speed can be considered as the average of unit cart speed.

The uncertainty sources include the unit length calibration, the time interval measurement, and the fluctuation of speed.

1) Unit length

Within the speed range of 100mm/s~2000mm/s, unit length is calibrated by laser interferometer under different speed for 5 times, and the maximum deviation is 70μm, when the air temperature is stable. So that the uncertainty of length calibration is U_L = 70μm/200mm = 0.04% (k=2).

2) Unit time interval

The uncertainty of time measurement is caused by the waveform of trigger and the performance of circuit. The uncertainty of time interval is calibrated in NIM, which is U_T = 0.0013% (k=2).

3) Fluctuation of towing

Although the displacement of towing is the same at each speed, the number of units in stable states varies from 19 to 31, caused by acceleration and deceleration. The cart speed is given by the mean value of stable section, and its uncertainty is

$$U_{\sigma}=2\sqrt{\frac{1}{k-1}\sum_{i=1}^{k}\left(v_i-\bar{v}\right)} \tag{10}$$

Where, k is the number of unit number of stability section, v_i is the ith unit, $\bar{v}$ is the average value of k units at this speed. The uncertainty introduced by the cart speed fluctuation process are shown in Figure 3, which is no larger than 0.01%.

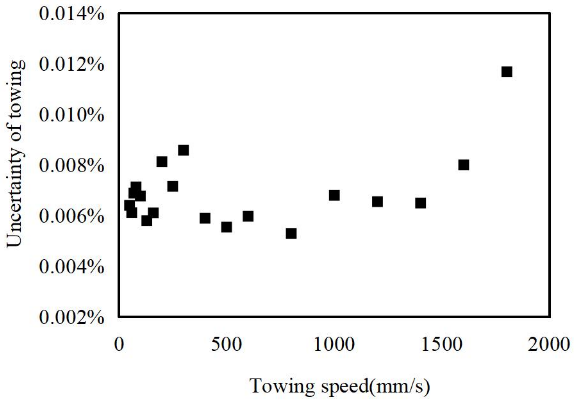


Figure 3: Uncertainty of towing speed fluctuation.

The uncertainty of cart speed measurement can be expressed by

$$U_{vs} = \sqrt{U_L^2+U_T^2+U_{\sigma}^2}<0.04\% \tag{11}$$

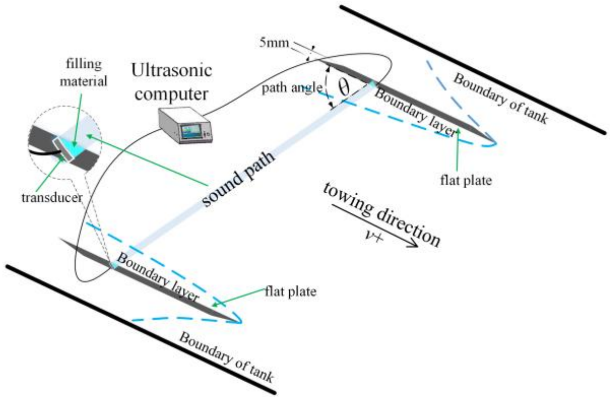
Therefore, on the premise of calibrating the unit length, the uncertainty of the cart speed measurement is about 0.04%. In addition, the gradual attenuation of periodic fluctuations in the water after towing is also one of the uncertainty sources. The water fluctuation presents a normal distribution of the 1mm/s maximum value, after a period of waiting, which is record by a current meter with 0.5mm/s resolution. After each testing, we take sufficient waiting time to reduce the residual velocity, the uncertainty U_V of the standard velocity can be expressed as

$$U_v=U_{vs}+U_{bk}=0.04\%v+2mm/s \tag{12}$$

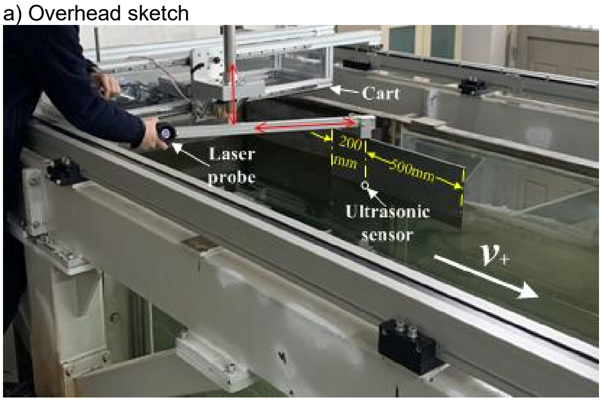
Where, the U_{bk} is the uncertainty of background current velocity.

3.2 Ultrasonic measuring device

According to the principle of measurement in Figure 2, the ultrasonic measuring device is consist of a pair of flat plates, a slideway that can move along the sound path, a bracket connected to the tow cart, a pair of ultrasonic transducers and an ultrasonic computer, which is shown in Figure 4.



a) Overhead sketch



b) Picture of the device

Figure 4: Ultrasonic measuring device and platform.

3.2.1 Geometry

The plates with the size of 0.7m*0.5m*0.005mm are placed along the length direction and parallel to the movement direction, and 0.4m in height is immersed in water. The probes are installed at half of the water depth and 0.5m away from the front edge of the plates. In order to suppress the interference flow field outside the boundary layer as much as possible, and improve the accuracy of the measurement results, the plate structure is modified. Firstly, aiming at the displacement effect formed in the finite boundary flume, the end of the plate is made into a sharp wedge to push the water nearby to the outside of measuring area as far as possible, when the plates are moving. Secondly, in order to avoid the vortex formation at the end of the probe, caused by the certain path angle, it is filled by a material which acoustic impedance is close to water.

The path angle of the ultrasonic measuring device is 67°, and the path length can be adjusted within 1m range along the slide. Path length and angle are the important parameters for boundary layer thickness calculation. In order to improve the accuracy of geometry, a laser tracker is used after adjustments, which indication error is calibrated by 8μm+0.5×10^{-6}L for length measurement and 15μm+2×10^{-6}L for space location. There are 4 working conditions for measurements, shown in Table 1. The uncertainty of geometric parameter measurement is less than 0.005%, which can be ignored.

Table 1: Geometric parameter of movable ultrasonic facility

	Condi 1	Condi 2	Condi 3	Condi 4
Path length(mm)	998.6	802.2	604.0	404.2
Path angle (°)	66.7	67.01	67.0	67.7

3.2.2 Transit time measurement

The ultrasonic measuring device consists of transducers and ultrasonic computer. The central frequency of transducers are 1MHz, with 32MHz sampling rate and 10bit vertical resolution, and the excitation frequency is 100Hz. The average transit time measurement is record once per second.

The Hilbert transformation is used to calculate the transit time[9]. The time difference is obtained by cross-correlation algorithm, and the exact solution is estimated by the parabola assumption. 1μs error of transit time measurement brings 0.15%~0.37% deviation, and 1ns error of time difference brings 2.7mm/s~6.7mm/s deviation to current velocity, in theoretically. The time difference is the main factor for the accuracy of measurement.

1) Time delay modification

The time delay caused by coupling of probes and measuring circuit can reach several μs, which is calibrated by standard sound speed. A high-precision sound speed meter, which accuracy is 0.01% and calibrated in pure water, is used. Three points are evenly settled on the sound path to obtain the average sound speed c, under static water, and the upstream transit time t_{ud} is recorded synchronously. According to

$$c = \frac{L}{t_{ud} + \tau} \tag{13}$$

The time delay can be obtained as 8.321μs. The temperature gradient during tow test is smaller than 0.02℃, which makes 0.004% deviation to transit time. Therefore, the uncertainty introduced by temperature gradient to the transit time measurement can also be ignored.

2) Zero-offset

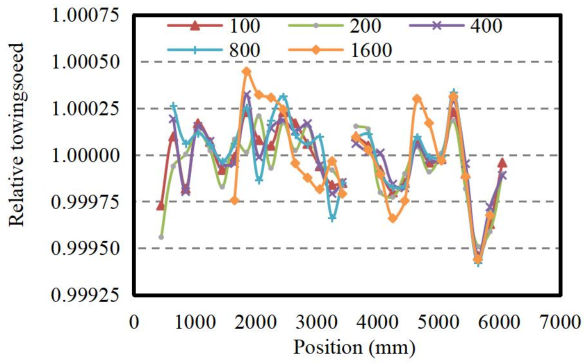
The change of time difference measurement is mainly manifested in the phenomenon of Zero-offset drift, which is caused by the joint action of many factors, such as acoustic characteristics, external environmental conditions, electron drift and so on. Long-term observation of the stability of time difference is taken in still water. We record the change of the time difference for over 18h with 1Hz record frequency, under working condition 1, about 65,000 data points is gained. The fluctuation range of time difference is about ±1ns and is normally distributed. Therefore, it can be considered that the time difference of ultrasonic measuring device is stable under the premise of no mutation occurs.

4. Results

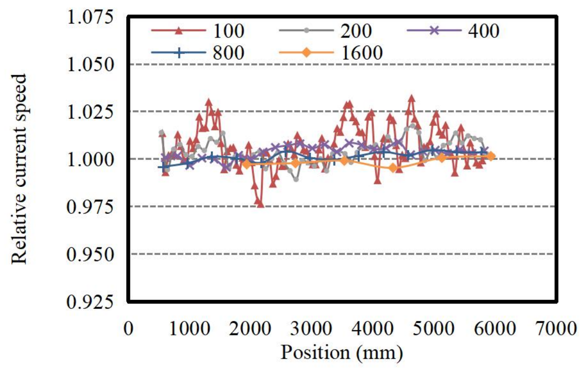
4.1 Towing speed

The experiments are taken from 100mm/s to 2000mm/s, and the towing process includes 4 steps: static at the starting point, forward moving, static at the end and reverse moving. The outflow velocity, the transit time and the time difference are recorded, respectively, and the corresponding measurement results when the velocity reaches a stable level are extracted. The characteristics length x is 0.5m when moving forward, and is 0.2m when moving backward. When the maximum speed testing is completed, the plate surface is cleaned to reduce roughness, wait for long time till the water is still enough. Four groups of results are obtained.

In order to observe the fluctuation of measurement results, the recorded ultrasonic transit time and time difference are converted into current velocity, a variety of results in working condition 1 are shown in Figure 5. The fluctuation of towing speed is about 1% of that of current velocity. The influence of towing speed, geometry and ultrasonic transit time is much smaller than fluctuation of current velocity, which means the main uncertainty source is background velocity and time difference measurement.



a) Towing velocity



b) Current velocity

Figure 5: Results of standard and measured velocity.

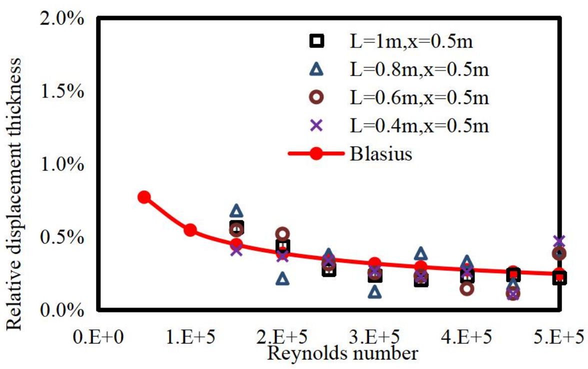
4.2 Displacement thickness

In order to illustrate the measurement results under different *x*, conveniently, a relative displacement thickness is used to represent the measurement results. The theoretical solution can be expressed as

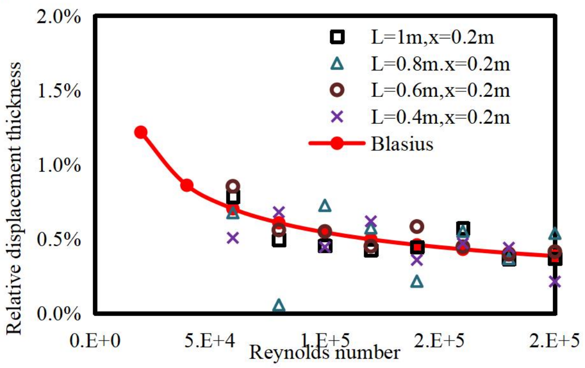
$$\frac{\delta^*}{x} = \frac{1.721}{\sqrt{\mathrm{Re}}} \tag{14}$$

Which is only related to Reynolds number, and to compare with the measurement results.

The measurement results of ultrasonic propagation time method under two characteristic lengths are shown in Figure 6. The measurement points represent the average value of 5 repeats under specific geometric parameters and flow velocity. Since there is no obvious systematic deviation between the measured result and the theoretical solution, the stability of measurement is expressed by the dispersion of the deviation. Although the characteristic length is different, the dispersion degree under each condition is about 0.001, and the longer the *x* the lower the dispersion. Therefore, in order to obtain more stable measurement results, the path length should be as long as possible when using the ultrasonic transit time method to measure the displacement thickness of the plate boundary layer.



a) *x*=0.5m



b) *x*=0.2m

Figure 6: Relative displacement thickness measured by ultrasonic propagation time method.

Comparing with the experimental results of LDA integrating method[10,11]. Considering that there is a certain difference between the gas and liquid media, the selected experiments are all carried out in water tank with uniform flow. The results of ultrasonic transit time is the average of 4 conditions, the relative displacement thickness is shown in Figure 7. The accuracy of ultrasonic and LDA method are almost the similar. The ultrasonic transit time method is closer to Blasius solution, which may because of the velocity distribution of towing in still water is more stable in low velocity.

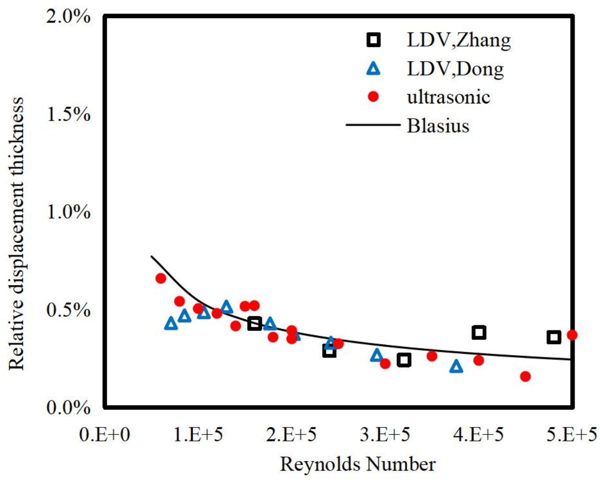


Figure 7: Comparison results of relative displacement thickness.

7. Conclusion

In this paper, a direct measurement method of boundary layer thickness based on the ultrasonic transit time method is proposed. The standard outflow velocity is provided by towing through still water, the influence of the standard velocity and transit time measurement is analyzed. The ultrasonic transit time method has the ability to measure the displacement thickness directly, which can provide the similar accuracy with LDA method, but save more cost and time. The resolution of the ultrasonic measuring device and the system response under low velocity should be comprehensively considered to ensure the reliability of measurement results.This method may also have applicability to measure other forms of boundary layers in the future.

Acknowledgments

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