Ultrasonic velocity profiling as a wall shear stress sensor for turbulent boundary layers

Yuichi Murai, Yuji Tasaka, and Hyun Jin Park
Faculty of Engineering, Hokkaido University, N13W8, Kita-ku, Sapporo, 060-8628, Japan

There are a number of technical problems pointed out in wall shear stress measurement as it is directly sensed with a shear transducer. This is because most of the sensors adapt mechanical displacement principle intrusively to boundary layer before converted to electric signals. Here we propose an alternative method that excludes mechanical parts, based on ultrasound velocity profiling (UVP) technique. By introducing universal turbulent log-law theory to UVP data, accurate wall shear stress measurement has been realized, which was successfully demonstrated by application to turbulent channel flows at $10^4 < Re < 10^5$ in this report. Our demonstrative experiments have confirmed that there is bias error less than 1 % in the wall shear stress while random error takes within 3 % as compared with Blasius' formula. In addition, we present its extended application to bubbly turbulent channel flows in which bubbles reduced wall shear stress, i.e., drag reduction, via modification of the turbulent velocity profiles in the log-law regions.

Keywords: Wall shear stress, turbulent flow, boundary layer, ultrasound velocity profiling, drag reduction

1. Introduction

Drag reduction is a major issue in fluid engineering, that contributes to energy saving. In turbulent boundary layers along a wall, frictional drag is originated by active fluid mixing in the buffer layer that lies between viscous sublayer and outer flow regions. For single-phase turbulent flows, plenty number of studies have been reported historically to elucidate the inner layer structure of wall turbulence and its correlation to wall shear stress. As its scientific understanding progresses, there comes up demands to measure the local wall shear stress accurately. For example, drag reduction by injection of additives such as polymer and bubbles induces significant fluctuation of wall shear stress both in time and space [1-3]. Artificial modification of wall surface such as by riblet and wettability also requires assessment with resolving their space-time effects.

There are some commercially available produces for local wall shear stress measurement, e.g. shear transducer so-called. Most cases are fluid–contact types which require a small tolerance allowing shear-sensing displacement as flash-mounted on the target wall [4]. If the sensing area is reduced to improve the spatial resolution, the contact problem leads to more serious error especially for high *Re*-number flows. This does because the tolerance alters original boundary layer structures as it faces with viscous sublayer on the order of a few micrometer. The authors have such rich experiences how natural contamination and artificial mixing of dilute particles/microbubbles lose the accuracy of shear transducers.

To exclude such a contact issue, we have here developed a new method of local wall shear stress measurement. It is based fully on ultrasound velocity profiling (UVP), and therefore the measurement procedure and the applicable targets are the same as UVP.

2. Measurement Principle

2.1 Log-law theory of turbulent boundary layer

In turbulent boundary layer, non-dimensionalized fluid velocity u^+ has the following profile within the logarithmic layer,

$$u^+ = \frac{1}{\kappa}\log y^+ + B, \tag{1}$$

where

$$u^+ = \frac{u(y)}{u_f},\quad y^+ = \frac{y}{l_f},\quad and\quad l_f = \frac{\nu}{u_f}\cdot \tag{2}$$

Here y is the spatial coordinate from the wall surface. u_f and ν are friction velocity and kinematic viscosity, respectively. The length scale l_f is called wall unit. Substituting all the definitions in Eq. (2) into Eq. (1) gives

$$\frac{u(y)}{u_f} = \frac{1}{\kappa}\log\left(\frac{u_f y}{\nu}\right) + B\cdot \tag{3}$$

Two parameters, κ and B, are known to be constants since the equation stands universally, and these are approximately given by κ = 0.4 (called von Kármán's universal constant), and B = 0.41. Nishioka [5] suggested the best accurate values on these parameters to be κ = 0.379, and B = 0.406, which the present authors employ in this study.

Friction velocity u_f is defined by the wall shear stress τ_w and fluid density ρ as

$$u_f = \sqrt{\tau_w / \rho}\,. \tag{3}$$

Here the wall shear stress is generally described by

$$\tau_w = C_f \frac{1}{2}\rho U^2, \tag{4}$$

where C_f and U are friction coefficient and outer flow velocity, respectively. Substituting Eq. (4) into Eq. (3) gives the following relationship;

$$u_f = \sqrt{\frac{C_f}{2}} U \cdot \tag{5}$$

Further substituting Eq. (5) to Eq. (3) obtains

$$\frac{u(y)}{U}\sqrt{\frac{2}{C_f}} = \frac{1}{\kappa}\log\left(\frac{Uy}{\nu}\sqrt{\frac{C_f}{2}}\right) + B \cdot \tag{6}$$

2.2 Estimation of friction coefficient

As velocity profile $u(y)$ is measured, all the values in Eq. (6) is fully given except the friction coefficient C_f. Therefore, C_f can be determined and Eq. (6) is satisfied. Unfortunately Eq. (6) cannot be converted to explicit equation regarding C_f, it needs graphical work or numerical approach to solve. Clauser [6] proposed graphical way, which is today known as Clauser's method. In principle, a single velocity data u at an arbitrary position of y within the logarithmic layer is enough for Eq. (6) to estimate C_f value. However, before knowing the velocity profile, y-coordinate range of the buffer layer is not judged as in practical applications. Thus, advantage of UVP takes place here. UVP obtains velocity profile $u(y)$ that constitutes the left-hand side of Eq. (6), and the logarithmic range can be identified.

Not only for the profile judgment, but also for accurate estimation of C_f, UVP has another advantage. That is, many equations can stand for Eq. (6) onto all the points of the measurable coordinate y. Hence, least square approach is introducible. We define local residual of Eq. (6) as two functions of C_f and y as

$$g\left(C_f, y\right) = \frac{u(y)}{U}\sqrt{\frac{2}{C_f}} - \frac{1}{\kappa}\log\left(\frac{Uy}{\nu}\sqrt{\frac{C_f}{2}}\right) + B \cdot \tag{7}$$

To have the minimum residual along all the range of logarithmic layer, we further define a squared cumulative function to best estimate C_f value as

$$G\left(C_f\right) = \int_{y_1}^{y_2} g\left(C_f, y\right)^2 dy \;\rightarrow\; \min., \tag{8}$$

where y_1 and y_2 are the lower and the upper borders of the logarithmic layer. Consequently, the friction coefficient C_f is determined to minimize the cumulative residual. Partial derivative of Eq. (8) respect to C_f only produces an implicit equation which needs numerical search to find the best estimate of C_f. After the search, the wall shear stress is immediately obtained by Eq. (4). Some other approaches are examined using DNS database [7], but which assumes zero-noise in measurement, being inapplicable to experimental measurement.

3. Channel Flow Measurement

The proposed method has been validated by application to a water channel flow measurement at turbulent flow states. In this section, applications to single-phase and bubbly two-phase turbulent flows are presented.

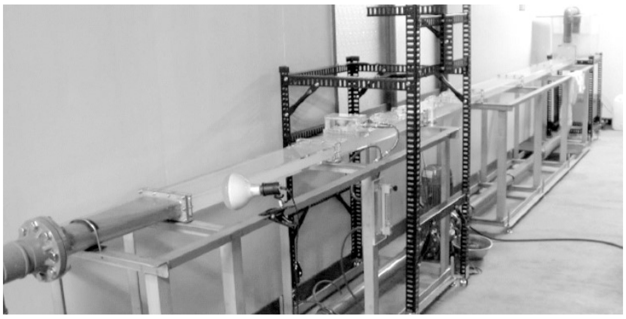
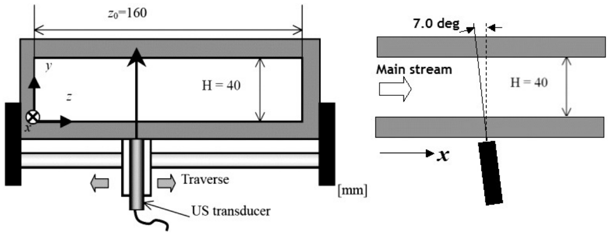


Fig. 1 Overview of horizontal channel flow facility



(a) Spanwise view (b) Streamwise view

Fig. 2 Measurement line of UVP

Fig. 1 shows overview of the experimental facility. The main channel flow section is L = 6 m in total length, H = 40 mm in height, and W = 160 mm in span width. Water flow rate is varied with a pump at less than Q = 0.01 m^3/s (600 l/min.). In case of bubbly flow experiments, air bubbles are injected from a hole-arranged plate mounted on the top wall of the channel.

Fig. 2 shows how the UVP measurement line was set at the rectangular channel section. The head of the transducer is submerged in a small water jacket to allow sufficient quality of ultrasound pulse. Setting parameters of UVP operation are summarized in Table 1. The beam angle uncertainty is estimated around 0.5 degree, but which does not affect the wall shear stress estimation significantly because of logarithmic impact as afore mentioned . We employ 4 MHz in basic frequency so that UVP covers all log-law region considering future application to ship boundary layers.

Table 1 Setting parameters of UVP

Base frequency	4.0	MHz
Temporal resolution	17	ms
Spatial resolution	0.78	mm
Beam angle	7	degree
Number of cycles	4	-
Number of repetitions	32	-

3.1 Single-Phase Flow Conditions

For a single-phase flow, channel flow structures keep dynamic similarity characterized by Reynolds number. We here define it using the channel central fluid velocity U and the channel half height H/2 as

$$Re = \frac{UH/2}{\nu}\,. \tag{9}$$

Fig. 3 depicts water velocity distribution measured by UVP, which is expanded in space–time domain. At Re = 28000, we can confirm significant velocity fluctuation activated by wall turbulence in the channel flow. Fig. 4 represents time-averaged velocity profiles as water flow rate Q increases, i.e., Re number increases. The data points at $y/H < 0.25$ include structured noises due to near-field beam characteristics of the ultrasound transducer which is set outside the channel wall with 10 mm in thickness. To the contrary, the data at $y/H > 0.25$ is obtained without noise, and we target this zone for the wall shear stress analysis.

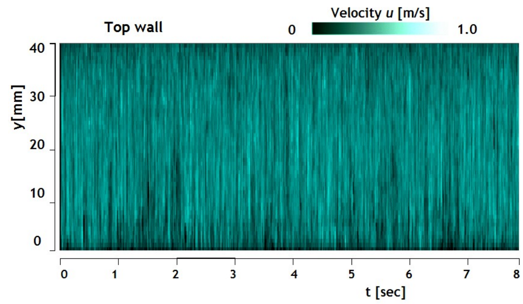


Fig. 3 Velocity distribution at Re=28000.

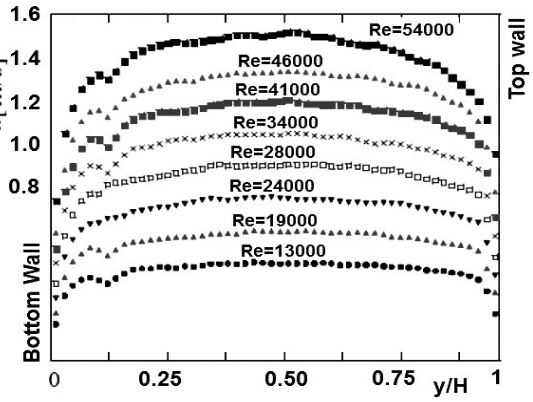


Fig. 4 Mean velocity profiles as water volume flow rate changes. Ultrasound transducer is outside the left edge of the graph. The wall surface coordinate was judged by an echo profile.

Fig. 5 shows a velocity profile obtained by UVP at Re = 54000, represented in semi-log graph. Many inclined lines are theoretical velocity profiles of Eq. (6) as various C_f-values are assumed. We made a numerical software which automatically finds the best C_f value. The matching accuracy has five significant numbers in digits.

Fig. 6 shows the friction coefficients C_f measured by the present method at eight different Re numbers. A curve in the graph is Blasius formula of the friction coefficient for a turbulent pipe flow in the same range of pipe-equivalent Re number. It is confirmed that the present method and Blasius theory agree to each other very well. There is no significant bias error while a small random error less than 3% comes up but which seems to be negligible in the authors' point of view as compared with unstable performance of existing shear transducers. Fig. 7 shows the wall shear stress, which is our final goal of the measurement. On the graph, error bars mean ±5% in relative error.

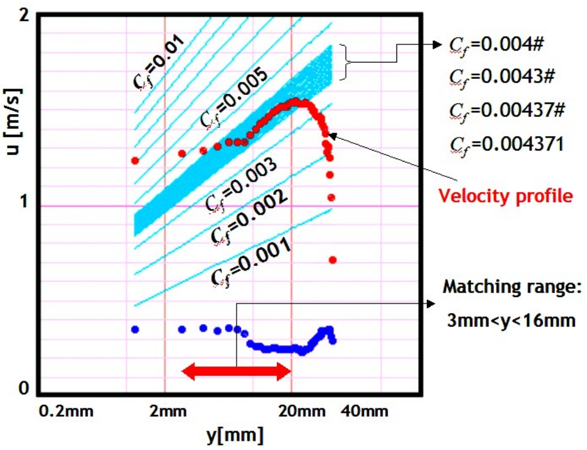


Fig. 5 Semi-log representation of measured velocity profile at Re = 54000 compared with theoretical log-law profiles with different friction coefficient C_f assumed in the process of numerical search for Eq. (8).

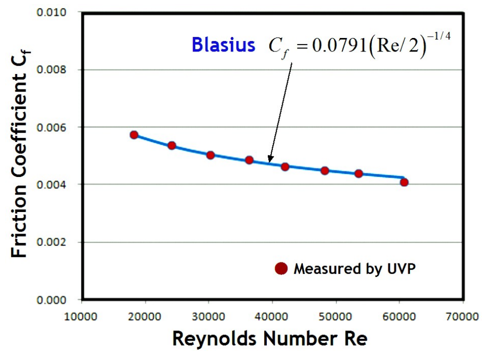


Fig. 6 Friction coefficients measured from UVP

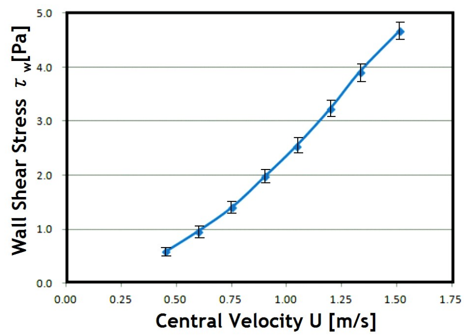


Fig. 7 Friction coefficients measured from UVP

3.2 *Bubbly Two-Phase Flow Conditions*

We have applied the present method to bubbly two-phase flow using the same channel flow facility. Bubble size ranges from 1 mm to 20 mm, subject to a broad deviation. We understand that Clauser's method is valid only for single-phase flow, but here we discuss its extensibility to multiphase flows as engineering purpose, expecting practical applications.

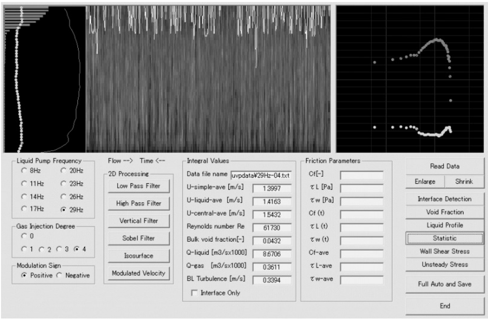


Fig. 8 UVP data analyzer for multiphase flow

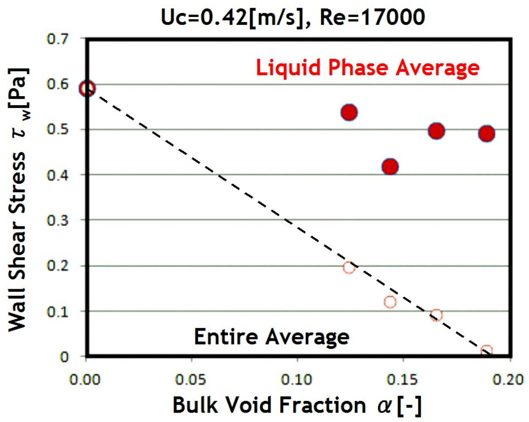


Fig. 9 Drag reduction performance at low speed flow

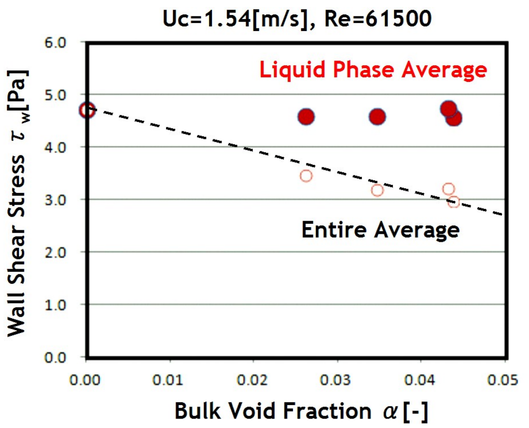


Fig. 10 Drag reduction performance at high speed flow

Fig. 8 shows a program window to process UVP data obtained for bubbly two-phase turbulent flow conditions. The process starts with interface detection based on Sobel filtering [8], and ends with wall shear stress estimation via log-law fitting. Details are explained in the presentation in ISUD.

Fig. 9 shows measured wall shear stresses as bulk void fraction of the channel increases. U_C is time-average flow speed of liquid phase at the center of the channel. Solid circles indicate the data of liquid in-phase value, and open circles are entire averages of the wall shear stress where the local wall shear stress is assumed to be approximately zero inside bubble passing periods (i.e. free-slip wall, evidenced by Murai et al [4]). The dotted line in the graph means linear fitting of the drag reduction, which has 5.2 factor to bulk void fraction. As entire drag is reduced, we can see that the liquid in-phase drag also decreases at around 10–30 %. To the contrary, a high-speed flow condition (see Fig. 10) has smaller impact to the in-phase wall shear stress but higher factor to bulk void fraction at around 8.2. These results infer that bubbles in high-speed flow, i.e. high Weber number bubbles ($We > 200$), can reduce entire drag effectively.

4. Conclusions

We proposed in this paper a method of wall shear stress measurement from UVP data as applied for velocity profiling of turbulent boundary layers. The measurement principle of Clauser's graphical approach has been converted to data processing software which numerically finds log-law region automatically and extracts corresponding friction coefficient. The method is applicable to any liquid which UVP can measure. By application to turbulent water channel flows, the present measurement principle has been validated successfully. The method was extendedly applied to bubbly two-phase channel flow, and drag reduction performance due to injection of bubbles has been obtained only by UVP information.

Acknowledgment

The present study is supported by Japan Soc. Promotion of Science: JSPS-KAKENHI (Grant No. 24246033). The authors also thank to Mr. J. Nagao for his supporting work for UVP measurement of two-phase channel flows.

References

[1] Murai Y: Frictional drag reduction by bubble injection (review), Exp. Fluids, 55: 1773 (2014)
[2] Park HJ, Tasaka Y, Oishi Y, Murai Y: Drag reduction promoted by repetitive bubble injection in turbulent channel flows, Int. J. Multiphase Flow, 75: 12–25 (2015)
[3] Park HJ, Tasaka Y, Murai Y: Ultrasonic pulse echography for bubbles traveling in the proximity of a wall, Measurement Science and Technology, 26: 085302 (2015)
[4] Murai Y, Fukuda H, Oishi Y, Kodama Y, Yamamoto F: Skin friction reduction by large air bubbles in a horizontal channel flow, Int. J. Multiphase Flow, 33: 147–163 (2007)
[5] Nishioka M: A new method for estimating friction velocity in turbulent boundary layers, Nagare (Bulletin of Japan Soc. Fluid Mechanics), 397–402 (2015)
[6] Clauser FH: The turbulent boundary layer, Adv. in Applied Mech., 4: 1–51 (1956)
[7] Rodriguez-Lopez E, Bruce PJK, and Buxton ORH: A robust post-processing method to determine skin friction in turbulent boundary layers from the velocity profile, Exp. Fluids, 56: 56–68 (2015)
[8] Murai Y, Tasaka Y, Nambu Y, Takeda Y, Gonzalez SR: Ultrasonic detection of moving interfaces in gas-liquid two-phase flow, Flow Meas. Instr., 21: 356–366 (2010)