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Sublayer Plate Method for Local Wall Shear Stress Measurement

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Abstract

A simple technique “sublayer plate” with using a thin rectangular plate attached on the wall is proposed for the local wall shear stress measurement. Availability in wall turbulence and sensitivity to flow angle has been investigated in the fully developed channel flow. The experiment shows the new method has sensitivity as same as the sublayer fence for the plate submerged in the linear sublayer. And, the plate has well directional resolutions to the flow angle.

Introduction

The local wall shear stress is the most essential quantity to discuss the similarity of turbulence in the wall layer of boundary layer, pipe and channel flows. The various devices and methods to measure the local wall shear stress have been proposed and applied to many experimental studies on the wall turbulence (see Winter [1] or Hanratty and Campbell [2]). Preston tube using a broad accessible simple pipe is easy to make itself and applied to non-equilibrium flows or the wall layer subjected to pressure gradients. The dynamic pressure pipe radius should be smaller than the thickness of the linear sublayer to obtain the wall shear stress to be independent of the influence such as pressure gradients and stream line curvature. However, the dynamic pressure with the small pipe in low Reynolds number flows is too low to keep measurement uncertainty to be negligible.

The sublayer fence employs back pressure behind itself and reduces measurement uncertainty. Some experimental studies with the originally produced sensors confirmed that the sublayer fence has ability to determine the local wall shear stress based on the relation of the wall shear stress and velocity profile within the linear sublayer. The pressure differences around the small fence and the local wall shear stress are given in a calibration curve with the similar non-dimensional parameters for Preston tube method. The relation between the wall shear stress and pressure difference can be reasonably expected to be universal for the wall bounded shear flows. However, the curve must be determined from calibration procedure for individual originally designed sensors.

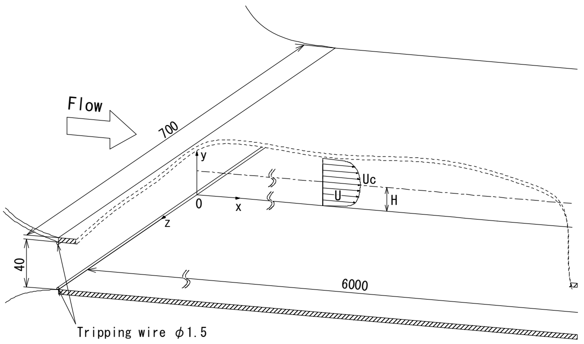

Figure 1. Schematic of two-dimensional Channel flow used for calibration of the Sublayer plate.

We are proposing the local wall shear stress measurement method with a simple device that is broad accessible and keeps sufficient accuracy in situation submerged the linear sublayer. The method called “sublayer plate” uses only a thin rectangular plate and two static pressures holes on the wall. In the present experiment, the ability of the new device for local wall shear stress measurement has been confirmed in the fully developed channel flow and boundary layer without pressure gradients.

Fully Developed Channel Flow

Figure 1 shows schematic flow field, nomenclature and coordinate system of the channel that is 700mm in width, 40mm in height and 6,000mm in length. The tripping devices of 1.5mm diameter small wires are attached on the both wall at the entrance. The Reynolds number based on the channel centre velocity and height $\mathrm{Re} = U_c H/\nu$ were varied for 8,000-20,000. The local wall shear stress was determined from streamwise gradient of the wall static pressure for the fully developed equilibrium state. The local wall shear stress coefficient as a function of Reynolds

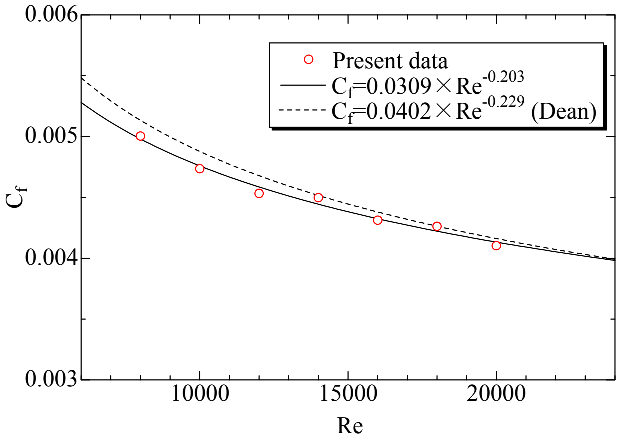

Figure 2. Variation the local skin friction coefficient in comparison with the semi-empirical curve.

number is plotted in Fig.2 comparing with semi-empirical formula proposed by Dean's survey [3]. The experimental data agree well with the semi-empirical formula at higher Reynolds numbers. For lower Reynolds numbers, effect of the aspect ratio might be considered due to the non-uniform shear stress around the corners on the friction law.

The logarithmic velocity profiles at downstream position after 80 times channel height (x=3,200mm) streamwise distance measured from the entrance are given in Fig.3 in comparison of the velocity profile in the present channel flow and the standard log-law. There are many arguments on the standard values involved in the logarithmic law [4]. Kármán constant $\kappa = 0.41$ and C=5.2 are employed here. For the wall layer expected by presence of the logarithmic velocity profile in the layer greater than y^+=100, the velocity profile well agrees with the standard log-law. These experimental facts confirm that the present channel flow is suitable one for calibration of the local wall shear stress devices.

Sublayer Plate

The sublayer plate is a simple thin rectangular plate placed on the wall see in Fig.4. For the present channel flow, thickness of the plate corresponds to 1.9 – 13.5 times wall unit. The width of plate w is 30mm for two cases of the aspect ratio, w/l=3 and 6 that selected for the test of the angular resolution. The thin plate is made of phosphor bronze and cut by electric discharge machining. For stagnation on the front face and separation on the rear face, pressure measurement was made with pressure holes of 0.3mm diameter close to the plate edge. The measured pressure must be influenced by the relative position of the pressure hole from the plate edge and open area of the pressure hole. Figure 5 shows effect of the relative positioning of the pressure hole to the plate on the measured pressure. The pressure is slightly reduced in the cases of too small and large open length Δx. The open area of the pressure holes should be independent of flow separation and reattachment on the wall. The half of the static pressure hole diameter Δx=0.15mm is chosen as the overlap length in the following experiment.

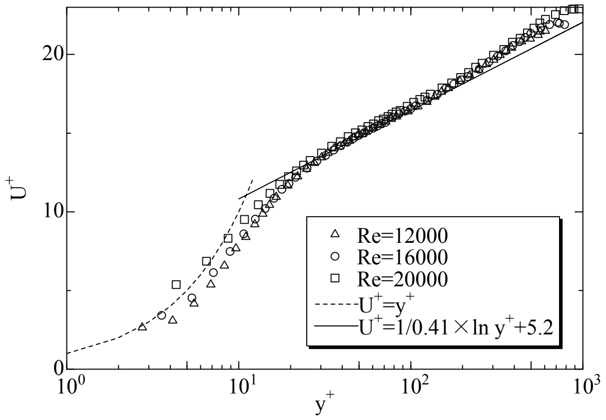

Figure 3. Logarithmic mean velocity profile measured in the two-dimensional channel.

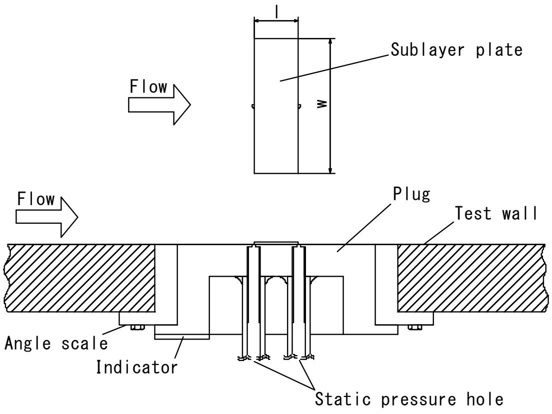

Figure 4. Downward and upward figures are showing side and top views of the Sublayer plate glued on the wall.

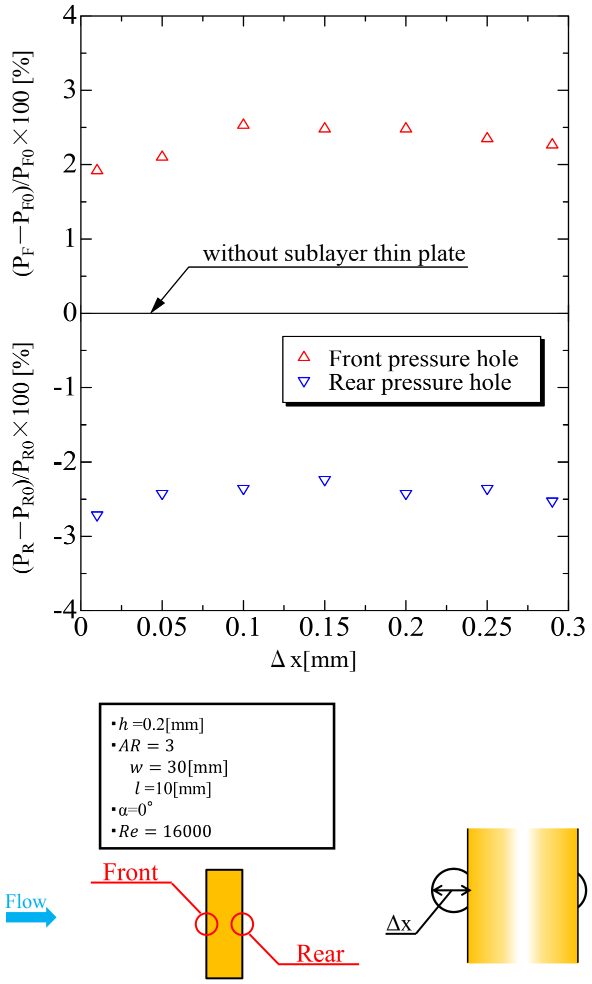

Figure 5. Effect of the relative positioning of the static pressure hole to the plate.

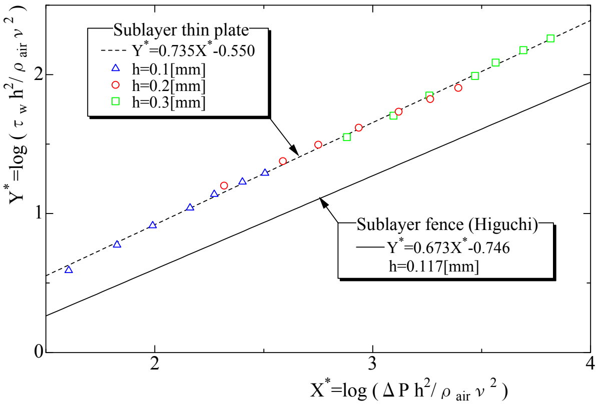

Figure 6. Calibration curve of the Sublayer plate in the non-dimensional wall shear stress and pressure difference.

Results and Discussion

Calibration Curve

Dimensional argument for universality of calibration curve relating the pressure difference and the local wall shear stress leads the two parameters,

$$X^* = \log\left(\Delta P h^2 / \rho_{air} \upsilon^2\right) \text{ and}$$

$$Y^* = \log\left(\tau_w h^2 / \rho_{air} \upsilon^2\right),$$

as similar for Preston tube [5] and sublayer fence. Figure 6 shows experimental results for the correlation of the two parameters and comparison with the semi-empirical calibration result for the sublayer fence given by Higuchi [6]. The present experimental results were obtained with three different thickness of the sublayer plate with the same aspect ratio of *w*=30mm and *l*=10mm. The experimental data obtained from three different thicknesses well collapse on the single straight line determined by least square method. The pressure difference normalized with the wall variables obtained from the streamwise pressure gradient in the channel flow is slightly smaller than that of the sublayer fence (Higuchi [6]). The smaller pressure difference could be explained by the smaller separation angle illustrated in Fig.7. The fence might produce higher angle of separation at high Reynolds number. However, the calibration curve strongly depends on specifications of the sublayer fence such as thickness, shape of the edge, and width. The sensitivity of the devices will be compared with other experimental results.

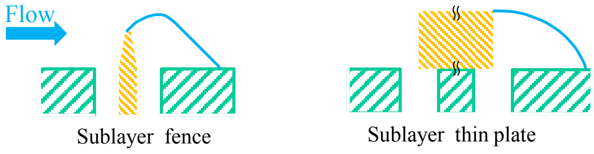

Figure 7. Separating streamline expected for the rectangular plate and fence with edge.

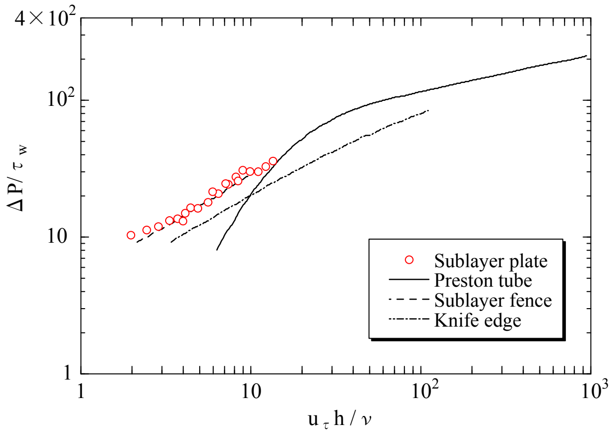

Figure 8. Comparison of the sensitivity of the local wall shear stress measurement devices.

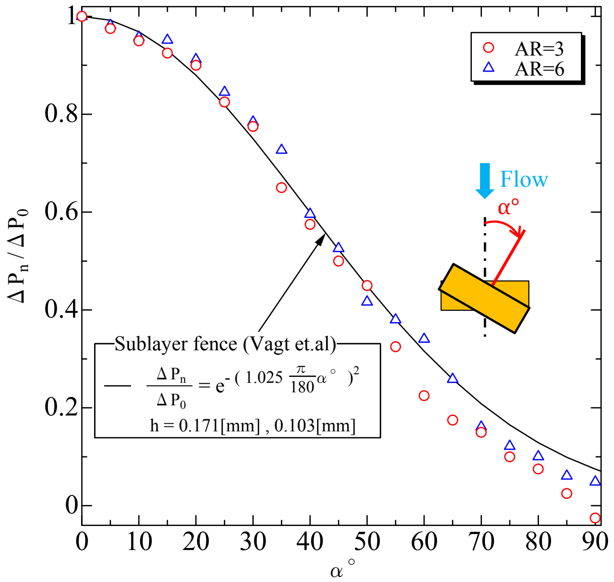

Figure 9. Sensitivity of the sublayer plate to the flow angle. Experimental data with two different aspect ratio AR (=*w*/*l*) =3 and 6 are plotted as a function of angle of attack.

The sensitivity of the local wall shear stress measurement devices is compared in Fig.8. This figure provides possibility whether four different devices [1] (Preston tube, sublayer fence, knife edge and sublayer plate) has relatively high accuracy in the near wall region beneath the logarithmic layer. Preston tube has low sensitivity for low Reynolds number, because only dynamic pressure at stagnation point of the forward face is used in pressure measurement. The sublayer plate has high sensitivity as well as the sublayer fence. Figure 8 suggests that the sublayer fence in Higuchi's experiment [6] has better sensitivity than that of the present sublayer plate.

Sensitivity to Flow Angle

In three-dimensional boundary layer generated by skew-induced or stress induced mechanism, the wall shear stress is not parallel to the mean velocity vector and logarithmic velocity law needs modification of the turbulence model. It is useful that the wall shear stress sensor can detect the direction of limited stream line. The response of the pressure difference to the flow direction is plotted in Fig.9 for two different aspect ratio AR of *w*/*l*=3 and 6. The pressure difference normalized by that of $\alpha=0°$ can be well represented by the line proposed in the experiment on sublayer fence [7]. At large angle of attack, the pressure difference is low compared with the semi-empirical line. However, for the practically useful angle of attack $\alpha \leq 50°$, it is recognized that

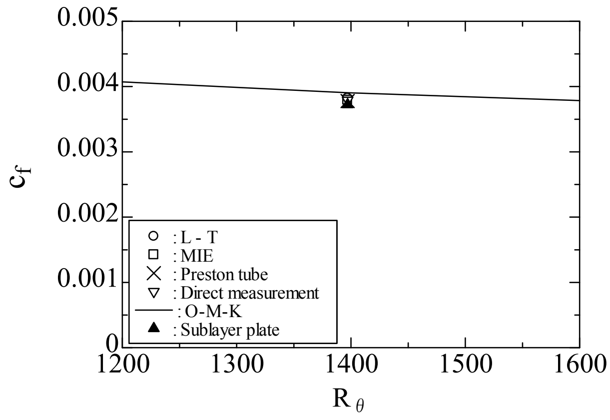

Figure 10. Comparison of the local skin friction coefficient measure by different method. L-T is Ludwieg-Tillmann's formula, MIE means momentum integral method, O-M-K means semi-empirical formula given by Osaka, Mochizuki and Kameda for zero pressure gradient boundary layer [8].

response of the sublayer plate is enough to resolve angle of attack and expressed by the semi-empirical curve given by the similar way for the sublayer fence.

Apply to Boundary Layer without Pressure Gradients

Ability of the sublayer plate method for local wall shear stress measurement was examined in a canonical flow, that is, boundary layer without pressure gradients (see Fig.10). The boundary layer was developed on a flat plate located in low turbulence wind tunnel in Yamaguchi University (see detail in another our contribution "Similarity in the Equilibrium Boundary Layer in Accelerating Free Stream Velocity" in 19th AFMC.) The Reynolds number based on momentum thickness and free stream velocity is 1400: the boundary layer is in low Reynolds number range. The experimental data obtained by different measurement method agrees well within 2% scattering.

Conclusions

A local wall shear stress measurement method with a simple thin plate submerged in sublayer of the wall turbulence called as sublayer plate was proposed and tested in fully developed channel and zero pressure gradient turbulent boundary layer. As the experimental facts, it was confirmed that the sublayer plate is useful method and has reasonable accuracy and resolution to flow angle. The sensitivity defined as ratio of the pressure difference to the local wall stress keeps relatively high for the situation that the sensor submerged in the linear sublayer. The experiment in a low Reynolds number turbulent boundary layer shows that the method is available to measurement technique of local wall shear stress.

Nomenclature

AR : Aspect ratio of the plate (=w/l)

C : Coefficient in the log law

C_f : Local wall shear stress coefficient

h : Thickness of the sublayer plate

H : Channel half height

l : Length of the sublayer plate

Re : Reynolds number based on Uc and H

R_θ : Momentum thickness Reynolds number

U : Mean velocity at local position

Uc : Mean velocity at the channel centre

w :Width of the sublayer plate

x : Streamwise distance from the origin

Δx : Streamwise length of the open area of the pressure hole

X* : Non-dimensional pressure difference

Y* : Non-dimensional wall shear stress

y : Distance from the wall

α : Angle of attack of the mean flow to the sublayer plate

κ : Kármán constant in the log law

θ : Momentum thickness

τ_w : Local wall shear stress

ρ : Fluid density

υ : Kinematic viscosity of fluids

ΔP : Pressure difference between the two static pressure holes

$(*)^+$: Normalized quantity with the wall variables

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