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Amplitude Modulation of Pressure in Turbulent Boundary Layer

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ABSTRACT

The interaction between large and small scale motions from the point of pressure fluctuation is studied. Using the small pressure probe, both the static pressure and wall pressure fluctuations were measured inside the zero-pressure gradient boundary layer at relatively high Reynolds numbers. How the large scales in outside affect the small scales near wall is analyzed by means of statistical method. High amplitude positive and negative pressure fluctuations are also analyzed which associate with coherent motions inside the boundary layer. Another interesting aspect is the amplitude modulations of pressure and this topic is reported in this paper.

INTRODUCTION

We have developed a small pressure probe and measured both static and wall pressure simultaneously in turbulent boundary layers up to Reynolds numbers based on the momentum thickness 21000. The statistical features were already reported in the previous studies [1,2]. Here, in this paper, we investigate the instantaneous feature of turbulence character, especially the large scale and small scale interaction of pressure fluctuations. In Fig.1, we plot the pressure intensity profile, which shows the logarithmic relation;

$$(p_{rms}{}^{+})^2 = -A_p \log(y/\delta) + B_p , \qquad (1)$$

where A_p and B_p are constant $A_p \cong 2.52$, $B_p \cong 2.30$, but B_p depends on flow field. Here, y is a distance from the wall, δ is a boundary layer thickness and subscript + indicates the normalization by inner variables. This relation is similar with that observed in the intensity of stream-wise velocity component predicted by attached eddy model [3,4];

$$(u_{rms}{}^{+})^2 = -A_u \log(y/\delta) + B_u , \qquad (2)$$

where A_u is constant $A_u \cong 1.25$ but B_u depends on flow field. This velocity logarithmic relation was derived by Perry et al. [4] based on the Townsend's attached eddy hypothesis. The basic Townsend's idea said [3],"It is difficult to imagine how the presence of the wall could impose a dissipation length-scale proportional to distance from it unless the main eddies of the flow have diameters proportional to distance of their "centres" from the wall, because their motion is directly influenced by its presence. In other words, the velocity fields of the main eddies, regarded as persistent, organized flow patterns, extend to the wall and, in a sense, they are attached to the wall." This idea was extended by Perry et al [4] that the distribution of eddies with a population density inversely proportional to distance from the wall. And in their model, they propose that $(u_{rms}{}^{+})^2$ is in proportion to the logarithmic of distance from the wall.

From the recent high-Reynolds number experiments, it was found that large scale motions in overlap region have significant interaction with the motions close to the wall [5]. A series of researches by Melbourne university group have reported the detailed properties of this interaction. This process is conceptually expressed as "footprint". We generally believe the attached eddy hypothesis relates with this footprint. The large-scale and small-scale interactions, or footprint, are characterized by statistical methods, such as space-time correlation, conditional sampling, joint-probability density functions etc. Among these, one possibility is the amplitude modulation method [6]. Although there are some discussions about the ability of this method [7], we apply this to the pressure fluctuation and discuss the similarity and difference with that of velocity fluctuations.

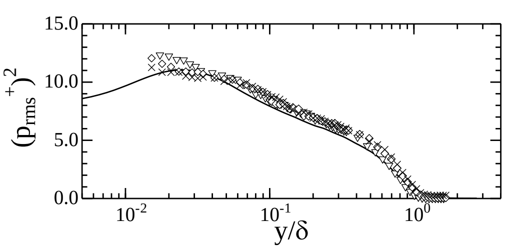

Fig.1 Square of pressure intensity normalized by inner variables at distance y/δ from the wall. The spatial resolutions of probes are corrected by PDF shapes.
○: $Re_\tau = 11260$, ∇: $Re_\tau = 16190$, ×: $Re_\tau = 20940$. Solid line is direct numerical simulation (DNS) data from Schlatter et al. (2010) at $Re_\tau = 4060$.

EXPERIMENTAL CONDITIONS

We measure pressure fluctuations by a technique developed in our group that uses a standard static-pressure tube probe (Fig. 2) attached to a small condenser microphone. The amplitude and phase delay associated with the resonance are carefully corrected. The detailed procedure is explained in [1,2].

The schematic view of pressure probe is shown in Fig.2, in which four static pinholes spaced 90° apart in the circumferential direction and located 12mm from the tip. The diameter of pinhole is $\phi = 0.08$mm. The tube outer diameter and material thickness are $d_1 = 0.3$ mm and $h = (d_1 - d_2)/2 = 0.05$ mm, respectively. The experiments were performed in the MTL wind tunnel at KTH and large wind tunnel at Melbourne university. A probe position in the wind tunnel is shown in Fig. 3. Here, a specially designed wall-normal traversing system is used that protrudes from the plate and allows us to traverse the range $0 \le y \le 2\delta$, where δ is the boundary layer thickness.

For the static pressure measurement we set the free-stream velocity to three different values ($U_0 = 20, 30, 40$ m/s), and the Reynolds number was varied up to $R_\theta = 21000$. Streamwise velocities were measured by a standard single hotwire, and the wall shear stress was obtained by oil film interferometry. The free stream intensities remained smaller than 0.02%.

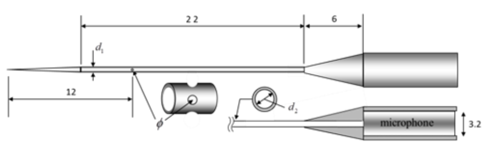

Fig.2 Schematic view of pressure probe.

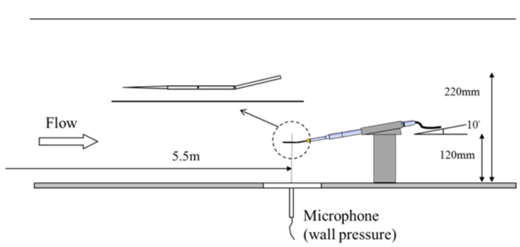

Fig.3 Configuration of probes in the test section of wind tunnel.

RESULTS AND DISCUSSIONS

A single-point amplitude modulation coefficient, defined as the correlation coefficient between the filtered envelope of the small-scale fluctuations, $E_L(p_s^+)$, and the large-scale component, p_L^+, is calculated by

$$AM(y^+) = \left\langle p_L^+ E_L(p_s^+) \right\rangle / p_{L.rms}^+ / E_{L,rns}(p_s^+) \ , \quad (3)$$

Here, the lower subscript rms means the root mean square of fluctuating quantities. To obtain the term in Eq.3, the pressure fluctuation is decomposed into the large scale p_L^+ and the small scale p_s^+, by choosing the cut-off wave lengt λ_{th} . The filtered envelope of small-scale contribution was obtained by via a Hilbert transformation.

In Fig.4 the amplitude modulation coefficients are plotted against the distance from the wall. The coefficient increases toward the wall, but it is almost constant in the overlap region and extends into the outer region. For the case of velocity signal, AM shows the increasing trend toward the wall, it is almost constant in $30 \le y^+ \le 150$ just below the log-region. From these trends, pressure has a different character of velocity fluctuations. That is, the large scale interacts with small scale in a different way in pressure. It is noted that the sign of AM is negative inside the boundary layer, or the large scale interact negatively with small scales. Close to the wall, the coefficient becomes positive but it has a small value. This means the interaction from the outer scale to the wall region is little. These are very interesting and unique features in pressure fluctuations. The similar analysis has already performed in wall pressure signal. It has been discussed that the large scale effect on the wall pressure for a long time. However, the present analysis of AM does not support clearly the large scale contributions. This may be discussed at the conference.

The cut-off wavelength is a key parameter for this analysis. The wave number λ_{th} is determined based on the pre-multiplied spectrum contours. It shows the large and small scale energetic modes at position y as a function of wave numbers. However, for the simplicity, the cut-off wave numbers are set as $\lambda_{th} = \delta, \delta/2, \delta/5, \delta/10$ in this analysis. In these high Re number experiments, there is little effect of λ_{th} on amplitude modulation coefficients.

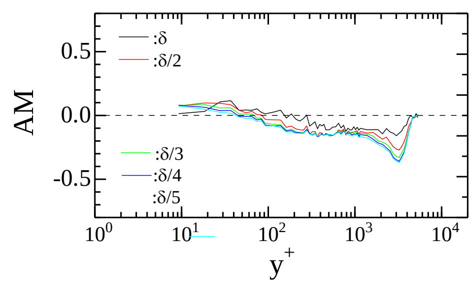

Fig.4 Amplitude modulation coefficient of pressure ($R_\theta = 11260$)

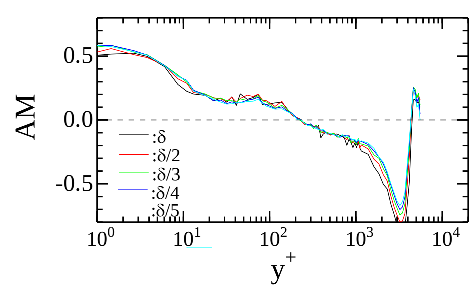

Fig.5 Amplitude modulation coefficient of velocity. ($R_\theta = 11260$)

As mentioned previously, the pressure intensity shows the logarithmic relation of y (Eq.1). It is another interesting point for us to investigate how large scales contribute to the pressure intensity profile and attached eddy model can predict the logarithmic relation of pressure. The instantaneous pressure fluctuations are divided into large and small scales by filtering at cut-off frequency λ_{th} and the pressure intensity was reconstructed from smaller and larger wave numbers separately. The results are plotted in Fig.6. The detailed things are presented at the conference, but the significant difference from the velocity was found, that is, the logarithmic relation is realized mainly by the small-scale fluctuations in case of pressure.

In Fig.7 probability density functions are shown. Small scale fluctuations have a negative long tail, which is a typical characteristic of pressure, but the large scale fluctuations obey the Gaussian distribution. This feature is less dependent of cut-off frequency. Because the negative long-tail is associated with small-scale eddies, the small scale structures play an important role in pressure fluctuations. These features are consistent with the results in Fig.6.

In summary, the logarithmic relation of pressure (Eq.1) may not the product of attached eddy model. But the small scale structure's contribution is significant.

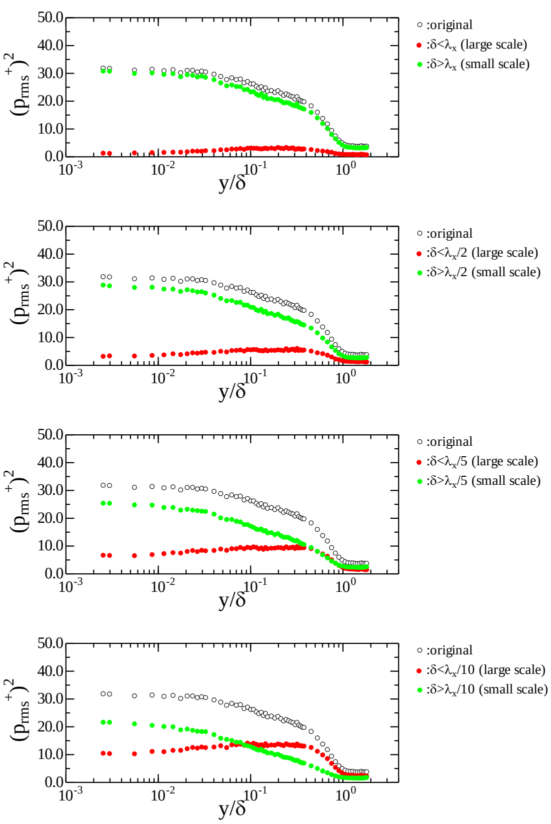

Fig.6 Pressure intensity profile in the boundary layer. ($R_\theta = 16170$) The contribution from smaller and larger scales are separated by the stream-wise wave number .

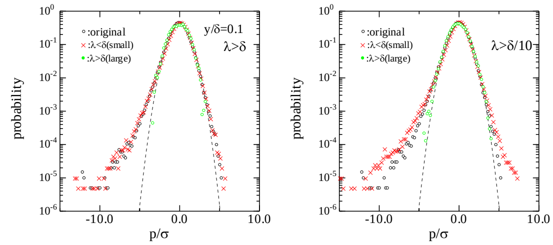

Fig.7 Probability density functions of pressure in the boundary layer at $y/\delta = 0.1$, $R_\theta = 16170$. Pressure is normalized by its standard deviations. The contribution from smaller and larger scales are separated by the stream-wise wave number. In left figure, cut-off wavenumber is boundary layer thickness, in the right it is ten times boundary layer thickness.

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