VORTICAL STRUCTURES RELATED TO WALL PRESSURE FLUCTUATIONS IN A TURBULENT BOUNDARY LAYER

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ABSTRACT

Stream-wise velocity fluctuations were conditionally sampled in a condition of peaks of wall pressure fluctuations and were averaged in a turbulent boundary layer. Two sets of pairs vortices in planes parallel to the wall were found in a region 0.8 times of the boundary layer, and two-dimensional span-wise structures were found outside the boundary layer. The pair vortices consist of counter-rotating vortices. The downstream pair vortices near the wall generate ejection-type flow. However, the upstream pair vortices generate sweep-type flow. The near wall structures decayed as move downstream, and their moving speed was about a half of the mean flow velocity. The outer structures related to the bulge structure did not decay, and their moving speed was about 0.8 of the mean flow velocity. In addition, it was found that the near wall structures were related to valleys of the outer structures.

INTRODUCTION

Willmarth and Tu (1967) measured wall pressure fluctuations and velocity fluctuations in a turbulent boundary layer, and calculated space-time correlations between these two fluctuations. They proposed a vortex line model in a turbulent boundary layer. The shape was saw-toothed which liked a connected lambda vortex side by side. Their experiments showed that the positive wall pressure fluctuations were related to upward flows downstream. The upward-flow is related to ejection-type flow. Brown and Thomas (1977) showed a flow pattern related to wall shear stress by enhanced correlations between wall shear stresses and velocities. The flow pattern shown in the section of stream-wise and normal to the wall shows slightly rotating large-scale span-wise vortices. The size of the vortices was that of boundary layer thickness. The vortices were related to the near wall structures. Kim (1983) averaged the numerical simulation data by VITA technique and he showed that vortices, which were related to sweep, had a negative sign of vortices related to a hairpin vortex that causes ejection. This type of vortex, which is related to sweep, were shown by K-S Chow (1987). He found the vortex in a condition of the maximum value of wall shear stress that he called near wall bursts. Kim(1985) also showed the same vortex related to sweep by v-w vectors in y^+-z^+ plane at x^+=-124 upstream from the detection. Thomas and Bull (1983) conditionally sampled wall pressure fluctuations and showed relationships between the wall pressure and the stream-wise component near the wall. Myose and Blackwelder (1994) carried on experiments in a turbulent boundary layer developed on a concave wall, and stated that the outer region of turbulent boundary layers played a role in the bursting process. The structures mentioned above were in the cross sections normal to the wall

Kobashi & Ichijo (1986) showed ensemble averaged stream-wise and span-wise velocity fluctuations in a condition of positive peaks of wall pressure fluctuations. The ensemble-averaged vectors, which had the two velocity components, showed that there were two sets of vortex pairs in planes parallel to the wall in a turbulent boundary layer. The downstream pair produces ejection type flow, on the other side, the upstream pair produces sweep type flow. The experiments were done up to 30% of the boundary layer thickness from the wall.

In the experiments presented here velocities that were only stream-wise components were measured in a region up to y/δ=1.6. Velocities were measured above a pressure hole, through which pressure fluctuations were measured, moreover measured at three downstream positions from the pressure hole.

EXPERIMENTAL FACILITIES

Experiments were conducted in a blow down type wind tunnel. The test section is 4.5m long with 500mm by 500mm cross section at the entrance. The upper-side wall of the cross section was flared down-stream in order to maintain a zero pressure gradient in the test section. A turbulent boundary layer was developed on a sidewall of the test section. The wall was made of acrylic resin. The boundary layer was transitioned to turbulence by a tripping wire of 12mm diameter that located at the entrance of the test section.

A Cartesian co-ordinate was used. Steam-wise, normal to the wall and span-wise were x, y, and z respectively. Velocity u, v and w are x, y and z directional fluctuations.

Stream-wise velocity (u) measurements were made with homemade constant-temperature hot-wire anemometers at 1630mm from the tripping wire. An eight wire span-wise (z) rake was used. The hotwires were 2.5μm diameter tungsten wire and were 0.5 mm long. The distance between each wire was 3mm. The maximum distance between the eight wires in y-direction was 014 mm or $y^+=6$.

Four holes, through which wall pressure fluctuations were measured, were located at velocities measurement location, 2,4 and 6cm upstream from the measurement location. The diameter of the hole was 0.5mm ($d^+=21$) and the length was 0.5mm. Condenser microphones of 6 mm diameter were directly attached to the holes on the other side of the measuring side that the boundary layer developed. The Helmholtz resonance frequency was 73kHz.

A frequency characteristic of pressure measurement equipments was flat from 5 Hz to 10kHz. The lower frequency was determined by the characteristic of the condenser microphone. The upper frequency was determined by a characteristic of the electric amplifier. The amplifier used was 741-type standard operational amplifier.

Characteristics of the boundary were as follows. Mean flow velocity U was 16m/s. The boundary layer thickness (δ) defined by 99% of mean flow velocity was 25.4mm. Reynolds number defined by momentum thickness was 3000. Friction velocity (u_t) was 0.65m/s. Mean flow turbulent level was 0.25 percents of the mean flow velocity (U).

Two pressures and eight velocities were acquired by 16 channels 16 bit A/D converter at a 10kHz sampling rate for 10 seconds. The acquirement repeated three times, then the acquired data length was 30 seconds. The data were stored into a digital computer. The data were analyzed by means of the computer.

The stored pressures and velocities were sampled on condition that peaks of pressure fluctuations were larger than 2.0 times its RMS value and were ensemble-averaged. By the condition, the number of pressure peaks sampled was about 4500 for 30 seconds. An average interval between a sampled pressure peak and the next peak was about 4δ.

RESULTS AND CONSIDERATIONS

Figure 1 (a) shows an ensemble averaged stream-wise velocity by VITA (Blackwelder and Kaplan 1976) at y/d=0.03($Y^+=yu_t/\nu=25$). In the experiments, parameters of VITA were that the threshold level was 0.8; the averaging time tu_t^2/n was 10.8. In the figure, T=tU/d is non-dimensional time defined by mean stream-wise velocity U and boundary layer thickness (δ). T<0 means downstream direction. <u> is an ensemble averaged stream-wise velocity fluctuations. The Figure 1 (b) shows a sharp positive peak of wall pressure fluctuations. It is reasonable that positive peaks of wall pressure fluctuations are adopted to educe velocity structures that are related to the near wall structures in a turbulent boundary layer.

Figure 2 shows conditionally averaged u-w vector on condition that peaks of wall pressure fluctuation larger than 3.5 times its RMS value. In the figure –T

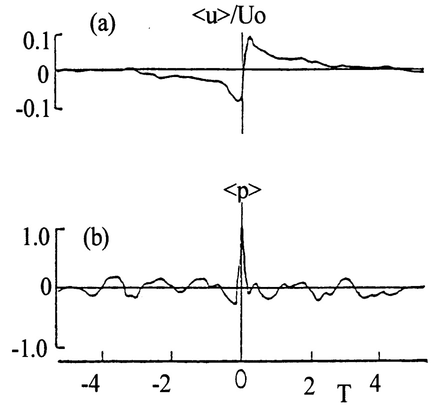

Figure 1 (a) Ensemble averaged stream-wise velocity fluctuations(<u>) in a condition of VITA of stream-wise velocity fluctuation(u). (b) Ensemble averaged wall pressure fluctuations (<p>) in the same condition of u. Two figures are referred from Kobashi and Ichijo (1986)..

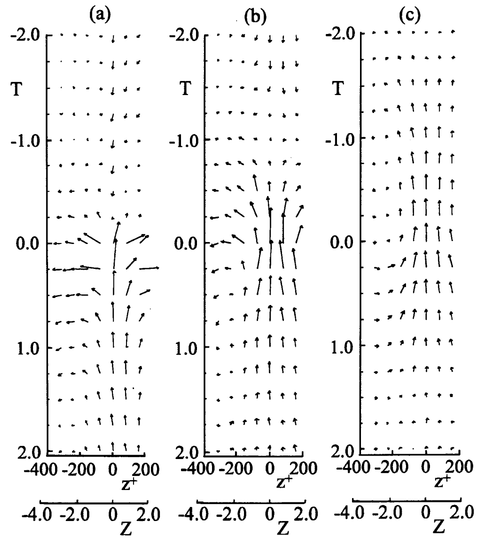

Figure 2. Ensemble averaged u-w vectors in a condition of peaks of pressure fluctuation from Kobashi and Ichijo(1986).

means stream-wise and Z means span-wise, and then Z direction was span-wise fluctuating velocity (w)

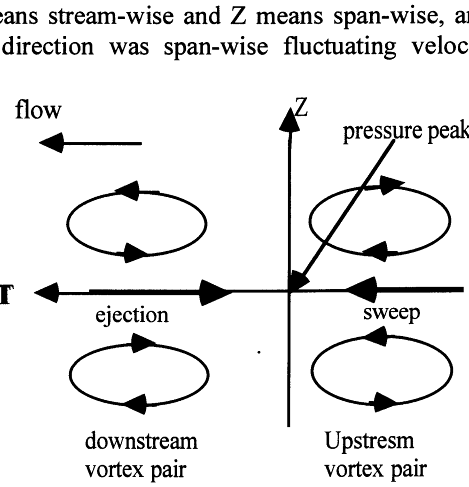

Figure 3. A model of two vortex pairs near the wall

direction. There seems to be two vortex pairs in the figure. Each pair consists of two counter-rotating vortices. The vortex pairs move downstream as they go away from the wall. Then the structures lean to the wall.

Figure 3 shows a model of the vortex pairs in a plane parallel to the wall. The downstream vortex pair, which may be a cross section of hairpin vortex in a plane parallel to the wall, produces ejection-type, or decelerated flow. On the other side, the upstream vortex pair produces sweep-type, or accelerated flow.

Figure 4 shows ensemble averaged pressure fluctuations.

Figure 4 (a) shows the ensemble-averaged pressure fluctuations in a condition of itself. Figure 4 (b) shows the ensemble averaged pressure fluctuations 4cm upstream. An averaged traveling speed of pressure fluctuations calculated from time difference between a peak in figure (a), where T nearly equal to

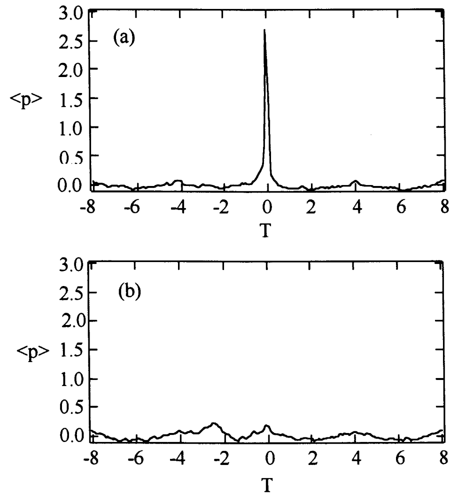

Figure 4. Ensemble averaged wall pressure fluctuations in a condition of pressure peaks.
(a) Itself. (b) 4cm upstream.

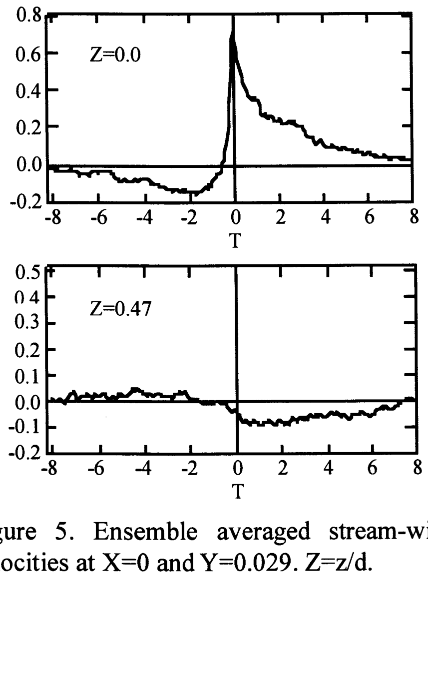

Figure 5. Ensemble averaged stream-wise velocities at X=0 and Y=0.029. Z=z/d.

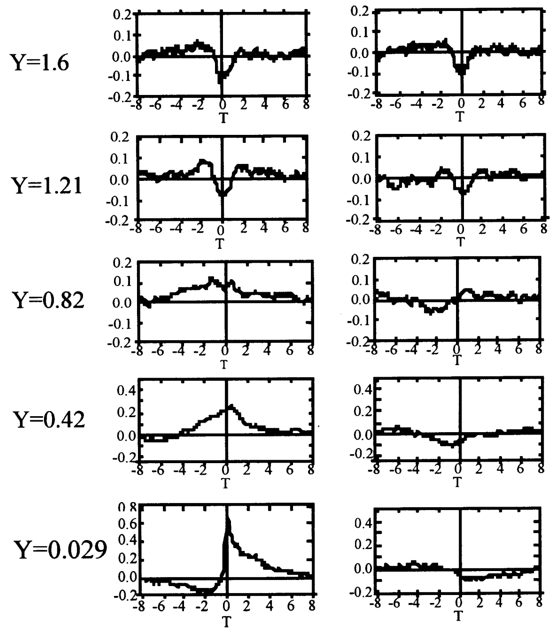

Figure 6. Ensemble averaged stream-wise velocity fluctuations at some distance from the wall. The left figures are just above the pressure hole. The right figures are 0.47 d span-wise fro m the pressure hole.

zero and a peak in figure (b), where T nearly equal to 2.5 is 0.66 U. Thomas and Bull(1983) showed 0.67U in their experiments. In addition, an average distance between positive peak s in figure (a) was calculated using the traveling speed is 2.56δ or 15.4δ*. And an average distance between bottoms in figure (a) is 2.69δ or 17.2δ*.

Figure 5 shows ensemble-averaged stream-wise velocities in condition that pressure peaks lager than 2.0 times its RMS value near the wall (Y=0.029, y^+=32). Z=0.0 means that velocities were measured just above the pressure hole. Figure shows that pressure peaks well sampled the near wall structure of velocity fluctuations, that is, ejection, decelerated flow and sweep, accelerated flow. Z=0.47 means that velocities were measured at the position 0.47δ span-wise distant from the pressure hole.

In the downstream side (T<0), the velocity is negative or decelerated at Z=0, but positive or accelerated at Z=0.47, however in the upstream side (T>0), vice versa. This corresponds to the model of vortex pairs shown in Figure 3.

Figure 6 shows ensemble-averaged stream-wise velocities<u> through boundary layer. As may be seen in the figure, the vortex pairs exist up to Y=y/δ=0.8.

The downstream vortex pair is related to a vortex pair in a section parallel to the wall of the hairpin vortex, but what is upstream vortex pair? The pair may be related to a vortex pair found on condition that wall shear fluctuations larger than a certain level that K-S Chow (1987) called near wall burst. In

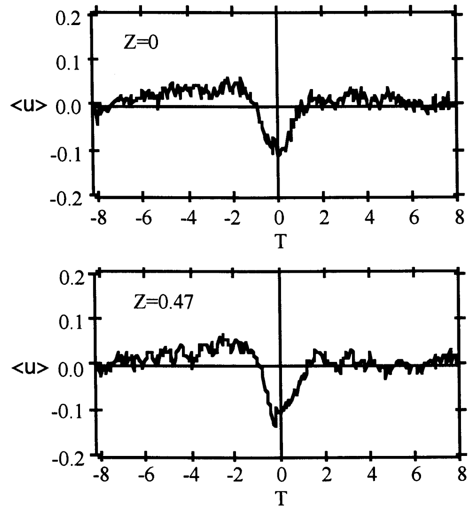

Figure 7. Ensemble averaged stream-wise velocity at X=0 and Y=1.6.

addition, the upstream pair may be related to velocity vectors, that Kim(1985) showed in a y-z plane upstream from the detection, in the plain parallel to the wall.

Figure 7 shows ensemble averaged stream-wise velocities at Y=1.6. Being different from the near wall structures, the structures show strong two-dimensionality in span-wise. Wavy variation of the stream-wise velocities in the figure is related to flows over the bulge structures. Pressure peaks that are related to turbulent structures near the wall seem to be related to the valleys of the bulges.

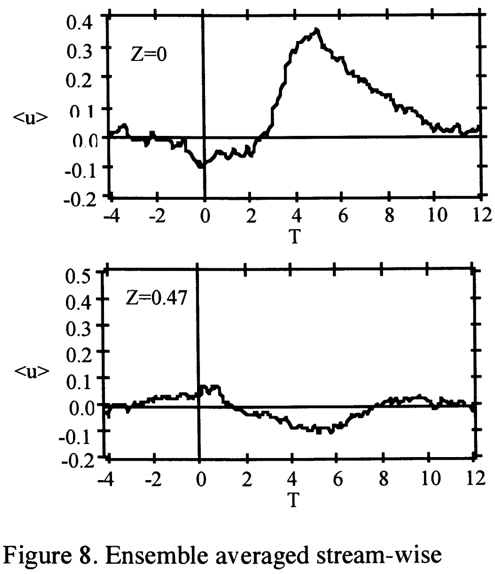

Figure 8. Ensemble averaged stream-wise velocity at X=2.36 and Y=1.6.

Figure 8 shows ensemble average velocities at 6cm(X=2.36) downstream from the pressure hole near the wall (Y=0.029). The near wall structures decay during they move downstream at Z=0.0. An averaged moving speed calculated from the delay time was 0.48 times mean flow velocities.

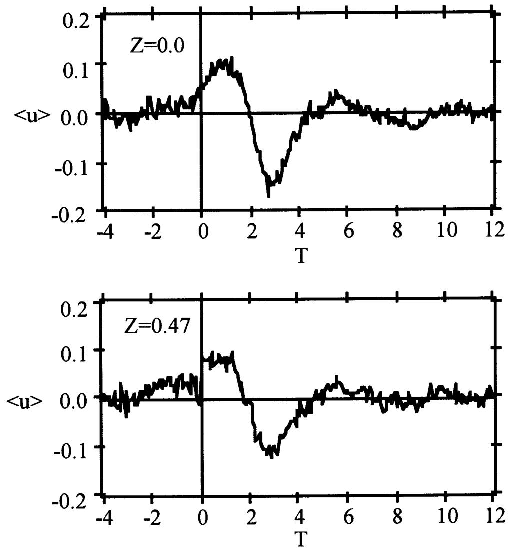

Figure 9. An ensemble averaged stream-wise velocities at X=2.36, Y=1.6

Figure 9 shows ensemble averaged stream-wise velocities at 6cm(Z=2.36) downstream from the pressure hole far from the wall (Y=1.6). The two dimensional structure does not decay or rather grow. This probably means the existence of a lean structure. The outer structure moving without decay is well known in visual studies.

The moving speed of the outer structure that was obtained in the present experiments, calculated from time delay, is 0.79 times mean flow velocity.

CONCLUSIONS

Two vortex pairs in planes parallel to the wall in a turbulent boundary layer were found experimentally. The downstream vortex pair produces ejection-type flow and the upstream vortex produces sweep-type flow. The near wall structure moves about a half of mean flow velocity and decays downstream. The outer structure moves downstream without decaying at speed of 0.8 mean flow speed. The near wall structures are related to the valley of the outer structure. Does each vortex of the downstream vortex pair connect upside like a hairpin? It is unknown how the vortices exit in stream-wise and span-wise direction.

Outer structure moving without decay is well known in visual studies.

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