Bursting Phenomenon of Turbulent Boundary Layers with Injection and Suction through a Slit

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Organized structures including bursting phenomenon of turbulent boundary layers with injection and suction through a slit have been investigated experimentally. Conditional sampling with VITA and quadrant analysis have been applied and space-time correlation has been measured. Moreover, the relationship between bursting phenomenon and wall pressure has been investigated.

The results show that the contribution from ejection of bursting phenomenon to mean Reynolds stress $\overline{\nu''}$ near the wall decreases by injection and increases by suction. This is the reason why the mean Reynolds stress near the wall decreases by injection and increases by suction. Space-time correlation of velocities indicates that a coherent structure with oblique angle to the wall exists in the boundary layer. The oblique angle to the wall becomes larger with injection.

Key Words: Turbulence, Boundary layer, Injection, Suction, Bursting Phenomenon, Conditional Sampling, Space-Time Correlation

1. Introduction

Organized structures which possess considerable coherence exist in the wall region of turbulent boundary layer and are called bursting. It is known that bursting phenomenon has an important effect on the characteristics of boundary layer. Kline et al. and Kim et al. investigated the structure of bursting. They verified that the production of turbulent energy near the wall region is closely related with the bursting phenomenon, and since then it was made clear by many studies that bursting phenomenon consists of a sequence process in which low-speed streaks appear and are lifted away from the wall, thereafter high-speed fluids from the outer region sweep. To get better understanding of the characteristics of turbulent boundary layer, the elucidation of bursting phenomenon related to the mechanism of turbulence production is very important. However, bursting is an organized structure in an irregular turbulent field, and has a complicated mechanism. Therefore, many studies carried out to clarify the bursting phenomenon are restricted to equilibrium flows, for example, a turbulent boundary layer on a smooth flat plate and there are few studies made on the non-equilibrium flows by sudden change of boundary conditions and external disturbance. Especially, as of now, studies on bursting of turbulent boundary layers with injection and suction through a slit, which are useful methods to control the boundary layer and are used in practical fluid machinery, are nonexistent.

In this paper, the analyses are carried out by using conditional sampling and space-time correlation. Instantaneous signals of velocity fluctuations and Reynolds stress are observed. Moreover, the relationship between bursting and wall pressure fluctuation is investigated. From these measurements, bursting phenomenon of non-equilibrium turbulent boundary layers disturbed by injection and suction through a slit is made clear.

2. Experimental Apparatus and Procedure

The experimental apparatus used in this study is the same as the one which was previously used to investigate the mean and turbulence characteristics of turbulent boundary layers with injection and suction through a slit with the exception that a pressure transducer is set up to measure wall pressure fluctuation. Slit width $L=50$mm is used. Injection and suction flow rate $Q$ is defined as follows:

$$Q = \frac{(\rho V_a L)}{\int \rho (\partial u/\partial x)_f} x = -1.5 \pm 5$$

Three values of $Q$ are chosen, namely $Q=0.13$ (injection), $Q=0.13$ (suction) and $Q=0$ (without injection and suction). The measurements are made at the position $x=100$ and $300$mm; where, $x$ indicates the streamwise distance from a slit. Even in the case of $Q=0$, the flow over the slit differs from an equilibrium turbulent boundary layer on a smooth flat plate. To measure wall pressure fluctuation, a condenser microphone is used as the pressure transducer. Here, this pressure transducer also picks up sound and vibration produced by the wind tunnel fan. To eliminate these influences, the low frequency component is taken off with a low-cut filter as.
Willmorth et al., did, did.

The conditional sampling with VITA developed by Blackweiler et al., and quadrant analysis are applied. In this measurement, the output signals from the hot-wire anemometer are recorded in a data-recorder, and are then recorded in a floppy disk of a personal computer by using an analog-to-digital converter at 100 μs intervals. The practical calculations are carried out with a large digital computer. Sampling number is about 25000 per one signal.

3. Experimental Results and Discussion

3.1 Velocity profile and Reynolds stress

Before showing the experimental results about bursting, the velocity profile and Reynolds stress of turbulent boundary layers with injection and suction through a slit are shown in Figs. 1 and 2. Solid lines in Fig. 1 present the law of the wall

\[ \frac{\partial}{\partial x} = \frac{1}{k} \ln \frac{\nu}{y'} + B \]  

where, \( x=0.1 \), \( B=5.0 \), \( y'=u_0/\nu \), \( u_0 \) friction velocity.

At the position \( x=100 \text{mm} \), shape parameter with injection takes a value as large as 1.77. Injection also makes the velocity profile largely deviate from the law of the wall at the outer layer region. The shape parameter with suction takes a value of 1.33. The differences between the velocity profile and the law of the wall appear little in the outer layer region. The shape parameter at \( Q=0 \) is 1.43. This value is slightly larger than that of the turbulent boundary layer on a smooth flat plate due to the effect of corner separation at the slit. The velocity profiles at \( x=500 \text{mm} \) are almost similar for all the experimental conditions. Therefore, the mean flow characteristic is near the equilibrium state.

Reynolds stress at \( x=100 \text{mm} \) increases by injection and decreases by suction in the region of \( y' \) greater than 80. In the near wall region, however, Reynolds stress decreases by injection and increases by suction. This is a very interesting behavior. At the position \( x=500 \text{mm} \), Reynolds stress keeps a similarity till \( y'=100 \). The increase of Reynolds stress by the effect of injection is seen in the outer layer region. From Figs. 1 and 2, it is supposed that velocity profile and Reynolds stress at the position \( x=100 \text{mm} \) are strongly affected by injection and suction through a slit, and the turbulent boundary layers are in non-equilibrium state. At the position \( x=500 \text{mm} \), though the velocity profile is nearly in an equilibrium state, the effect of injection is observed in Reynolds stress at the outer layer region.

3.2 Conditional sampling with VITA technique

For conditional sampling with VITA technique, we have to decide the averaging time \( T \) and threshold level \( k \) to detect bursting. In this study, \( T=12 \) and \( k=1.8 \) are employed for all the values of \( Q \). These values are nearly equal to those used by Blackweiler et al., and Sakurai et al. A streamwise velocity fluctuation signal \( u \) at the position \( y'=20 \) is used as a detection signal of bursting. Figure 3 shows the time traces of instantaneous velocity profile before or after bursting occurs. The dashed lines in Fig. 3 give the mean velocity profile obtained by conventional averaging, and the solid lines indicate a conditionally averaged profile obtained with the VITA technique. In Fig. 3, \( T(U_\delta) \) is a non-dimensionalized delay time, where \( \delta \) is the delay time, \( U_\delta \) is the free-stream velocity and \( \delta \) is the boundary layer thickness. \( T=0 \) corresponds to midway time at which burst is detected. In the case of \( Q=0 \), the first and second deviations of the mean averaged velocity profile from the mean velocity profile occur in the outer region, and a momentum excess is observed. As the degree of the momentum excess is strengthened, retardation occurs near the wall and low-speed fluids appear. Low-speed fluids exist until \( T=0 \), then they vanish and high-speed fluids in the outer region move towards the wall, and the velocity near the wall increases. When this stage is over, the velocity profile recovers to the mean velocity profile. This sequence of the event in \( Q=0 \) is almost the same as that reported for equilibrium turbulent boundary layer.
In the case of injection, the first deviation from the mean velocity profile starts from an acceleration in the outer regions, and then an intrush of high-speed fluids is seen in wall region the same as at Q=0. However, the retarded fluid motion, which is observed at Q=0, does not appear. The degree of acceleration at larger \( \gamma' \) becomes larger than that at Q=0. In the case of suction, a reversed behavior as compared with Q=0 and +0.13 is observed. Namely, first deviation from the mean velocity profile starts from a deceleration in the wall region, and a low-speed fluid clearly emerges.

The time traces of the conditionally averaged streamwise velocity fluctuation \( \langle u' \rangle \) are shown in Fig. 4. At Q=0, a retarded flow appears earlier at \( \gamma' \) near the wall, and then a very strong acceleration occurs at about \( \gamma' = 0 \). With an increasing \( \gamma' \), the degree of acceleration is weakened. In the case of Q=+0.13, few retarded flows are seen at all the measurements positions. Bursting is composed only of an accelerated fluid motion. The degree of acceleration is weakened at the regions \( \gamma' \) less than 0.10 as compared with Q=0 and +0.13. In the case of Q=+0.13, the retarded fluid motions are more clearly seen than at Q=0 and +0.13, and an outward expansion of the retarded region is recognized up to \( \gamma' = 0.15 \). Figure 5 shows a conditionally averaged normal velocity fluctuation \( \langle \phi' \rangle \). At \( \gamma' = 0.15 \) for Q=0, \( \langle \phi' \rangle \) accelerates from about \( \gamma' = 0.4 \) and has positive values. This means that a fluid motion towards the outer region from the wall region occurs. From the time \( \gamma' = 0 \), \( \langle \phi' \rangle \) takes negative value due to strong deceleration. Namely, a fluid motion towards the wall region occurs, and then approaches the mean value. Unlike in Fig. 4, \( \langle \phi' \rangle \) takes positive value when \( \langle u' \rangle \) is negative, and \( \langle \phi' \rangle \) takes negative value when \( \langle u' \rangle \) is positive. It means that a low-speed fluid motion towards the outer region from the wall region (ejection) and a high-speed motion towards the wall region from the outer region (sweep) exists in boundary layer. Near the wall region at Q=+0.13, the fluid motions towards the outer region from the wall region and towards the wall from the outer region are weakened. At Q=+0.13, the process of acceleration and deceleration of \( \langle \phi' \rangle \) clearly begins. Especially, the fluid motion towards the outer from the wall
region expands to a considerably outer region. From the measured results from Fig. 3 to Fig. 5, it is seen that the contribution of ejection to Reynolds stress near the wall decreases by injection and increases by suction. This is the reason why Reynolds stress near the wall decreases by injection and increases by suction.

Reynolds stress is conditionally averaged. The results are shown in Fig. 6. At \( y^* = 25 \) and 30 in \( Q = 0 \), two peaks are formed before and after the reference time \( T = 0 \). This means that Reynolds stress is produced by lifting up of low-speed fluid and intruding of high-speed fluid as seen in Figs. 4 and 5. As the probe departs from the wall, the peak values decrease and then disappear. Near the wall at \( Q = 0.13 \), a peak at \( T = 0 \) is hardly seen, and Reynolds stress occurs at about \( T = 0.5 \). At \( y^* = 25 \) in \( Q = 0.13 \), although it is not so clear compared with injection, the peak value at the time \( T = 0 \) is larger than that at \( T = 0 \). With an increasing \( y^* \), the variation in time of the conditionally averaged Reynolds stress is smaller than that at \( Q = 0 \) and -0.13, and it is nearly constant.

The measured results of the conditionally averaged wall pressure fluctuation \( \langle \rho \rangle \) are shown in Fig. 7. In the case of \( Q = 0 \) and -0.13, \( \langle \rho \rangle \) suddenly decreases at about \( T = 0 \) and takes negative value. It is to be noted that in the conditionally averaged velocity profiles, the wall pressure becomes negative when low-speed fluids move in the outward direction and they are positive when high-speed fluids rush in toward the wall. In the case of \( Q = 0.13 \), the rapid decrease of wall pressure, which is seen at \( T = 0 \) for \( Q = 0 \) and -0.13, is hardly observed. The phenomenon in which the wall pressure becomes positive is recognized in the time region of \( T \) greater than zero. The conditionally averaged wall pressure fluctuations show a good correspondence with the velocity fluctuations which are shown in Figs. 3 to 6.

Fig. 6 Conditionally averaged Reynolds stress

Fig. 7 Conditionally averaged wall pressure fluctuation

3.3 Conditional sampling with quadrant analysis

In this analysis, instantaneous Reynolds stress \(-\nu \dot{\nu}\) is classified as one of the four quadrants in \( u-v \) plane. The second quadrant represents an ejection event in which a low momentum fluid ejection outwards from the region near the wall, and the fourth quadrant represents a sweep event in which a high momentum fluid sweeps towards the wall from the outer region, respectively. These events make a positive contribution to Reynolds stress production. The first quadrant is called outward interaction and the third quadrant wallward interaction. These events make negative contributions to Reynolds stress. To make the organized structure of bursting more clear, the ratio of contributions to Reynolds stress from each quadrant \( (\mu)_{kv}/\mu \) is computed with an introduced threshold value \( H \) from the following equation:

\[
\frac{1}{\mu} = \int_{-\infty}^{\infty} \frac{1}{r} \left\{ \int_{-\infty}^{r} \alpha(r) \, dr \right\} \, d\alpha
\]

where the subscripts \( i \) refers to the \( i \)th quadrant. \( I(i, H) \) is an intermittency function and defined as follows.

\[
I(i, H) = \begin{cases} 
1 : & \text{if the point } (u, v) \text{ in the } u-v \text{ plane is in the } i \text{th quadrant and } |u| > H_{\text{interm}} \\
0 : & \text{otherwise}
\end{cases}
\]

Figure 8 shows the results of conditional sampling which is carried out at various values of \( H \). In this figure, the amplitudes of Reynolds stress are large and if \( (\mu v) \) have non-zero values in wider of \( H \), the phenomenon corresponds to a larger scale structure. At the position \( y^* = 25 \) and 30 in \( Q = 0 \), the values of the second quadrant are larger than those of the fourth. The comparison between the first and the third quadrant reveals that the

Fig. 8 Ratio of contributions to Reynolds stress
negative contribution from the third quadrant is larger than that of the first. At the position of \(y^+ = 70\) and 110, the contribution from the second quadrant is equal to that from the fourth. In the case of injection, the contribution from the fourth quadrant is larger than that from the second. However, in the results obtained by Wallace et al. and Brodkey et al., the second quadrant was larger than the fourth in the region where \(y^+\) was greater than 15. Therefore, it is understood that the contribution from the fourth quadrant, namely the sweep event, increases in wide ranges of \(y^+\) of \(Q = 0\) and 0.13. This is the reason why the Reynolds stress increase in the region away from the wall. From the comparison between the first and third quadrant for the case of injection, it is clear that the negative contribution from the first quadrant is larger than that from the third. This reveals that outward interaction is strengthened by the effect of injection through a slit.

In the case of suction, the largest contribution comes from the second quadrant, a reverse trend to injection. The negative contribution from first quadrant is larger than that from the third at the position \(y^+ = 25\) and 30. These results are qualitatively in accord with the results obtained by Brodkey et al. But, the ratios of \((\omega u/\nu)\) and \((\omega u/\nu)\) at \(y^+ = 25\) and 30 are larger than those of theirs. It means that ejection and wallward interaction are strengthened by the effect of suction through a slit. The ratios of contributions to Reynolds stress from each event are revealed at various positions of \(y^+\) under the condition of \(H = 0\) in Fig. 9. At the value of \(H = 0\), the summation of Reynolds stresses in each quadrant event is equal to unity. It is recognized that the sweep event is most important for injection and the ejection event is most important for suction. To investigate the intermittency characteristics of each quadrant, intermittency factor \(\gamma_i\), which represents a fraction of time of the appearance of the \(i\)th quadrant event to total time, is calculated. The results are shown in Fig. 10. \(\gamma_i\) is the greatest value in injection, and \(\gamma_i\) is in suction. However, the largest contribution to Reynolds stress comes from the fourth quadrant in the case of injection and from the second quadrant in the case of suction as can be seen in Figs. 8 and 9. This means that the motion classified as ejection comes up most frequently in the case of injection, but its amplitudes are not large. The motion classified as sweep has large amplitudes in short time period. In the case of suction, the reversed phenomena are observed as compared with injection. Figure 11 shows the variations of \(\gamma_i\) for different values of \(Q\). \(\gamma_i\) is nearly equal to 0.3 for three different boundary layers. This value is in accord with the results which are reported by the other investigators. On the contrary, \(\gamma_i\) is influenced by injection and suction, being smallest for injection and largest for suction. But, the differences are hardly seen in \(\gamma_i\) between the results with and without suction. Therefore, it is expected that \(\gamma_i\) decreases by the effects of injection and corner separation. Figure 12 shows the average period time and average duration time of each event. Both quantities are normalized with the free-stream velocity \(U_\infty\) and the boundary layer thickness \(\delta\). Though the average period of the fourth quadrant event at \(Q = 0.13\) is slightly smaller compared with the other events, no large differences are observed. In the average duration time, the second and fourth quadrant events are slightly larger than the first and the third quadrant events.
3.4 The instantaneous velocity and Reynolds stress signals

An example of the time traces of velocity and Reynolds stress signals which are obtained at the position $x=30$ is shown in Fig. 13, where $D/D_{rms}$ is the value obtained from the bursting detector normalized with its r.m.s. value. The arrows in Fig. 13 indicate the reference time which is detected in the VITA analysis. A large amplitude of Reynolds stress occurs intermittently, and concurrently with the bursting detected by VITA for all the values of $Q$. In Fig. 13, $S$, $E$, $I_w$ and $I_0$ described at the time when the amplitudes of Reynolds stress are large reveal that $S$ is a contribution from sweep, $E$ from ejection, $I_0$ from outward and $I_w$ is that from wallward interaction. A large amplitude of Reynolds stress mostly occurs in sweep event in the case of injection, and in ejection event in the case of suction. For an interaction, outward interaction increases by the effect of injection and wallward interaction increases by suction. These results are in agreement with the results of VITA and quadrant analysis.

The above results are obtained at the position $x=100$mm. The velocity profile and Reynolds stress in this position are strongly influenced by injection and suction and the characteristics of boundary layers are in non-equilibrium state. In the next step, we present the measured results at the position $x=500$mm. Figure 14 shows a conditionally averaged streamwise velocity fluctuation, and Fig. 15 shows a wall pressure fluctuation. Figure 16 shows the measured results of quadrant analysis. For all the measured results, differences between $Q=0$ and -0.13 are hardly seen. It is already shown in the earlier report that the mean flow and turbulence characteristics at $x=500$mm can be regarded to have reached the equilibrium state. Therefore, it is natural that the structure of bursting does not change between $Q=0$ and -0.13. In the case of injection, a retarded fluid motion is observed till about $x=30$ as seen in Fig. 16. This reveals that the contribution from ejection once weakened by the injection recovers when advancing downstream and when approaching the equilibrium state. This is also ascertained from the existence of non-uniform pressure at about $x=0$, which does not appear at $x=100$mm, as seen in Fig. 15. The contribution from the second quadrant is larger than that from
the fourth at \( y' = 30 \) of \( \varphi = 0.13 \) in Fig. 16. However, this relationship is reversed at \( y' = 110 \). At the position \( x = 500 \text{mm} \), the influence of injection appears in the outer layer region and Reynolds stress increase in this region. It is considered that this increase is closely related with the increase of contribution from the sweep event.

3.5 Space-time correlation

The space-time correlation is measured at \( x = 100 \text{mm} \) to make clear the organized structure in the wall region. The results are shown in Fig. 17 which gives the space-time correlations of \( u \) taken with a fixed probe \(( y' = 20 \) and outer probe traversing the boundary layer. When the outer hot-wire probe is placed near the wall and the two hot-wire probes do not separate too much from each other, the peaks of correlations appear at about \( T = 0 \). As the outer hot-wire probe departs from the wall, the peaks of correlations move in the negative time direction and the peak values decrease. The displacement of the peak position in the negative time direction means that the organized structure is composed of oblique bursting to the wall. The experimental results for the case in which the peak of correlation appears at the time \( T = 0 \) when the outer hot-wire probe is moved in downstream direction are shown by dashed lines in Fig. 17. The positions of outer hot-wire probe are plotted in Fig. 18. Brown et al.\(^{112} \) reported that the oblique angle of bursting was \( 18^\circ \). Sakurai et al.\(^{112} \) and Blackwelder et al.\(^{110} \) obtained almost the same results as Brown et al. did. But the oblique angle is \( 47^\circ \) in the case of the turbulent boundary layer with injection through a slit. In the case of suction, the oblique angle is \( 18^\circ \) and this value agrees with the result reported for an equilibrium turbulent boundary layer. To make clear the shape of the organized structure near the wall, a space-time correlation map is made. The results are shown in Fig. 19(a). In this figure, space-time correlations are measured with the fixed probe set at the position \( y' = 0.05 \), the other probe transversing the boundary layer. The streamwise distance between the two probes is equal to the boundary layer thickness. The distance from the wall where the correlation value becomes 0.1 is about \( y' = 0.3 \) in spite of differences in the experimental conditions. It is expected that there is a relationship between the wall and the outer intermittent region. The dashed lines in Fig. 19(a) are oblique angles evaluated from Fig. 18 and are in good agreement with the direction of inclination. The influences of injection and suction are hardly seen in the normal direction but are clear in the streamwise direction. Figure 19(b) shows the space-time correlation measured under the condition that the distance from the wall of two hot-wire probes is same with one probe fixed and the other located at \( x' \) downstream of the fixed probe. These measurements are made to make clear the decay behavior of the eddy in downstream direction. In the case of injection, a rapid decay of correlation is observed with an increasing \( x' \), as expected from Fig. 19(a), and the organized structure in the streamwise direction is weakened. In the case of suction, the decay of the correlation is weakened and distribution of eddies in the streamwise direction expands as compared with that at \( \varphi = 0 \). However, this trend is not so clear as that of injection.
4. Concluding Remarks

Experimental analyses for the turbulent boundary layers with injection and suction through a slit are made to investigate the bursting phenomenon. The main results obtained in this paper are summarized as follows:

(1) Reynolds stress near the wall decreases by injection and increases by suction. This is because the contribution from the ejection decreases by injection and increases by suction.

(2) Reynolds stress increases at a departing distance from the wall by the effects of injection and corner separation. This is due to the fact that the contribution from sweep increases with larger values of y'.

(3) The larger contribution comes from the sweep event rather than the ejection in the case of injection, and from the ejection in the case of suction.

(4) Injection strengthens the contribution from the outward interaction, and suction strengthens that from the wallward interaction.

(5) Intensity of bursting depends on the amplitude of signals, and not on the intermittency factor of each event.

(6) Intermittency factor in the second quadrant η is not influenced by injection and suction, whereas η decreases by injection.

(7) Bursting has an oblique structure to the wall. The oblique angle becomes larger with injection. In the case of suction, it is in agreement with the earlier reported results for equilibrium turbulent boundary layer.

(8) The decay of eddy in downstream direction is weakened by the effect of suction and strengthened by injection. The expense of eddy in the normal direction hardly changes by injection and suction, and it expands to the outer intermittent region.

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