主　論　文　の　要　約

論文題目　Experimental Study on Large-scale Structures in Turbulent Boundary Layer
（乱流境界層における大規模構造に関する実験的研究）

氏　　名　陳　暁楠

論　文　内　容　の　要　約

It is well known that various kinds of coherent structures exist in the turbulent boundary layer (TBL). These structures are mainly classified into two types according to their scales. One is the small-scale structures dominating the dynamic process of the fluid flow in the near-wall region. The other is the large-scale structures including large-scale motions (LSMs) and very-large-scale motions (VLSMs), which refer to the elongated uniform momentum regions existing in the logarithmic region and having a length of several boundary thicknesses. The low-speed and high-speed uniform momentum regions are termed as negative LSMs/VLSMs and positive LSMs/VLSMs, respectively in the present manuscript. These coherent structures in TBL are closely related to the turbulent production and the wall friction, and are therefore of great engineering interest. Great progress has been made in research on the coherent structures in TBL over last several decades, but there are still many unknowns. Clarifying the origin mechanisms and characteristics of the coherent structures in TBL will not only deepen our understanding of TBL but also give us insights in engineering applications. In this study, the following four concerns are mainly examined and addressed. Firstly, the meandering bend features of the LSMs and VLSMs were quantitatively studied. Secondly, to understand the origin process of the VLSMs, the relationship between the spatial distribution of hairpin vortices and the meandering VLSMs was depicted. Thirdly, the effect of LSMs and VLSMs on the near-wall small-scale bursting phenomenon was investigated. Finally, the effect of artificially created VLSMs on the near-wall bursting phenomenon was explored and a new approach for suppressing the near-wall Reynolds stress was presented.

In the first two sections of Chapter 1, a full literature review is provided to explain current understandings of structures in the near-wall and logarithmic regions, respectively. In the final section of Chapter 1, the questions that need to be clarified and goals of the present study are addressed.

The experimental setup is described thoroughly in Chapter 2 including the wind tunnel and test section, the hot-wire anemometer systems, and the plasma actuator. In the present study, the TBL was developed on a smooth flat plate that was mounted in the test section of the wind tunnel under zero pressure gradient. The fluctuation velocities of multiple positions were measured simultaneously using a multi-point hot-wire probe associated with a self-made constant-temperature anemometry circuit. The first section gives an overview of the wind tunnel and the test section, as well as their size. In the second section, the capacity of hot-wire anemometry systems and the design of the hot-wire probe are explained. The third part describes the dimensions of the self-made dielectric barrier discharge plasma actuator (DBD-PA) array that was utilized to generate a wall-jet for the artificial VLSMs. The experimental conditions are provided in the final section.

The analytical methods used in this study are outlined in Chapter 3. In the first section, the method for extracting meandering LSMs and VLSMs from the pseudo-spatial fluctuation velocity field is described. In addition, the method for quantifying the meandering features of the LSMs and VLSMs, which include the meandering bend length, amplitude, and angle, is explained. In the second section, the variable-interval time-averaging (VITA) technique, which was employed to detect the bursting event in the near-wall region and the hairpin vortex in the logarithmic region, is introduced.

The findings of a naturally generated TBL are discussed in Chapter 4. In the first section, statistics such as the mean velocity profile and the turbulence intensity profile are presented and compared to the past data in the literature. They were found to be very similar to those identified in the literature. In the second section, the characteristics and meandering bend features of the LSMs and VLSMs were discussed. It was revealed that for both the LSMs and VLSMs, the probability density of all the meandering bend characteristics such as length, amplitude, and angle do not follow the Gaussian distribution and tend to be skewed on the negative side. In the third section, the relationship between hairpin vortex and LSMs/VLSMs were studied by visualizing the spatial distribution of hairpin vortices and meandering LSMs/VLSMs. It was observed that the hairpin vortices tend to exist at the upstream edge of low-speed structures or at the downstream edge of high-speed structures. This result indicates that both the LSMs and VLSMs were formed from hairpin vortex packets. Moreover, the relationship between the asymmetry of the hairpin vortex and the meandering bend direction of the large-scale structures was investigated. It was found that the asymmetry of the smaller-scale hairpin vortex detected in the logarithmic region is independent with the meandering bend direction of the LSMs and VLSMs. In the fourth section, the effects of LSMs and VLSMs on near-wall bursting phenomenon were explored. It was found that bursting phenomenon became active under high-speed structures, while it was suppressed under low-speed structures. However, the frequency became constant when normalized using the local inner-variables. Furthermore, some bursting phenomena were observed to occur simultaneously with the hairpin vortex in the logarithmic region, implying that some bursting events were triggered by the leg of hairpin vortex.

In Chapter 5, the experimental results on TBL modified by the DBD-PA array are discussed. The mean velocity profile and turbulence intensity profile are presented in the first part. The properties of artificial VLSMs (AVLSMs), which include negative AVLSMs (nAVLSMs) and positive AVLSMs (pAVLSMs), were examined in the next section. These AVLSMs appeared from the near-wall region to around $y/\delta = 0.3$. In addition, it was found that the nAVLSM flanked on two sides by the pAVLSMs could be detected continuously for a long time in the near-wall region. At a higher position, these artificial large-scale structures were observed to meander and therefore became unstable. The influence of the AVLSMs on turbulent intensity was thoroughly studied in the third section. As a result, the turbulence intensity was shown to be reduced in the pAVLSMs but enhanced in the nAVLSMs. These results could be explained as that the pAVLSM transports the outer low-turbulent flow into the near-wall region and the nAVLSM lifts the near-wall high-turbulent flow to a higher position. In the last section, the effects of the AVLSMs on the near-wall bursting phenomenon were discussed. The change of near-wall bursting frequency under AVLSMs is consistent with the change of the turbulent intensity. It was also found that the bursting frequency normalized by local inner-variables are not the same in different types of AVLSMs when the turbulence intensity in the pAVLSM is significantly low. However, it becomes the same in the downstream region where the turbulence was developed. This finding implies that the QSQH theory is only valid when the turbulence is fully developed.

Chapter 6 summarizes the study. The main conclusions are as follows. Firstly, the meandering bend features of the LSMs and VLSMs were clarified. Secondly, both the LSMs and VLSMs are formed from hairpin vortex packets. Thirdly, bursting phenomenon becomes active under the positive LSMs/VLSMs in the naturally-developed TBL while it is suppressed under the negative LSMs/VLSMs. Finally, bursting frequency is reduced in the pAVLSMs in the TBL modified by the DBD-PA but increased in the nAVLSMs. This chapter also addresses remained questions. Firstly, the mechanism that makes the LSMs and VLSMs meander remains unclear. Secondly, it needs to be investigated whether strong large-scale streamwise vortices as the ones generated in the artificial TBL exist in natural TBL, because it is indicated from the present study that existence of such vortices breaks the QSQH theory. Finally, optimal specifications and operating conditions of the DBD-PA as a device for generating artificial VLSMs must be explored.