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論文内容要旨

The flow states inside the boundary layer can generally be categorized into laminar or turbulent states. The physical characteristics such as the skin friction and the heat transfer at the wall, are drastically different between the two. Especially, the laminar state is preferable if the demand is on the reduction of the skin friction at the wall, which realizes less energy consumption. In order to keep the laminar boundary layer flow area as large as possible on the body surface, revealing both the transition process and the structure at the interface between the laminar and turbulent states is important. Furthermore, the novel control technique aimed at suppressing the turbulent motion is required in the engineering field.

In the present study, the transition process and the interface between the turbulent and laminar states in boundary layer flows have been studied both experimentally and numerically. The suppression control of the turbulent region expansion is also attempted through destroying the structure at the interface.

The contents of this thesis consist of six chapters as outlined below.

Chapter 1 is the introduction.

In chapter 2, the instability modes in the three-dimensional boundary layer near the attachment-line region on the yawed cylinder are studied in detail. The boundary layer on the swept wing, which modern aircrafts adopt in order to avoid the shock wave formation on the wing surface, becomes three-dimensional since the direction of pressure gradient does not coincide with the free stream direction. This imbalance results in the appearance of a secondary flow, called the cross-flow, inside the boundary layer, perpendicular to the external streamline. The transition to turbulence consequently takes place much earlier compared to the Tollmien-Shlichting (T-S) wave type transition, which is generally observed in two-dimensional boundary layers. This early transition leads to a rapid increase in the skin friction. The instability modes in the three-dimensional boundary layer have been studied for a long time aimed at reducing the skin friction, however these studies mainly treated the boundary layers with the averaged characteristics which cover large portions of swept wings. Where the cross-flow instability is found to be dominant instability mode, the boundary layers develop in response to a weak favorable pressure gradient and a small streamline curvature. On the other hand, in recent years, another instability mode, called the streamline-curvature instability, was theoretically predicted near the attachment-line region of a swept wing, where a strong pressure gradient, a large wall-curvature and a large streamline-curvature exist. In spite of its importance, there were few experimental studies concerned with the streamline-curvature instability, which is because it is difficult to measure inside such thin boundary layers.

In this chapter, the behavior of the point source disturbance which is introduced into the boundary layer by the alternating blowing and suction at the wall is studied using a direct numerical simulation (DNS). The instability modes are identified by studying the characteristics of the velocity fluctuating wave originated from the point source disturbance. In the low Reynolds number case, the wedge shaped distribution of the velocity fluctuating region develops downstream. Using the two-dimensional Fast Fourier Transform filtering technique, the velocity fluctuating wave is successfully divided into two instability waves, namely, the streamline-curvature instability wave and the cross-flow instability wave. In the high Reynolds number case, the developed velocity fluctuation wave deriving from the cross-flow instability is found. With the increase in the frequency of the excitation, the wall-normal profiles of the amplitude and phase of the velocity fluctuation, which is commonly used for the mode identification, started to exhibit the features of the T-S wave instability. It is demonstrated that the features of the wall-normal profiles can change by the direction of the velocity component which is evaluated. The risk of judging the instability mode using only the wall-normal profiles is pointed out. These findings are important in identifying the instability mode and are also useful in the designing more efficient wings.

In chapter 3, the breakdown process of the Klebanoff mode, which is found at the later stage of the T-S wave type transition in the flat plate boundary layer, and the start of turbulence, are experimentally studied using a single type hot-wire probe. The T-S wave type transition has been studied for the last 80 years, so most features are already disclosed. However, how the flow structures collapse and turbulence starts at the final stage are not completely clarified yet. This is because both of temporal and spatial scales of the phenomenon occurring at the final stage are quite small and the phenomena can interact with each other because of its strong non-linearity. So, detailed investigations of both the temporal and spatial developments are necessary in order to understand the mechanism of the structure breakdown and the start of turbulence, which has been difficult in both the experiments and numerical studies.

The T-S wave is excited by a combination of a two-dimensional roughness attached on the flat plate and an acoustic wave in the free stream. The direct excitation of the Klebanoff mode against the T-S wave is attempted using an array of the uni-morph piezo-electoric actuators, which is also attached on the flat plate. A pair of oblique waves is successfully excited by driving the array of the piezo-electoric actuators. By exciting both the T-S wave and the pair of oblique waves, a peak-valley structure whose streamwise and spanwise ratios corresponded to the Klebanoff mode, is successfully generated. It is confirmed that the disturbance energy at the peak location grows faster than at the valley. From the two-dimensional mode analysis, it is found that the elongated structures in the streamwise direction grow at the location where the turbulent starts. Another lambda-shaped shear layer, named the *child* shear layer, is found between the lambda vortices (*parent* shear layers) which are originally excited by the array of the piezo-electoric actuators. High-frequency instability wave known as the spike is found at the *child* shear layer. It is also confirmed that, at the timing the triple spikes appears on the *child* shear layer, the turbulence starts at the upstream end of the *parent* shear layer in the near-wall region. A phenomenon where the turbulence spreads along the parents shear layer is newly found. The knowledge obtained in this chapter is important in understanding the physical mechanism of the breakdown process and the start of turbulence, and is useful for the establishment of a more exact method to predict the transition point.

In chapter 4, the structure at the turbulent/laminar interface is experimentally studied aimed at the establishing a more novel technique for a turbulent flow control. In order to reveal the mechanisms how the turbulent region expands into the laminar region and how the turbulent motion can be sustained, the turbulent spot and the turbulent wedge have been used as research targets. Usually the growth mechanism of the turbulent region is explained as an *entrainment process*, which means that the turbulent region expands by drawing the laminar fluid inside the turbulent region across the border. However, the spanwise borders are close to each other in the turbulent spots or in the turbulent wedge, so there are interactions between the two. Furthermore, the structure, which contributes to the local spanwise expansion of the turbulent region, has not been found yet. Thus, in this chapter, the structure of the turbulent/laminar interface of the turbulent wedge, whose spanwise scale is comparably larger than the ordinary one is studied using a rake of the six single probes and two X-wires. The conditional sampling technique combined with the ensemble-averaged method is used for the analysis. A verification of the analyzing method is also carried out.

Two bi-morph piezo-electoric actuators are used for the boundary layer tripping. It is confirmed that the spanwise growth rate of the turbulent region is similar to the previous researches. It is found that in the intermittent region, the turbulent region is continuously sticking out into the laminar region at the middle height of the boundary layer. A pair of the streamwise vortices aligned in the wall-normal direction is found at the turbulent/laminar interface. The flow induced by the vortices is found to be the cause for the turbulent fluid to be pushed into the laminar region. The mechanism which the turbulent region expands in the spanwise direction is revealed. This finding implies the possibility of a suppression control of the turbulent region expansion. In addition this, the risk in using the conditional sampling method is also pointed out. In studies such as the investigation of the flow structure at the turbulent/laminar interface, the conditional sampling technique is a powerful tool and very likely the only tool available. However, it is shown that the importance of choosing the legitimate condition can not be over emphasized, since the conclusion can change depending on the choice of the condition.

In chanter 5, the suppression control of the turbulent region expansion in the spanwise direction is carried out. The boundary layer control has been attempted in many researches aimed at reducing the skin friction at the wall. However, most of them are against fully developed turbulent flows and no practical control techniques have been established yet. So the suppression of the turbulent motion and keeping the laminar state in the boundary layer flow should still be categorized as a dream. On the other hand, from an engineering point of view, to control and to suppress the expansion of the turbulent region are also very important, since the skin friction or the heat transfer is strongly affected. In this chapter, the suppression control of the turbulent region expansion is attempted by destroying the structure at the turbulent/laminar interface found in chapter 4.

For the suppression control, a thin plate whose wall-normal length is approximately one half of the boundary layer thickness is set parallel to the streamwise direction and normal to the wall near the turbulent/laminar interface. It is found that the suppression effect of the turbulent region expansion depends on the spanwise location of the plate setting. The convection velocity of the streamwise vortices, which is responsible for the induction of the flow from the turbulent region toward the laminar region, is found to be approximately 0.8 of the free stream velocity. The control to suppress the expansion of the turbulent region is successfully achieved by destroying the pair of streamwise vortices. From this fact, it can be confirmed again that the pair of streamwise vortices is playing the key role in the expansion of the turbulent region. This technique is not only a new proposal for the turbulent flow control, but is also a practice one.

Chapter 6 describes the conclusions.

As mentioned above, in the present thesis, the transition mechanism and the interface between the turbulent and laminar states in the boundary layer flows are studied and several new features are revealed. The suppression control of the turbulent region is also conducted. It can be expected that these findings contribute to the improvement of the efficiency of high speed transportation systems such as airplanes, cars and high-speed trains.

論文審査結果の要旨

境界層流れは層流状態と乱流状態に大別できるが，両者では物体表面における摩擦抵抗や熱伝達の特性が大きく異なるため，両者間の遷移過程および界面の構造を解明しその制御法を確立することは工学上重要な課題となっている.

本論文は境界層流れにおける層流と乱流間の遷移過程およびその界面構造の解明と制御に関する研究成果をまとめたもので，全編 6 章より構成される.

第 1 章は緒論である.

第 2 章では，数値シミュレーションにより壁面上から導入した点源攪乱の挙動を追跡し後退円柱境界層の安定性を解明している．低レイノルズ数の場合くさび状の速度変動領域が形成され，2 次元 FFT による分離からこの領域には流線曲率不安定性と横流れ不安定性が存在していることを明らかにしている．また，従来用いられてきた振幅と位相分布のみから不安定性を特定する手法の危険性について指摘している．これらは不安定性の特定に関する重要な知見であり，工学的に有用な成果である.

第 3 章では，T-S 波型遷移過程における流れの構造の崩壊と乱流の始まりに関する実験的研究を行っている.音波と表面粗さにより励起した T-S 波を，ピエゾセラミックアクチュエータを用いて Klebanoff 型で 3 次元化することに成功している．また，Klebanoff モード構造崩壊の直前にはラムダ渦が直接作るせん断層の間に新たなせん断層が現れ，乱流開始点はこの真下付近にあること，およびその乱流はラムダ渦が直接作るせん断層に向かって広がることを見い出している．この結果はより正確な遷移位置予測法の確立につながる，工学的に重要な知見である.

第 4 章では，乱流がどのように層流領域を浸食して広がるのかを実験的に調べ，乱流と層流の界面に存在する壁面垂直方向に並んだ一対の縦渦により誘起される流れが乱流領域の拡大をもたらすことを明らかにしている．これは乱流領域拡大抑制制御の可能性を示唆する工学的に有用な知見である.

第 5 章では，第 4 章で見いだされた界面構造を，流れに平行かつ壁面に垂直に設置された板で壊す制御を試み，乱流領域の拡大抑制に成功している．これは抵抗低減法へと発展する可能性が高い新たな制御手法の提案であり，工学的に重要な知見である.

第 6 章は結論である.

以上要するに本論文は，境界層流れの層流状態と乱流状態間の遷移過程と乱流の始まりおよびその界面構造ついて明らかにし，さらに乱流領域の拡大抑制制御の可能性も示したものであり，機械知能工学の発展に寄与するところが少なくない.

よって，本論文は博士(工学)の学位論文として合格と認める.