EJECTION AND SWEEP FLOWS IN TRANSITIONAL BOUNDARY LAYERS

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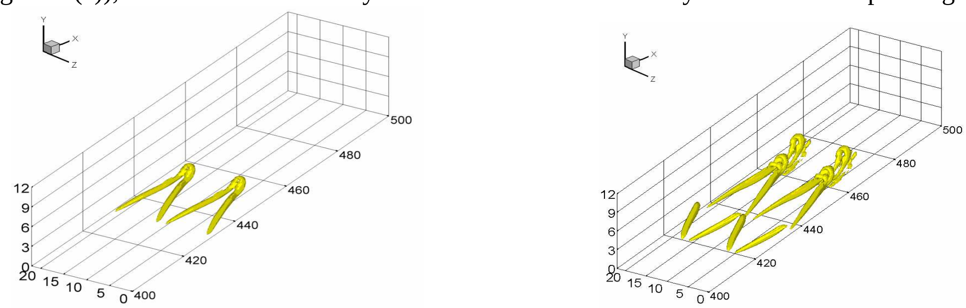
Summary At the late stages of compressible transitional boundary layers over a flat-plate, the events of ejection and sweep flows and their formation mechanism and influence on voritcal structures of the flow field were investigated by means of direct numerical simulation with high order accuracy. The numerical results with high resolution clearly represented the complex phenomena of ejection and sweep flows in the transition process of boundary layers, and their close relationships with typical vortex structures and spike structures were revealed. The details of formation mechanisms of ejection and sweep flows were analyzed. The numerical results demonstrate the new experimental findings, and the corresponding mechanisms were analyzed.

Introduction

Ejection and sweep flows are important discoveries in the study on late stages of the boundary layer transition, which are the products of the voritcal structures. In recent years, Lian Q X et al revealed the relationship between sweep flow and vortical structures in the experimental work [1]. Borodulin, Kachanov, et al [2] analyzed the ejection and sweep flows induced by the vortical structures in the boundary layer transition process through experimental and numerical methods. In present study, a spatial transition of the flat-plate boundary layers in the compressible flow was conducted by direct numerical simulation (DNS) method. Based on DNS results, the formation mechanism of ejection and sweep flows in the transition process is analyzed, and the relationship with vortical structures in transitional process is investigated. The second ejection and sweep flows, and their contributions to the formation and evolution of spike structures (localized high intensity streamwise velocity disturbance) are discussed mainly.

The first ejection-sweep flow and Λ-vortex

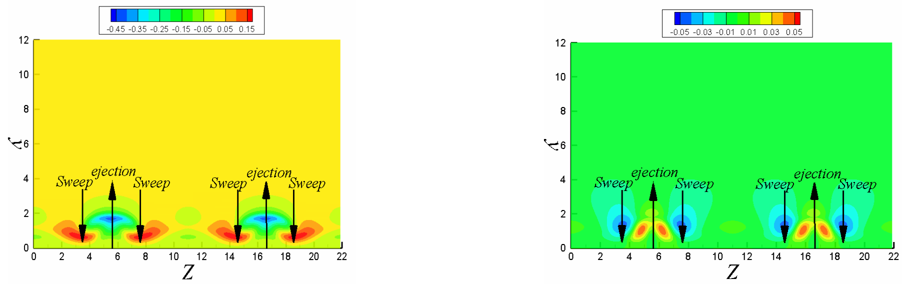
According to the results of numerical simulation, a vortex identification method introduced by Jeong& Hussain [3] is applied, which use iso-surface of a λ_2-eigenvalue to visualize vortex structures. At the stage of the Λ-vortex generation (Figure 1 (a)), the streamwise velocity and normal direction velocity field and corresponding disturbance



(a) t=6.2T (b) t=6.6T

Fig1. Evolution of vortex structures in transitional boundary layer ($\lambda_2 = -0.005$)

field is shown in Figure 2. The location is at the tip of the Λ-vortex ($x = 446$). Quadrant analysis is adopted, x-axis is the streamwise direction and y-axis is the normal direction. Correspondingly, u is streamwise velocity and v is normal velocity. From the disturbance velocity field in Figure 2(a) and Figure 2(b), at the center of the Λ-vortex structure ($z = 5.5$ and $z = 16.5$) $u' < 0$ and $v' > 0$. According to the definition of motion, this is an updraft motion usually called ejection. Beside the center plane of every Λ-vortex structure, $u' > 0$ and $v' < 0$. This is a downdraft motion usually called sweep.



(a) u' (b) v'

Fig2. Velocity field at the tip of the Λ-vortex ($x = 446\delta_{in}$, $t = 6.2T$)

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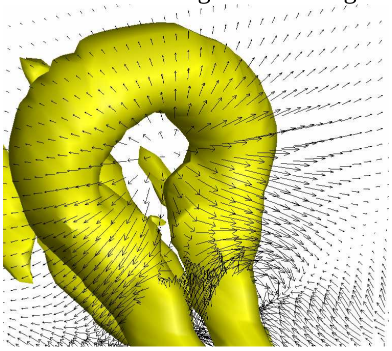
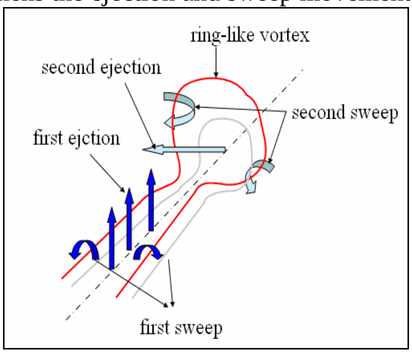
For clarification purposes, directions of motion are indicated using arrow signs in Figure 2(a) and Figure 2(b). From the DNS results, it is shown that the flow field in near the wall region has been largely changed by these sweep and ejection movement. The ejection flow exists at the center plane of the Λ -vortex, sweep flow appears both sides of the Λ -vortex. Obviously, these movements are induced by the rotations of Λ -vortex legs.

The second ejection-sweep flow and ring-like vortex

At the stage of the ring-like vortex formation the ejection and sweep intensified. We need to study the three dimensional flow structures around the ring-like vortex. The ring-like vortex using λ_2 visualization method and three dimensional disturbance velocity vectors is shown in Figure 3. At the center of the ring-like vortex, flow first moves updraft and then quickly changes direction and goes downward. The downdraft movements are located beside the center plane of the ring-like vortex and move down towards the wall. They merge with the first sweep generated by the rotating vortex legs. In order to distinguish this from the first sweep generated by the vortex legs, according to previous experiment work [4], this movement is defined as the second sweep. In present work, based on num erical simulation result, the movement image of the second sweep flow in the vicinity of the ring-like vortex is directly represented, and flow structures can be observed from a more intuitive perspective. The existence of the second sweep suggested in the experimental work is confirmed. The updraft movement in the center of the ring-like vortex is identified as the second ejection, which will merge with ejection from the vortex legs. The mixing strengthens the ejection and sweep movements.



(a) DNS results (t=6.8T)



(b) Sketch of flow structure

Fig3 Three dimensional flow structure around the ring-like vortex

CONCLUSIONS

Based on DNS results in present study, ejection and sweep flows in transitional boundary layers were presented through detail numerical results from direct numerical simulation. The formation mechanisms of ejection and sweep flows and their influence on the transition process were investigated, and the results were compared with the experimental observations. The following conclusions can be made.

1. Two different kinds of ejection and sweep flows are revealed at the late stages of the boundary layer transition. The newly observed second sweep in experimental work was verified, and its intensity is much stronger than the first sweep.
2. The close relationship between ejection-sweep flow and typical vortex structures were revealed by analyzing three dimensional flow structures around Λ -vortex and ring-like vortex.
3. The formation mechanism of the second sweep induced by ring-like vortex was investigated. Through the interaction between the ejection from the center of the ring-like vortex and the mean flow, the flow direction has to be quickly changed and the flow moves down towards the solid wall to form the second sweep.
4. The Second ejection forms the negative spike, while the second sweep produces the positive spike,which was newly observed in experimetal work in the near wall region. The ejection and sweep flows play a vital role in the formation and evolution of spike structures.

References

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