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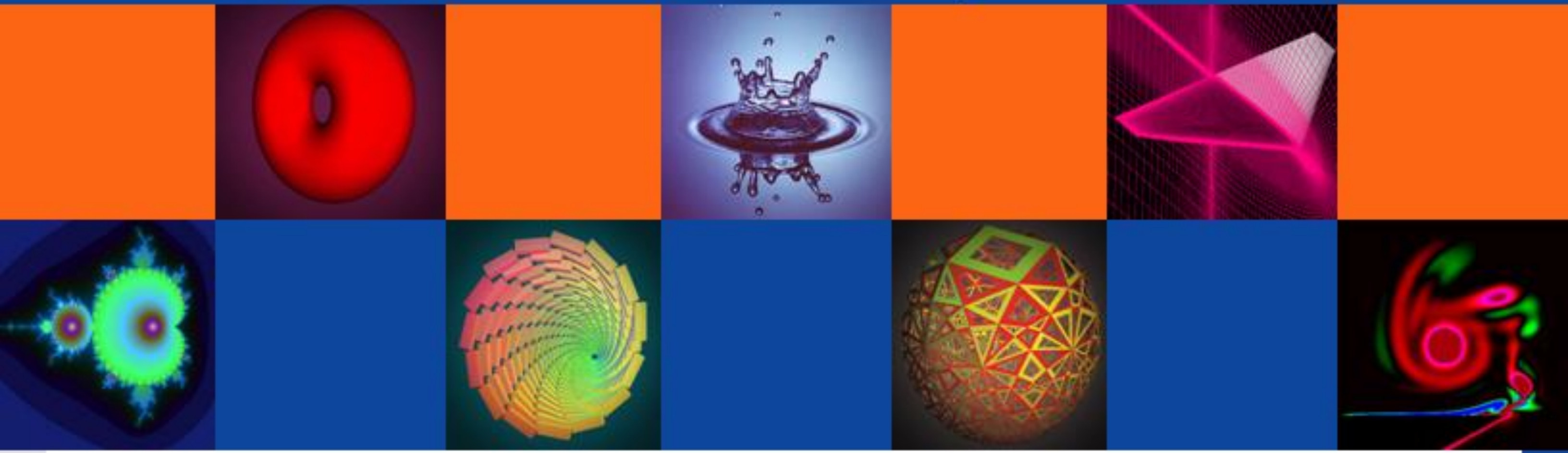

DNS Study on the Evolution of Vortical Packets and Their Interactions in Boundary Layer

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DNS Study on the Evolution of Vortical Packets and Their Interactions in Boundary Layer

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Vortical structures like the Λ-vortex and ring-like vortex play a critical role in the boundary layer transition process. In this paper, the mechanisms of the formation of the vortical packets and their mutual interactions are studied by DNS. It is found that the shear layer instability is the key of the vortex generation. On the other hand, in the process of evolution of vortical packets, the vortical structures(including vortex tubes and other kind of rotation cores) will continue to create high shear layers in the boundary layer by both sweeps and ejections. The generation and evolution process of the first ring-like vortex structure is studied in detail.

I. Introduction

It is widely accepted that the late boundary layer transition starts with the ring-like (hairpin or Ω-shaped) vortex formation[1,2]. These structures are commonly found with the vortical packets in almost every boundary layer transition stage. Both experimental and numerical results have shown that the mechanisms of disturbance development predominant at late stages of boundary-layer transition are rather universal.

The ring-like vortex was found to be related to Λ-vortex (Λ-shaped vortex). The formation and development of Λ-vortex was observed by Hama[1] and Hama and Nutant[2]. They found that the 'Ω-shaped vortex' was formed in the vicinity of the Λ-vortex tip. Moin[3] investigated the deformation of the vortex loop in a developed turbulent boundary-layer during the bursting phenomenon. Formation of vortices was also observed by Knapp and Roache[4] by means of smoke visualization in air.

Clear understanding of the formation of all the vortical structures(like Λ-vortex and ring-like vortex) and the evolution of vortical packets, of course, becomes very important, since it relates vitally to the formation of the turbulent flow. Therefore, the mechanisms of formation of Λ-vortex and first ring-like vortex structure are critical steps for boundary layer transition. In order to get deep understanding on the late flow transition in a boundary layer, we conducted a high order DNS to study the mechanism of the late stages of flow transition in a boundary layer[5-10]. In our previous work[10], we investigated the origins of Λ-vortex and ring-like vortex and their formation according to our DNS results. It is found that λ_2 iso-surface represents only the rotation center, but it is not necessarily to be the vortex tube. Λ-vortex is really a pair of open rotation cores. The roots of Λ-vortex are not vortex tubes. They are only the aggregation of vortex filaments and act as rotation cores. Vortex ring is not part of the Λ-vortex, they are formed separately and independently. The widely recognized process that the Λ-vortex deforms to ring-like vortex does not exist. The ring vortex structure is generated by shear layer instability near the top edge of the boundary layer. The shear layer was formed by a low speed region generated by ejection due to the rotation effect of the Λ-vortex legs. Thus, the ring-like vortex is not generated by the Λ-vortex directly or by Λ-vortex break down.

The purpose of this paper is a try to further investigate the mechanism of formation of ring-like vortices and also investigate the mechanism of the vortical packet generation in detail and their evolution. The formation and evolution of the first large ring-like vortex structure is studied. In Section II, we give the brief introduction on case setup and the code validation; in Section III, the new findings about our DNS observation of Λ-vortex and ring-like vortices are specified; in Section IV, process and mechanism of the generation and evolution of the first ring-like vortical packet is studied in detail; in Section V, the interaction among the vortical packets is also studied. Finally, we give our conclusions.

II. Case Setup and Code Validation

A. Case setup

The transition process on a flat plate is studied with DNS in this paper. The grid level for our simulation is 1920 $\times$128$\times$241, representing the number of grids in streamwise (x), spanwise (y), and wall normal (z) directions. The grid is stretched in the normal direction and uniform in the streamwise and spanwise directions. The length of the first grid interval in the normal direction at the entrance is found to be 0.43 in wall units (y^+=0.43). The parallel computation is accomplished through the Message Passing Interface (MPI) together with domain decomposition in the streamwise direction. The flow parameters, including Mach number, Reynolds number, etc are listed in Table 1. Here, x_{in} represents the distance between leading edge and inlet, Lx , Ly , Lz_{in} are the lengths of the computational domain in x-, y-, and z-directions, respectively, and T_w is the wall temperature.

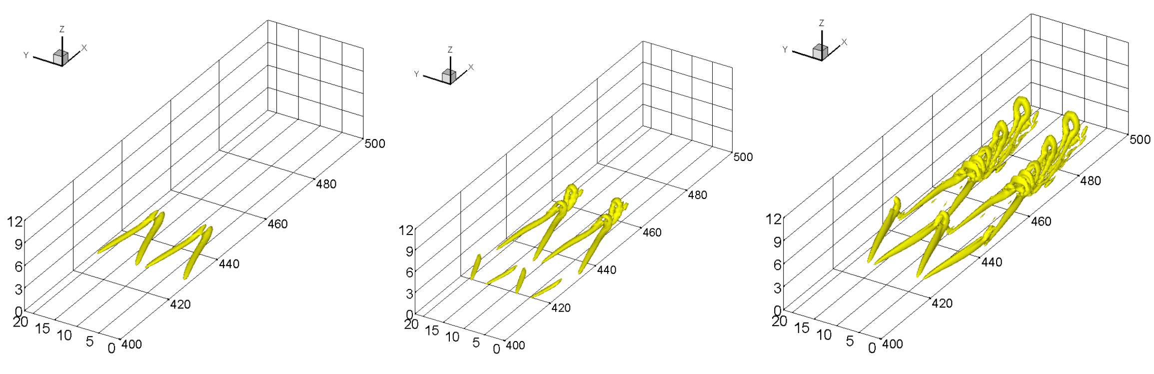
M_∞	Re	x_{in}	Lx	Ly	Lz_{in}	T_w	T_∞
0.5	1000	300.79 δ_{in}	798.03 δ_{in}	22 δ_{in}	40 δ_{in}	273.15K	273.15K

Table 1. Flow parameters

B. Code Validation

The DNS code we use– "DNSUTA" has been validated by NASA Langley and UTA researchers[6,7] carefully to make sure the DNS results are correct. The DNS results are very well validated by comparison with theoretical and experimental data and coincide with other DNS results[7-10].

By this λ_2-eigenvalue visualization method, the vortex structures shaped by the nonlinear evolution of T-S waves in the transition process are shown in Fig. 1. The evolution details are briefly studied in our previous paper[7,8,10] and the formation of ring-like vortices chains is consistent with the experimental work8 (Fig. 2) and previous numerical simulation by Rist and his co-authors (Bake et al[11]).



(a) $t = 6T$ (b) $t = 6.4T$ (c) $t = 7.0T$

Figure 1. Evolution of vortex structure at the late-stage of transition (Where T is the period of T-S wave)

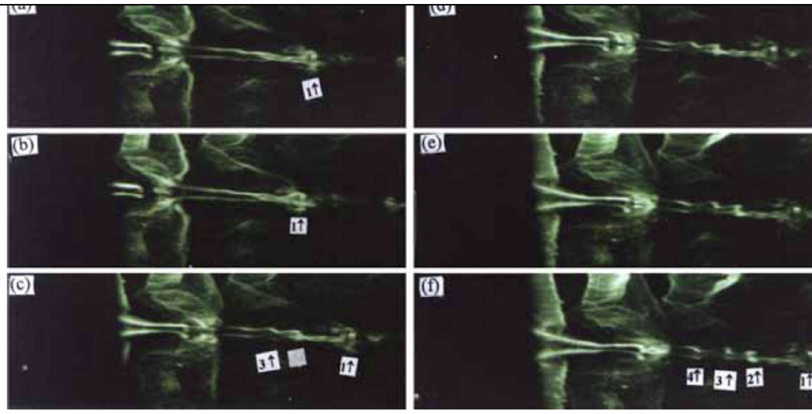
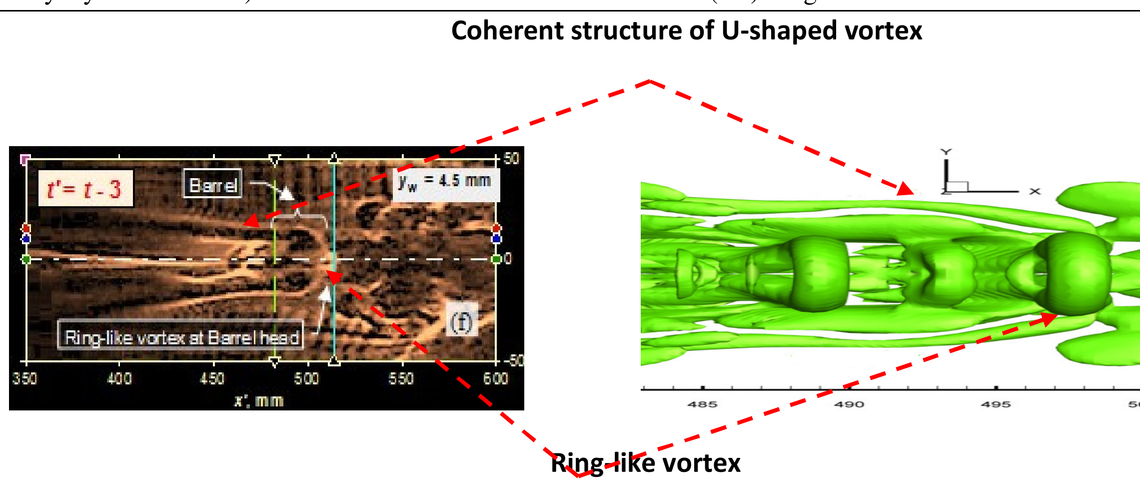


Figure 2. Evolution of the ring-like vortex chain by experiment (Lee et al, 2007)

Fig.3(a) represents an experimental investigation[12] of the vortex structure including ring-like vortex and barrel-shaped head (U-shaped vortex). The vortex structures of the nonlinear evolution of T-S waves in the transition process are given by DNS in Fig. 3(b). By careful comparison between the experimental work and DNS, we note that the experiment and DNS agree with each other in a detailed flow structure comparison. This cannot be obtained by accident, but provides the following clues: 1) Both DNS and experiment are correct 2) Disregarding the differences in inflow boundary conditions (random noises VS enforced T-S waves) and spanwise boundary conditions (non-periodic VS periodic) between experiment and DNS, the vortex structures are same 3) No matter K-, H- or other types of transition, the final vortex structures are same 4) There is an universal structure for late boundary layer transition 5) turbulence has certain coherent structures (CS) for generation and sustenance.



(a). Experiment results given by Guo et al (2010)	(b). DNS result of U-shaped vortex

Figure 3. Qualitative vortex structure comparison with experiment

All these verifications and validations above show that our code is correct and our DNS results are reliable.

III. DNS Observations on the Λ-vortex and Ring-like Vortices

Generally, the concept that the Λ-vortex can self deform to a hairpin vortex directly, is accepted by the transition community. Such a process indicates that the roots of the ring-like vortex will join with the Λ-vortex, and ring-like vortex tube is part of the Λ-vortex tube.

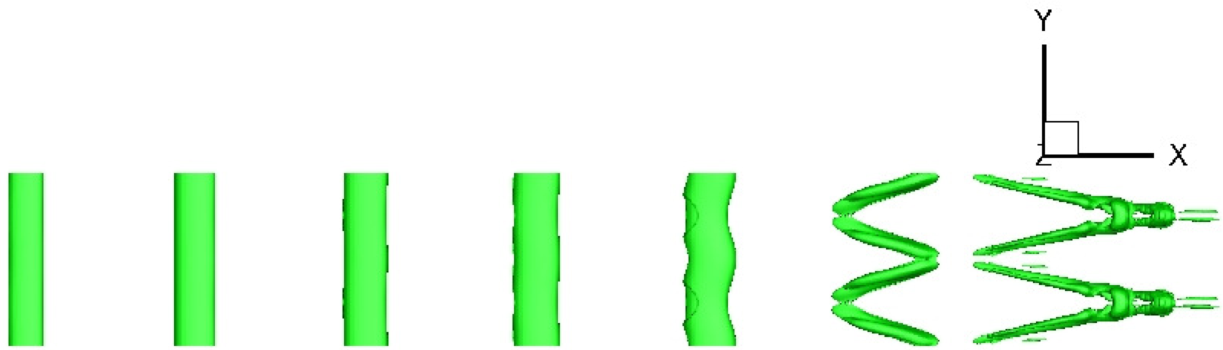


Figure 4. Ring-like vortex and Λ-vortex shown by the Iso-surface of λ_2

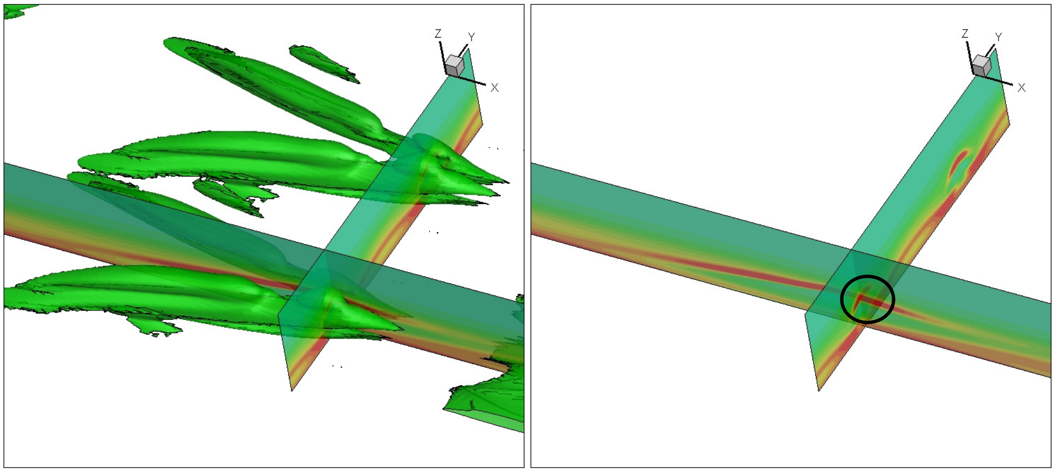
Fig. 4 shows the process which is visualized by the iso-surface of λ_2 from our DNS results. We can see that the Λ-vortex is first formed and the ring-like vortex structure is then formed at the head of the Λ-vortex. In Ref 10, we verified that the roots or legs of Λ-vortex are not vortex tubes since vortex tube does not allow any vortex filaments to cross its surface. According to our DNS observation, the roots of Λ-vortex are only the aggregation of vortex lines but not vortex tubes. In addition, the iso-surface of λ_2 only represents the rotation cores but is not necessary the vortex tubes.

In addition, we also concluded that the ring-like vortices and the Λ-vortex roots are generated separately by different mechanisms[10]. Λ-vortex and ring-like vortex are two different structures. There is no such a process that the Λ-vortex can self deform to a hairpin vortex directly as many literatures indicated. The evolution process of Λ-vortex and ring-like vortex which accepted by the transition community should be revisited.Thus, the formation of Λ-vortex becomes the critical step in the flow transition.

IV. Observations and analysis on the Formation of the First Ring-like Vortex packet (still working on it)

4.1 Formation of the first level vortical structures in a vortical packet

In our previous papers[9,10], it is pointed out that the high shear layer between the roots of Λ-vortex(see Fig. 5) plays an important role in the generation of ring-like vortices. The high shear zone and ring-like vortex are related. Λ-shaped low speed flow at the lower boundary layer is found and it is rolled up by the rotation effects of the roots of the Λ-vortex. Once the low speed zone is formed, a high shear layer would be generated on the upper boundary layer[10]. This is considered as the mechanism of the high shear zone and thus the ring-like vortex(see Fig. 6).



(a) **(b)**

Figure 5. (a) A Λ-vortex, (b) the distribution of streamwise vorticity and stream track on the spanwise plane which is across the Λ-vortex at t=6.1T

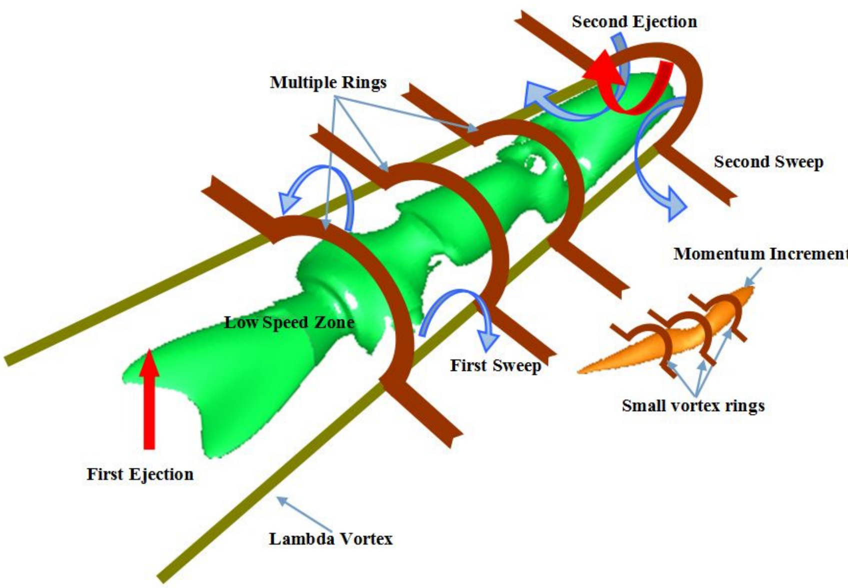
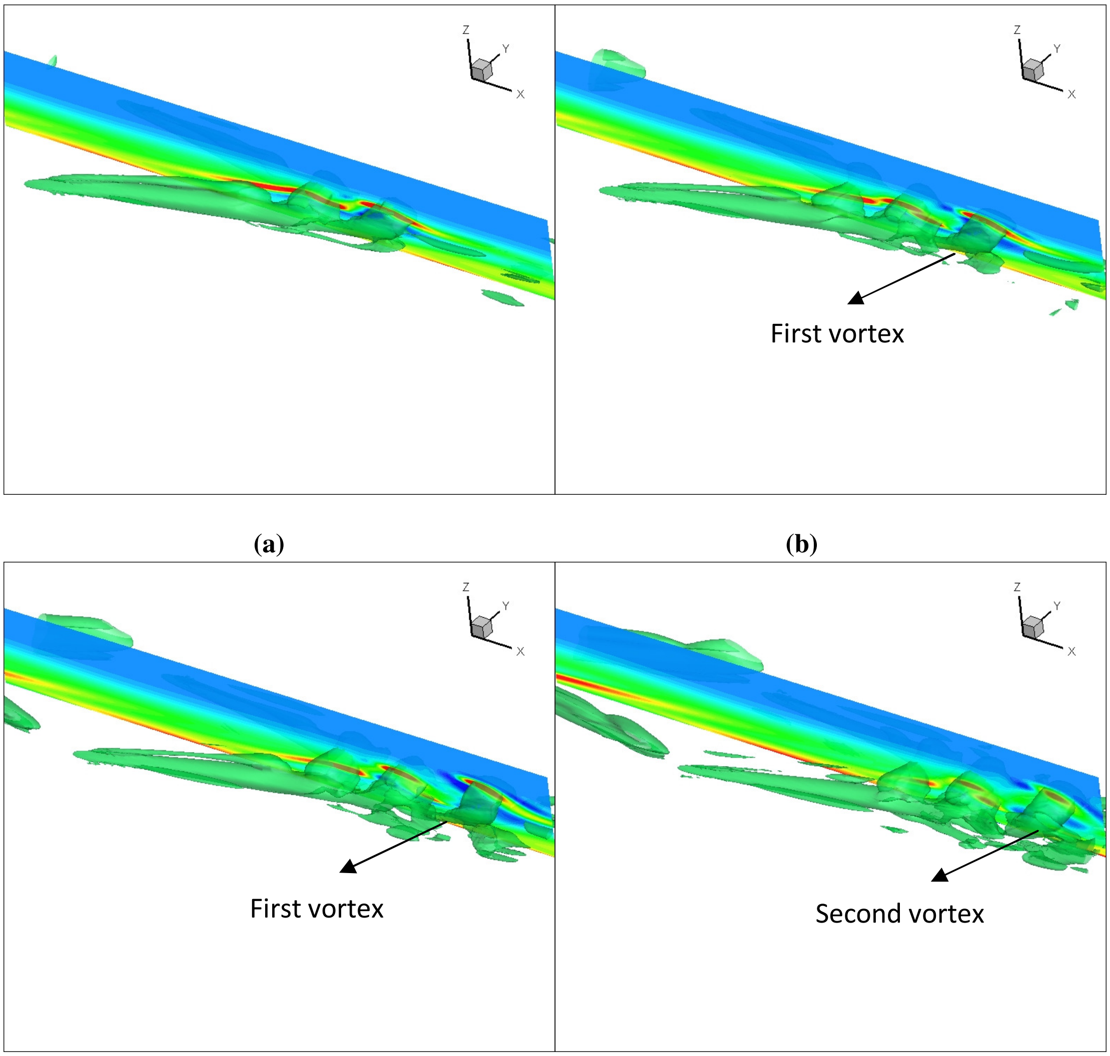


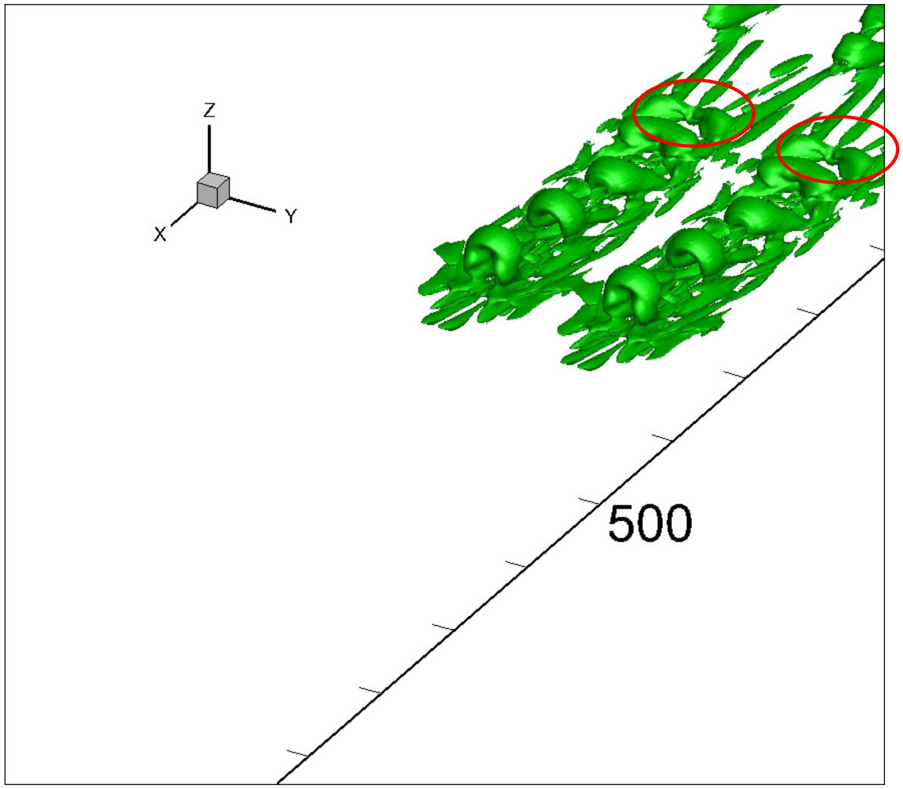
Figure 6: Sketch of mechanism of multiple rings formation and small vortices formation

The shear layer in the middle of Λ-vortex(see Fig. 5b) will finally break down to the vortices. In Fig.7, the iso-surface of ring-like vortices is shown along with the spanwise vorticity distribution on the central plane. It shows that the first breakdown of the shear layer forms the first ring-like vortex (Fig. 7a). After that the shear layer in the upper stream breaks again, and there appears a vortex pair (Fig. 7b). Among this pair, the first vortex is located in a lower position and the second one is higher. The lower one will move to the lower viscous boundary layer due to the induction of the other vortices (Fig. 7d) and finally is dissipated at the boundary (Fig. 7d). Mean while, the higher vortex of the pair forms the second ring-like vortex in upper boundary layer. The generation of the third and fourth ring-like vortices follows the same mechanism (Fig. 7d). The phenomena of unstable shear layer breaking down into vortex pairs and it's relation to the ring-like vortex formation shows that the high shear layer instability generated by the Λ-vortex roots is the key factor in formation of the ring-like vortices. Actually, the high velocity shear layer and the corresponding Kelvin-Helmholtz instability play a key role to attract and gather spanwise vortex filaments and finally lead to the formation of new ring-like vortices.

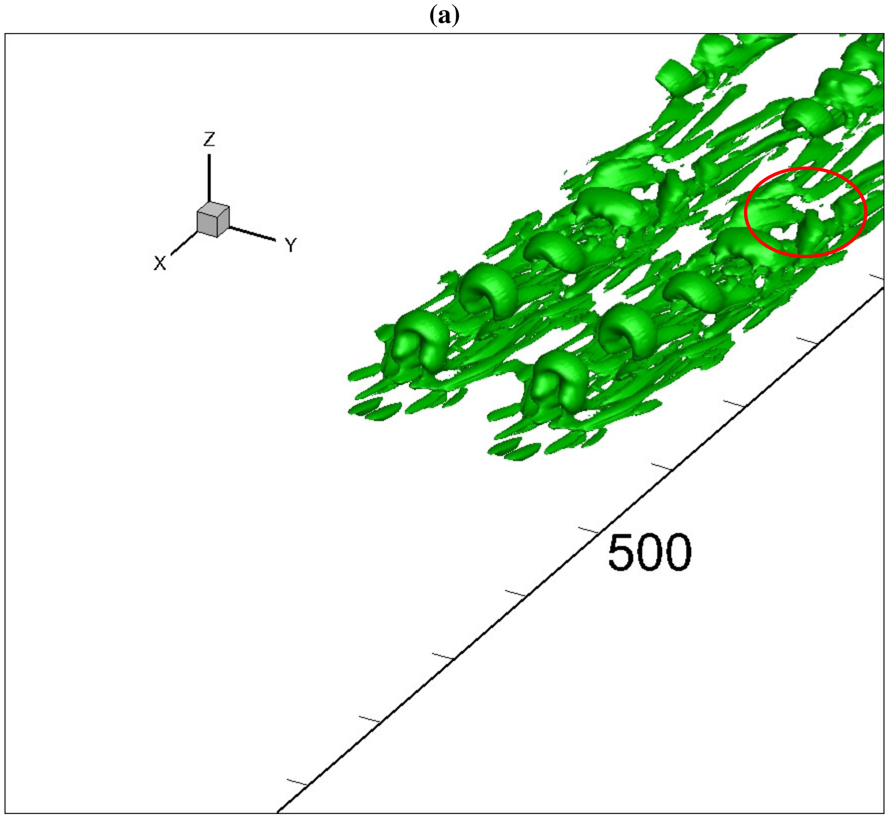


(c) (d)

Figure 7. Iso-surface of Ring-like vortex and spanwise vorticity distribution on the central plane (a) t=6.3T (b) t=6.4T (c) t=6.5T (d) t=6.7T



(a)

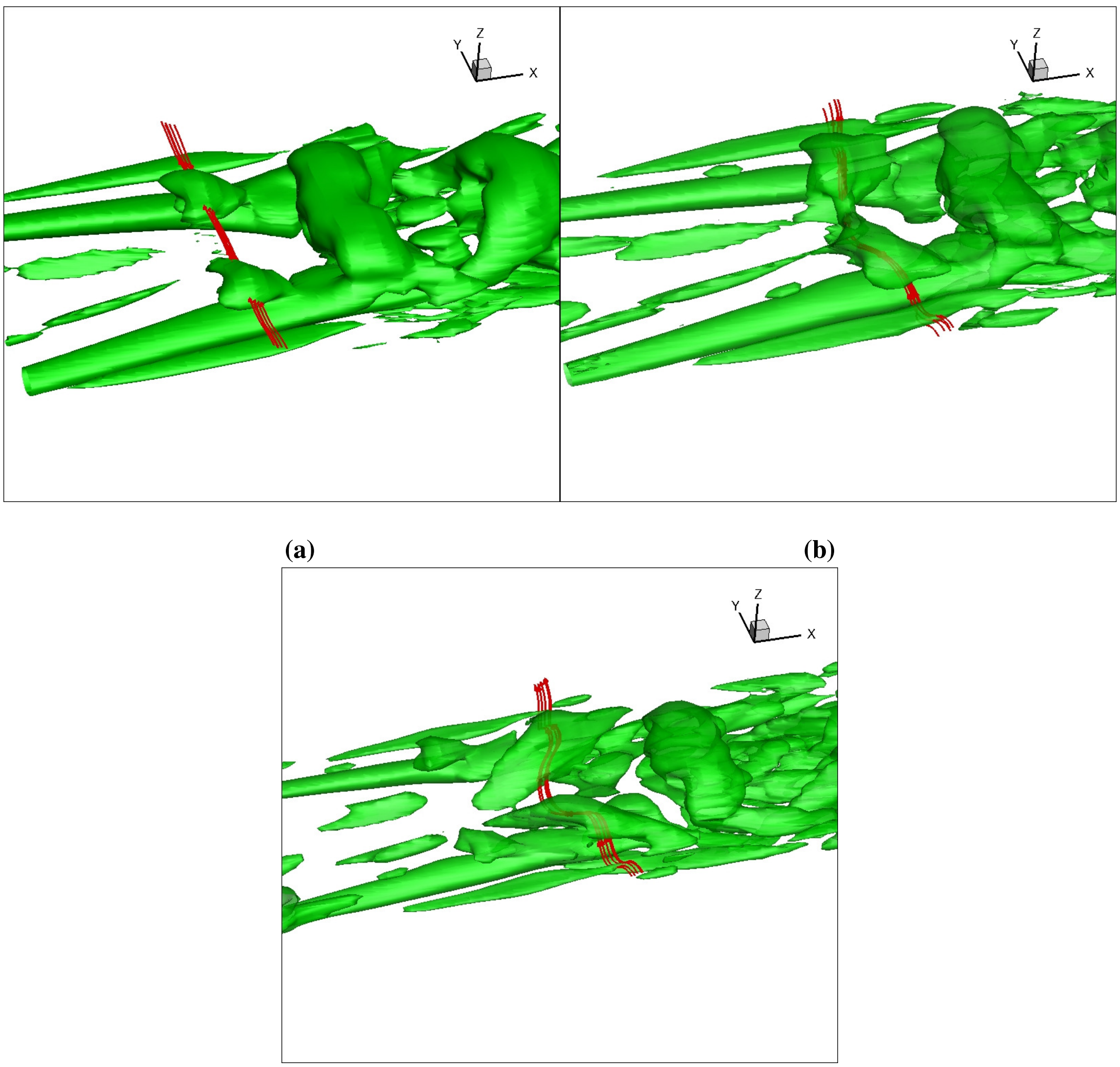


(b)

Figure 8. Vortex structure by λ_2 at sequential time steps (a) t=7.0T (b)7.2T

From Fig. 7d we can found that the fouth ring-like vortex is the last vortex structure formed by the high shear layer in the middle of Λ-vortex. The shear layer becomes weak and finally disappears after the generation of fourth ring-like vortex. However, Fig. 8a shows a vortical packet with 5 ring-like vortices at t=7.0T. After that, the fifth ring-like vortex seems to break down into an reverse Λ-shaped structure, the sixth reverse Λ-shaped structure is also generated soon (Fig.8b). However, in any case, vortex tube cannot breakdown, and vortex structure is quite stable.

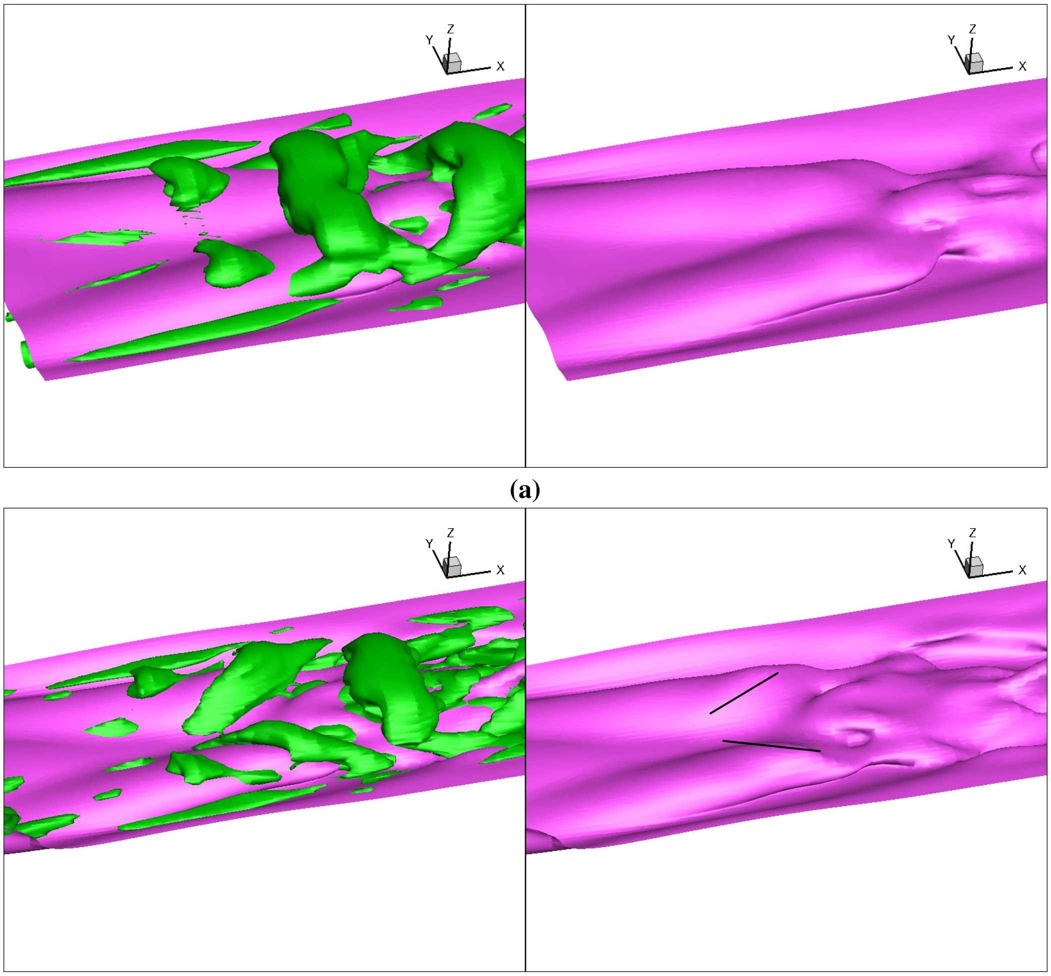
To study the mechanism of the fifth λ_2 structure, vortex filaments are investigated in Fig. 9 at three sequential time steps during its generation. We can see that in the beginning the fifth vortex structure is verified to be a vortex tube since all the filaments are constrained inside (Fig. 9a, b). However, when it forms a reverse Λ structure, the fifth λ_2 structure fails to be a vortex tube since those filaments perpetrate its surface.



(a) **(b)**

(c)

Figure 9. Vortex filaments in the fifth λ_2 structure at (a) t=6.85T (b) t=6.95T (c) t=7.15T

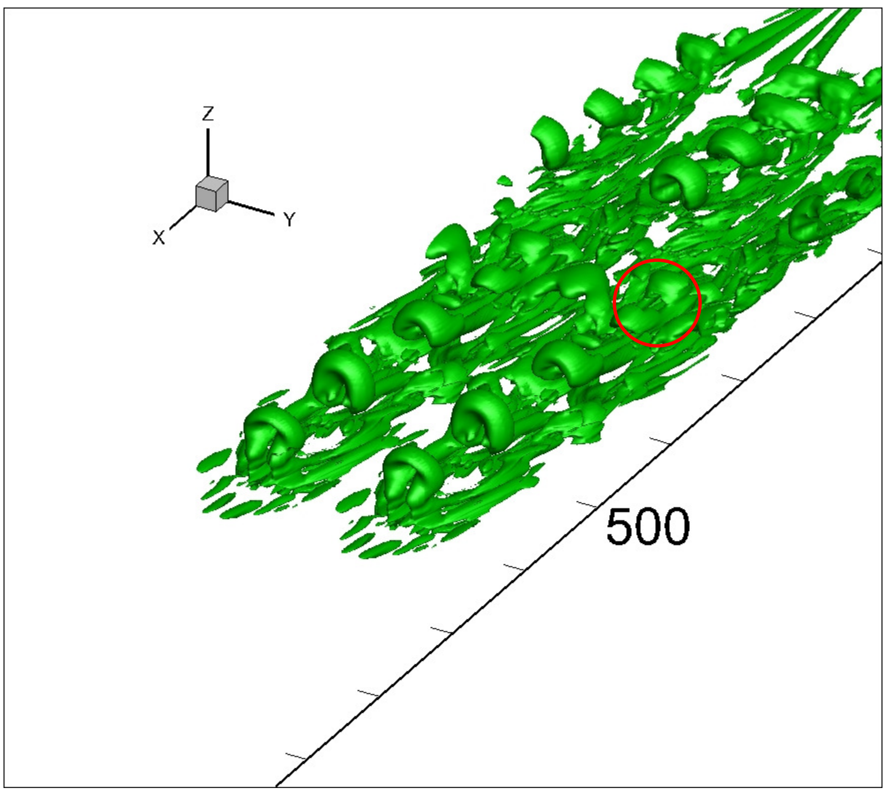


(a)

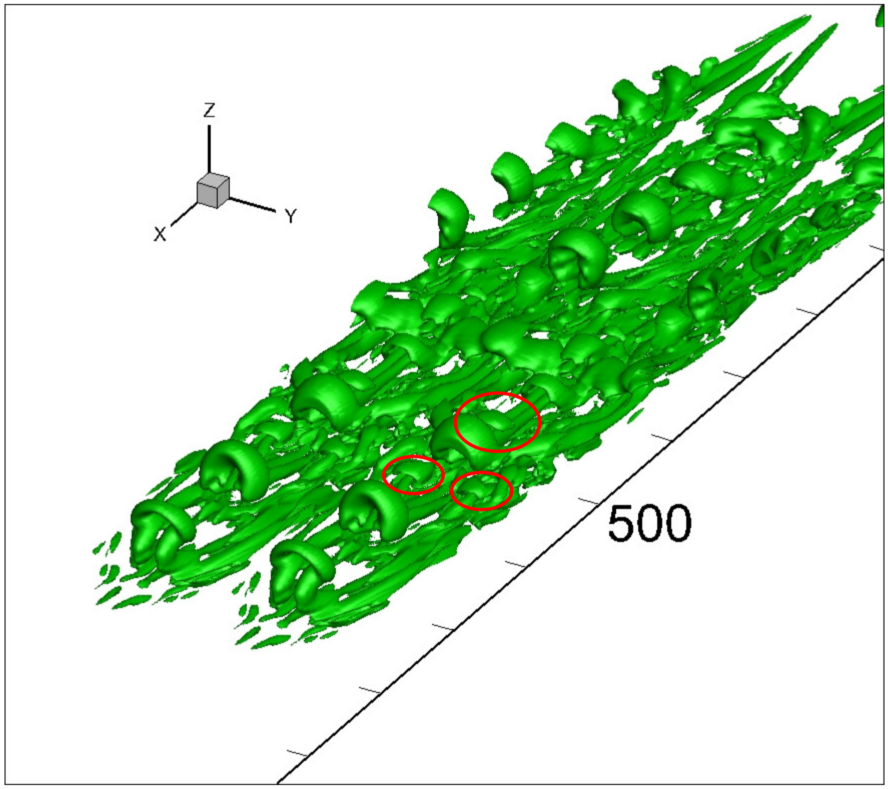
(b)

Figure 10. Iso-surface of λ_2 structure(green) and streamwise velocity with $u=0.5U_\infty$ (purple) at (a) t=6.85T (b) t=7.15T

Fig. 10 gives the iso-surface of λ_2 structure and streamwise velocity. It shows that although the low speed zone which forms the high shear layer at the central position of Λ-vortex disappears in the upper stream of the fourth ring-like vortex, there are still two low speed zones above the two roots of Λ-vortex. Two sides of the fifth vortical structure is generated at the upper bound of the two low speed zones simultaneously due to the shear layer instability, which is in a good agreement with the vortex filaments distribution in Fig 9a. Since the vortex filaments cannot be broken, they also concentrate in the middle and thus makes the two sides of the fifth vortical structure jointed together to be the fifth ring-like vortex at t=6.95T(Fig. 9b). However, the preceding ring-like vortex (the fourth one) influences the fifth a lot after that. When the fourth ring-like vortex becomes stronger, the ejection effect (see Fig 6.) changes the shape of the low speed zones much (see Fig. 10b). A reverse Λ-shaped low speed zone is formed under the fifth vortical structure. This makes the fifth vortical structure evolve to reverse Λ-shape as well due to the shear layer instability. However, the reverse Λ-shaped low speed zone cannot generate a reverse Λ-shaped vortex tube filled with vortex filaments since the flow is still dominant by the streamwise velocity component. It can only generate a Λ-shaped rotation core which is illustrated by the iso-surface of λ_2. This answers why we have the vortex filaments distribution pattern in Fig. 9c. In other words, iso-surface of λ_2 is a rotation core, but vortex tube is a gathering of vortex filaments, which can never break down.



(a)



(b)

Figure 11. Vortex structure by λ_2 at sequential time steps (a) t=7.6T (b) t=7.9T

After the generation of the sixth vortical structure(reverse Λ-shaped structure), no more vortical structure in the downstream is observed to generate in the first vortical packet since the vortical packet in the downstream catches up and the vortical structures become more complicated(see Fig. 11). However, in the upstream, some secondary vortical structures become to be generated in the first vortical packet(see Fig. 11a,b). These secondary vortical structures are studied in the next part.

4.2 Formation of the secondary level vortical structures in a vortical packet

Once the ring-like vortex is formed the second ejection and sweep(see Fig. 6) could become very strong and thus the secondary momentum deficit or increment zone would be formed. On the upper bound of these momentum deficit or increment zone, there also exist high sheer layers and the shear layer instability again will generate the secondary vortical structures.

At t=7.6T(see Fig. 11a), the fouth ring-like vortex generates another ring-like vortex in the downstream due to it's ejection. The same phenomenon is observed behind the third ring-like vortex at t=7.9T(Fig. 11b).

Another kind of secondary ring-like vortical structure is observed in Fig. 11b on the lower boundary, between the second and third ring-like vortices. Fig. 12 shows the enlarged secondary ring-like vortex between the second and third first level ring-like vortices. To study the mechanism of these secondary vortices, Fig. 13 shows the vorticity distribution besides the first level vortical structures. A strong shear layer is observed on the spanwise plane(see Fig. 13a, in the blue circle) due to the second ejection of ring-like vortices(Fig. 6). This high shear layer finally breaks down and forms the secondary vortices in Fig. 12. In Fig. 14, the iso-surface of streamwise velocity and vortex lines pass through the secondary vortices are provided with the vortical structure, it can see clearly that the mechanism of the generation of these secondary vortical structures is shear layer instability again.

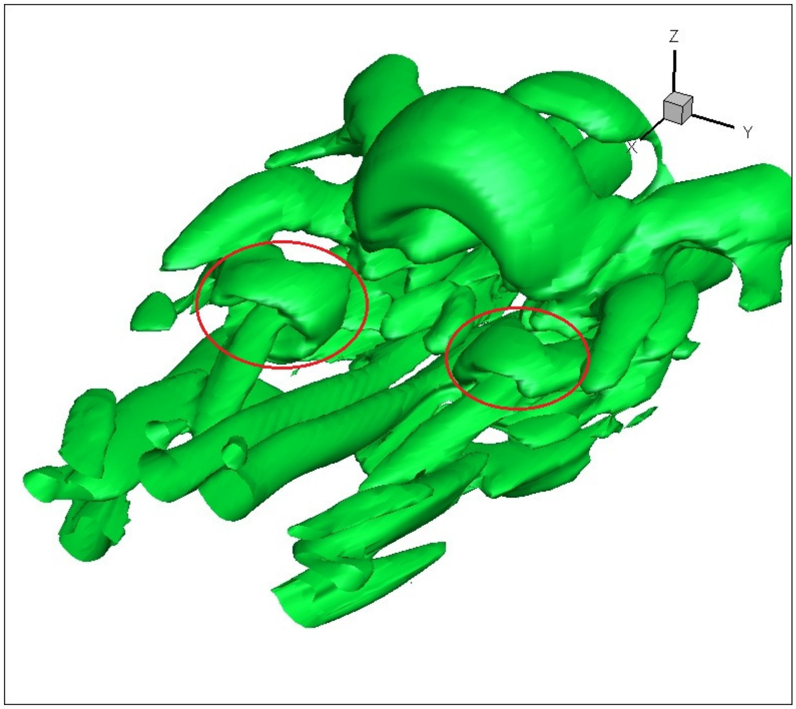


Figure 12. Vortex structure by λ_2 for the secondary ring-like vorices at t=7.96T

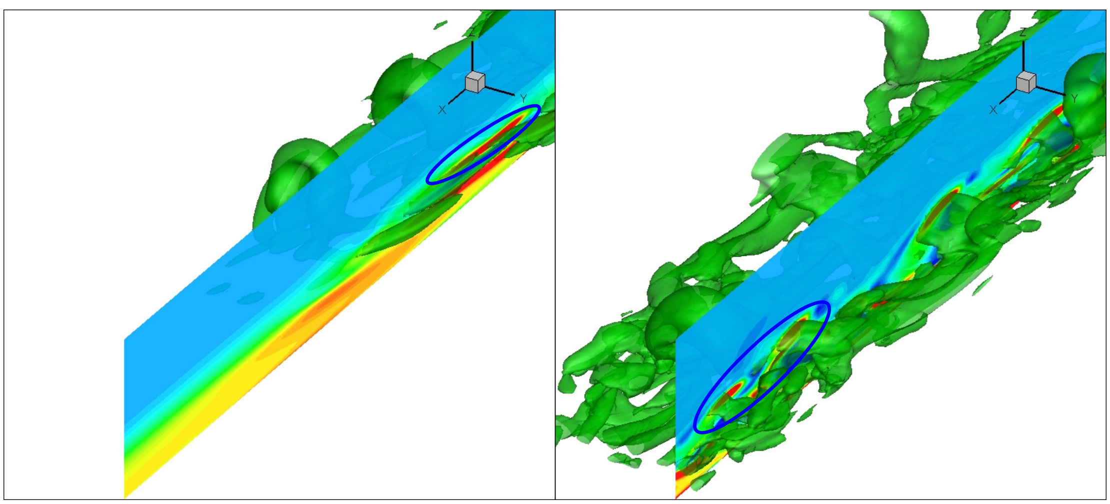


Figure 13. Vortex structure by λ_2 and spanwise vorticity distribution on a streamwise plane at (a) t=7.25T (b) t=7.96T

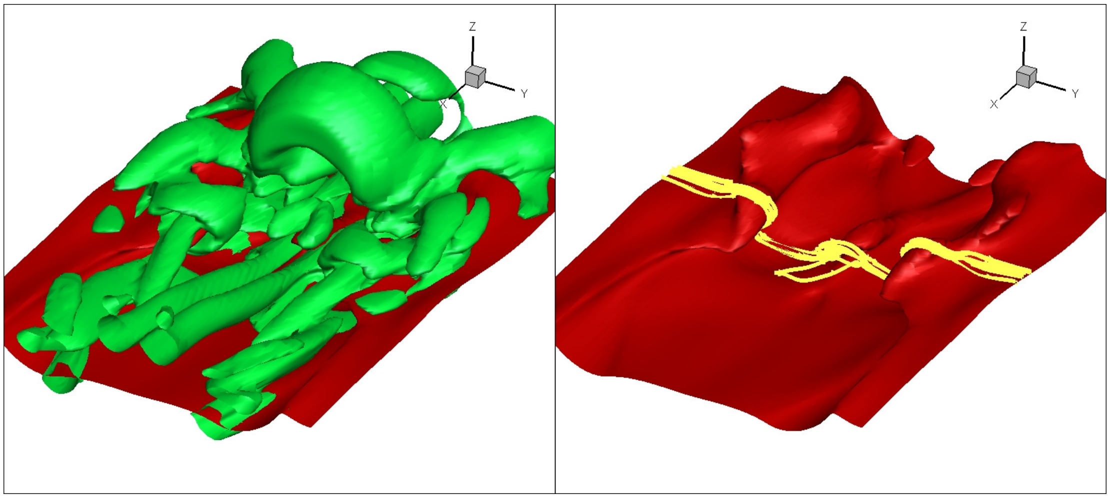
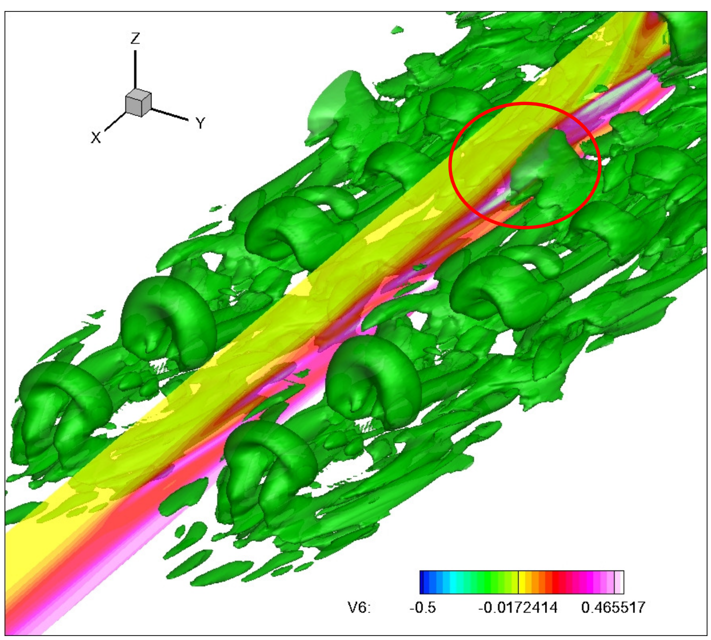


Figure 14. Vortex structure(green) by λ_2 , iso-surface of streamwise velocity(red) with U=0.6U$_\infty$, and vortex lines(yellow) passing through the secondary vortices at t=7.96T

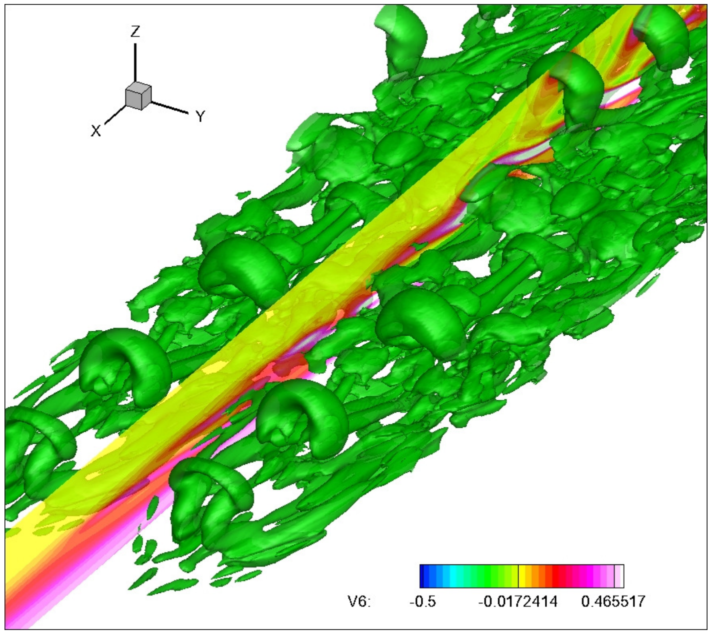
IV. DNS Observations on the Interaction among Different Vortex packet (still working on it)

5.1 Formation of the vortical structures between two spanwise vortical packets

With the evolution of vortical packets, the vortical structures will contentiously induce or indirectly create more vortical structures(both spanwise and streamwise vortical structures, see Fig. 11) and bring the energy from the free stream to the boundary layer. During this process, the spanwise neighboring vortical packets become mutual contacted and joined together. In the meanwhile, the streamwise vortical structures belong to the 2 spanwise neighboring vortical packets will together generate new low speed zone and thus jointed spanwise vortical structures(Fig. 11b,15).



(a)



(b)

Figure 15. Vortex structure by λ_2 and spanwise vorticity distribution on a streamwise plane at (a) t=7.6T (b) t=7.9T

5.2 Formation of multi-layer vortical packets

Since the first level ring-like structure travels faster than the spanwise vortical structure(such as Λ-vortex) in the lower boundary layer, the vortical packet in the downstream will catch up with the one in the upper stream. Thus, multiple layer of vortical packets will form in the boundary layer(see Fig. 16, 17). Finally, the typical forest of vortical structure in the boundary layer will be formed.

Detailed investigation of the interaction between vortical packets will give more information about the the evolution of transition process in boundary layer at very late stage.

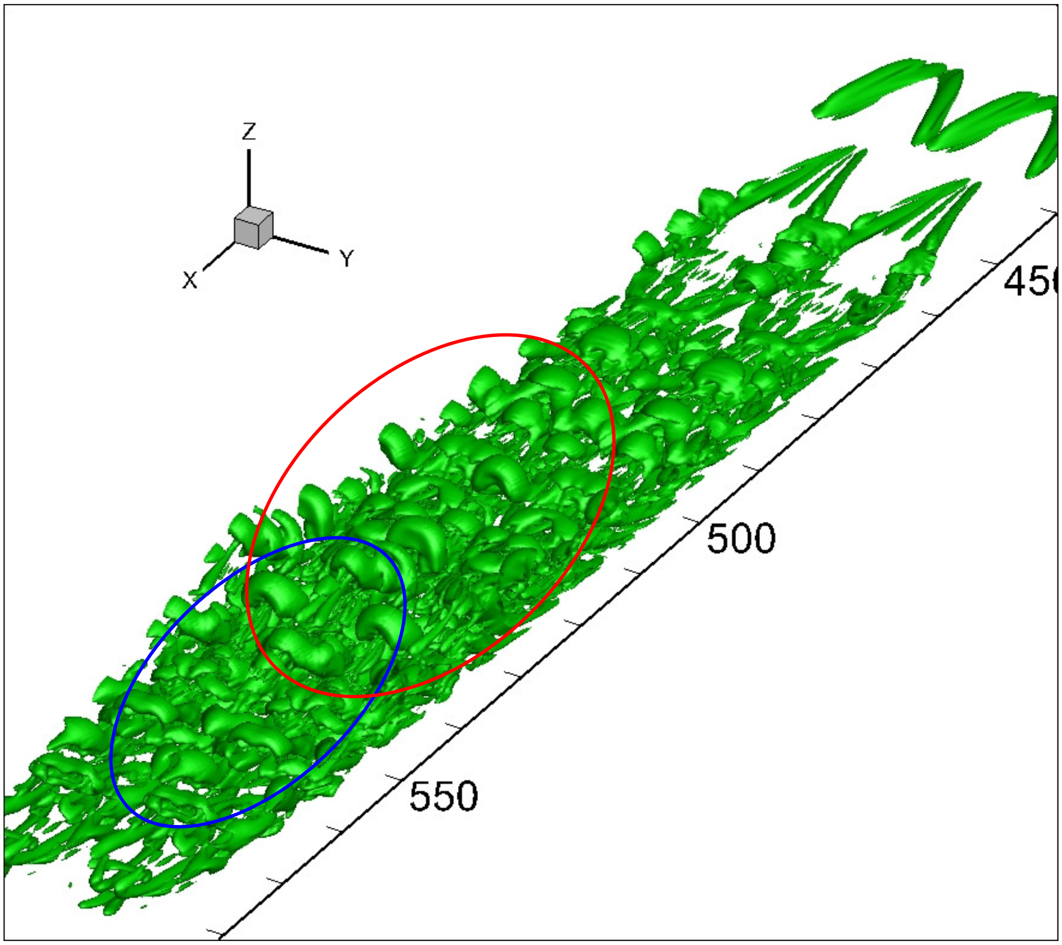


Figure 16. Vortex structure(green) by λ_2 at t=9.0T

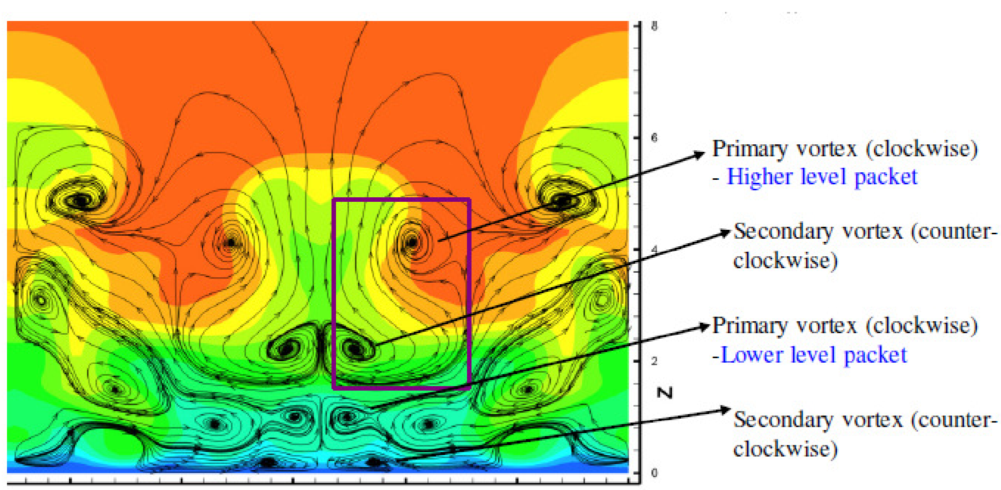


Figure 17. Velocity distribution and stream trace on a spanwise plane

VI. Conclusions

In this paper, the mechanisms of the formation of the vortical packets and their mutual interactions are studied by DNS. It is found that the shear layer instability is the key of the ring-like vortex generation. On the other hand, in the process of evolution of vortical packets, the vortical structures(including vortex tubes and other kind of rotation cores) will continue to create high shear layers in the boundary layer by both sweeps and ejections. The generation and evolution process of the first ring-like vortex structure is studied in detail. The interaction between vortical packets and the multi-layer vortical packets are also studied.

VII. Acknowledgments

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