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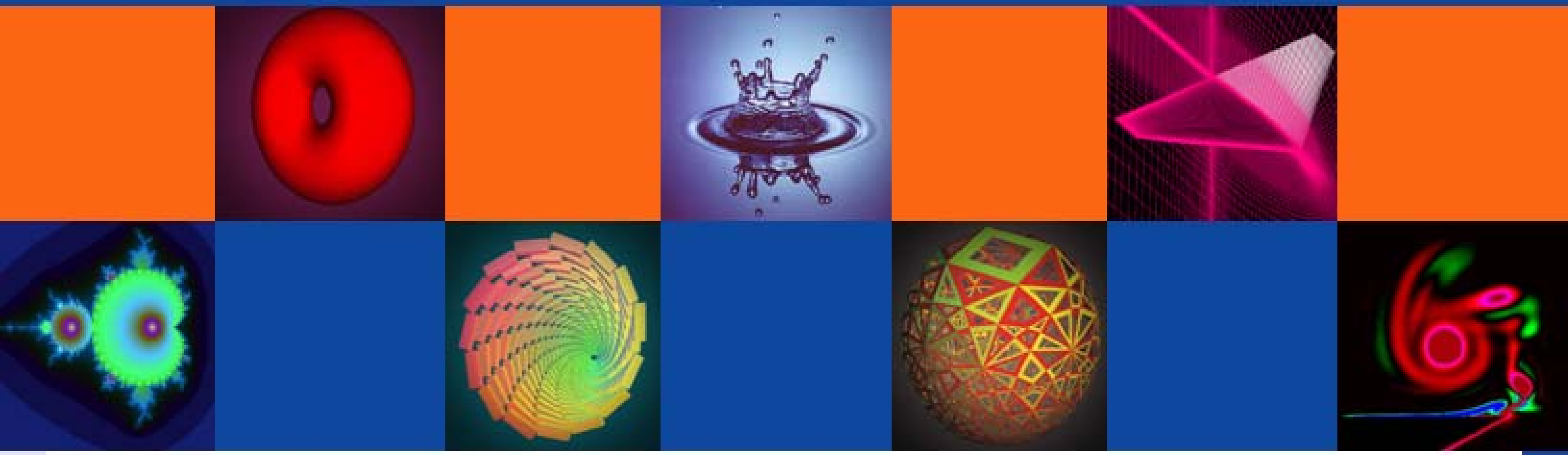

DNS for Ring - Like Vortices Formation and Roles in Positive Spikes Formation

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DNS for Ring - Like Vortices Formation and Roles in Positive Spikes Formation

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A high order direct numerical simulation (DNS) of flow transition over a flat plate at a free stream Mach number 0.5 has been carried out. Formation and development of typical 3-D perturbations, typically shown as Λ-vortices, hairpin vortices and ring-like vortices were observed. Numerical results show that there is a strong downward motion excited by every ring-like vortex at two sides of the structure centerline. Such downward motions lead to formation of intensive high speed streaks associated with positive spikes observed by experiment in near wall region. Superimposition of two downward motions induced by the first and second ring – like vortices results in maximum streamwise velocity disturbance.

Ⅰ. Introduction

The flow transition process from laminar to turbulent flow in boundary layer is a basic scientific problem in modern fluid mechanics and has been the subject of study for over a century. Many different explanations of the mechanism involved have been tried based on several investigations. The early stages of the transition process in boundary layer, including the stages of wave growth, as well as the initial formation of the Λ-structure, are basically understood. The late stages, including the evolution and breakdown of coherent vertical structures (hairpin vortex and ring-like vortex), are still not understood as well as the earlier ones. In recent study, researchers found that the ring – like vortices (associated with the well – known negative spikes) induce some rather intensive positive velocity fluctuations (positive spikes) in the near wall region[1~2]. In the present paper, we perform the DNS of spatially evolving compressible flat-plate boundary layer transition process at a March number of 0.5. The goal of the present work is to shed some light on the formation of ring-like vortices and their roles in the formation of the positive spikes.

Ⅱ Numerical Method and Computational Procedure

The governing equations we used are the three-dimensional time-depaendent compressible Navier-Stocks equations [3]. A sixth order compact scheme is used for spatial discretization in the streamwise direction and wall normal direction [4]. In the spanwise direction, where periodic conditions are applied, the pseudo-spectral method is used. The governing equation is solved explicitly by a 3rd order TVD Runge-Kutta scheme [5]. The adiabatic and the non-slipping conditions are enforced at the wall boundary on the flat plate. On the far field and the outflow boundaries, the

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non-reflecting boundary conditions [6] are applied. The inlet boundary condition is two dimensional laminar flat-plate boundary layer flow profile with enforced disturbances. The inflow disturbance includes a two-dimensional Tollmien-Schlichting (T-S) wave and a couple of conjugate three-dimensional T-S waves.

$q = q_{lam} + A_{2d} q'_{2d} + A_{3d} q'_{3d}$, where

$x = 300 - 1100\,\delta_{in}; \quad \delta_{in} : \textit{inlet boundary layer displacment thickness}$

$q_{lam} : \textit{Blasius solution}$

$q'_{2d} : \quad 2D \quad T-S \quad Wave$

$q'_{3d} : \quad A \quad pair \quad of \quad oblique \quad T-S \quad Waves$

$\omega = 0.114027$

$\alpha = 0.29919 - i\,5.09586 \times 10^{-3}$

$\lambda_x = \dfrac{2\pi}{\alpha_r}$, α_r *is the wave number in x and* λ_x *is the wavelength*

$\lambda_y = \dfrac{2\pi}{\beta_r}$,

$A_{2d} = 0.03$

$A_{3d} = 0.01$

The T-S wave parameters are obtained by solving the compressible boundary layer stability equations.

The computational domain is displayed in Figure1. The grid level is $1920 \times 128 \times 241$ representing the number of grids in streamwise (x), spanwise (y), and wall normal (z) directions.

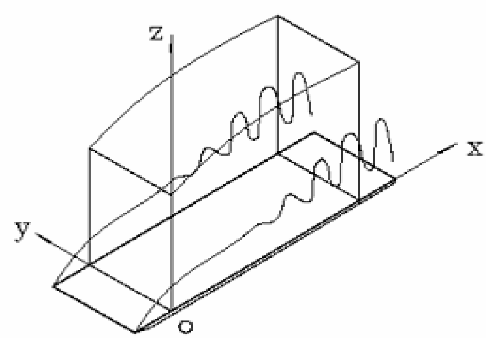


Figure 1. Computational domain

The parallel computation is accomplished through the Message Passing Interface (MPI) together with a domain decomposition in the stremwise direction. The computational domain is partitioned into N equal-sized subdomains along the streamwise direction. N is number of processors used in the parallel computation. The Mach number is 0.5. The Reynolds number at the inflow boundary based on the displacement thickness and the free-stream velocity is 300. The length of computational domain along the direction Lx is $800\,\delta_{in}$, the width along the spanwise direction Ly is 22 δ_{in}, and height at the flow boundary Lz is 40 δ_{in}.

$Ma_\infty = 0.5$
$Re = 1000$
$x_{in} = 300.79\delta_{in}$
$Lx = 798.03\delta_{in}$
$Ly = 22\delta_{in}$
$Lz_{in} = 40\delta_{in}$
$T_w = 273.15K$
$T_\infty = 273.15$

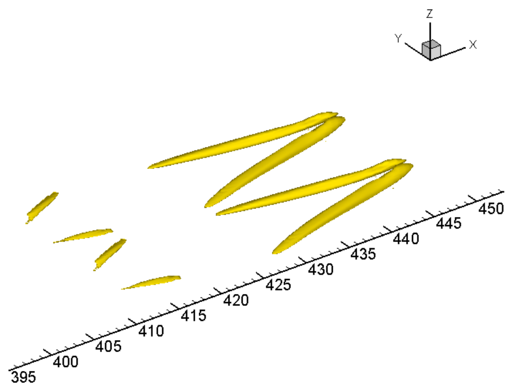
Table1. Flow parameters

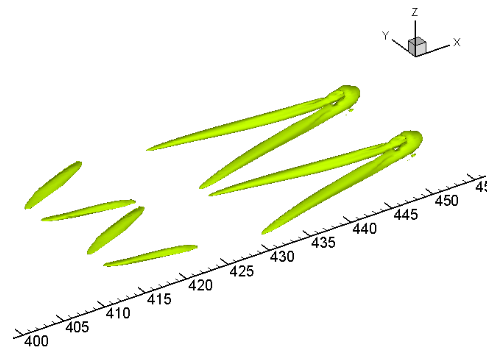
The inflow boundary condition is given with Blasius solution and enforced T-S modes:

Ⅲ Results and Discussion

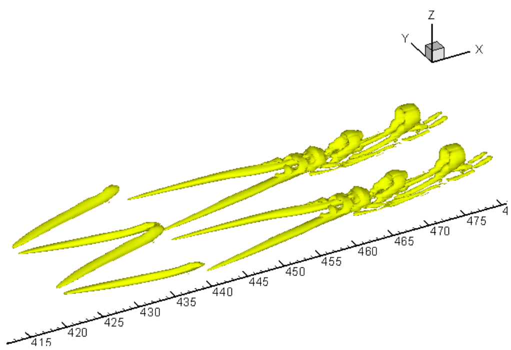
A. Ring-like vortices formation

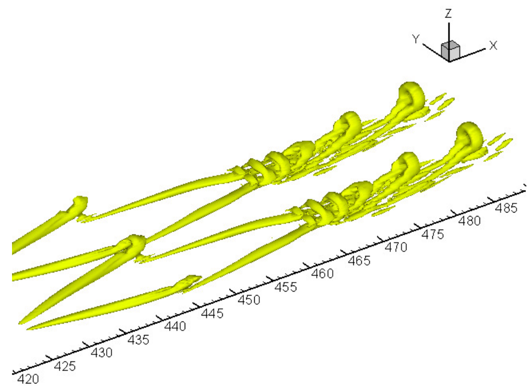
In Figure2, vortex structures at four different instants are presented with help of λ_2-method. From these pictures, formation process of ring-like vortices can be seen very clearly. From figure 2(a), the Λ-vortices formed from peak and valley structures of TS-waves can be seen at two different streamwise locations. The Λ-vortices are close together at the tip and wider apart at the tail. Compared with the Λ-vortices generated later (from x=412 to x=418), the Λ-vortices generated earlier (from x=427 to x=447) are much longer. From figure 2(b), we can see that the Λ-vortices are stretched and moved downstream by the mean flow, the Λ-vortices generated earlier has formed into hairpin vortices. The head of hairpin vortex formed at the tip of legs(x=452) rise up gradually. From figure 2(c), the hairpin vortex has developed into ring –like vortices. The ring –like vortex generated later is far away from the wall compared with earlier ones. At this moment, the Λ-vortices generated later (from x=423 to x=440) has stretched completely. In figure 2(d), we found that the ring –like vortices propagate downstream and more ring–like vortices are generated. At this moment, the Λ-vortices generated later (from x=425 to x=445) has developed into hairpin vortices.





(a) t=6T (b) t=6.2T





(c) t=6.8T (d) t=7T

Figure2 Vortex visualization at four different times Iso-level λ_2=-0.004

B. Positive spikes formation

In figure2 (d), two trains of ring –like vortices are formed from x=465 to x=490. The corresponding spanwise coordinate y are 5.5 and 16.5 respectively for the central line of ring–like vortices. We will further pay more attention to the ring–like vortices at y equals to 5.5. From figure 3, the contour of velocity disturbance u in the (x, z) plane at t=7T (x=4.2) are presented. We can see that very intensive streamwise velocity streaks are appeared in the near wall region at two sides of central line of ring –like vortices. Two large velocity disturbances of u are located at x=481 and x=474, where the latter are more notable when the maximum value reaches to 0.4. These large velocity disturbances of u are corresponding to the positive spikes seen in a time history. The details of positive spike forming process are shown in Figure 4. From figure 4 (a) to figure 4(d), we can see there is a strong downward motion induced by the first ring-like vortex.

Such downdraft motion leads to the formation of intensive, strongly localized high speed spots in the near wall region at two sides of central line of the ring –like vortices. From figure 4(e) to figue4 (f), we can see that, besides the high speed spots generated by the first ring–like vortex, a pair of high speed spots generated by downward motion induced by the second ring – like vortex appear in a little far away from the wall. The downward motions induced by first and second ring–like vortex superimpose gradually. This results in the appearance of the maximum velocity disturbance of u at x=474.

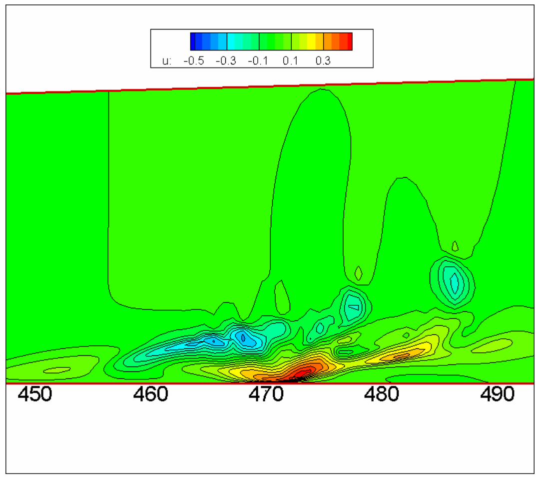
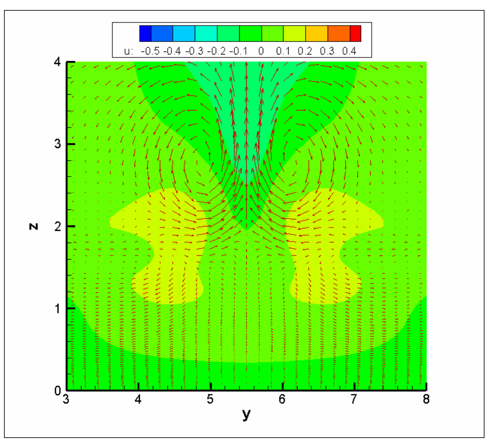
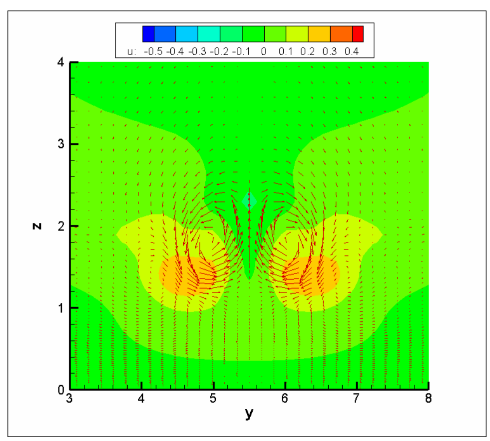


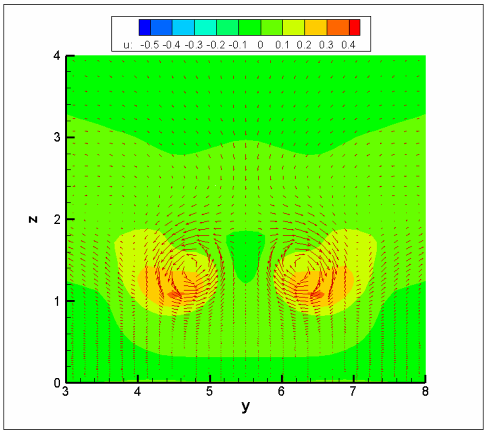
Fig 3 Contour of velocity disturbance u in the (x , z) plane in t=7T (x=4.2)



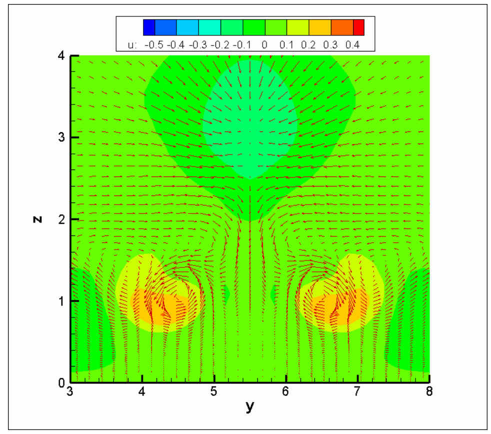
(a) x=485



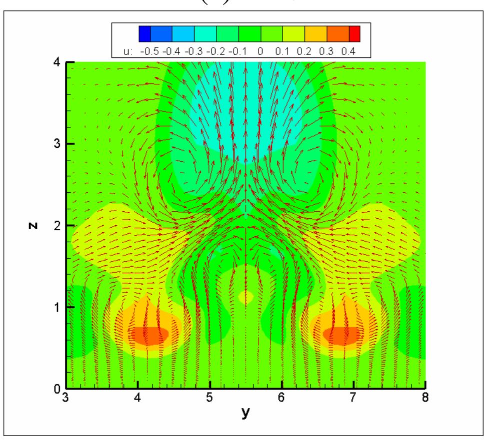
(b) x=483



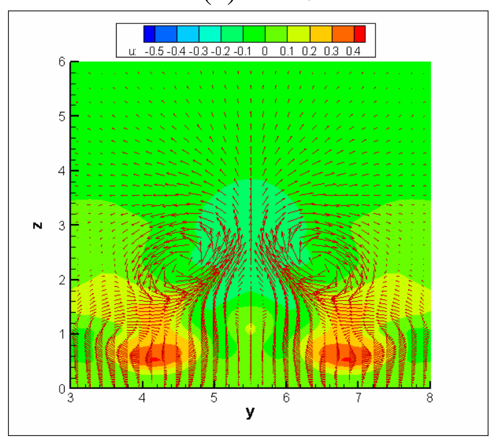
(c) x=481



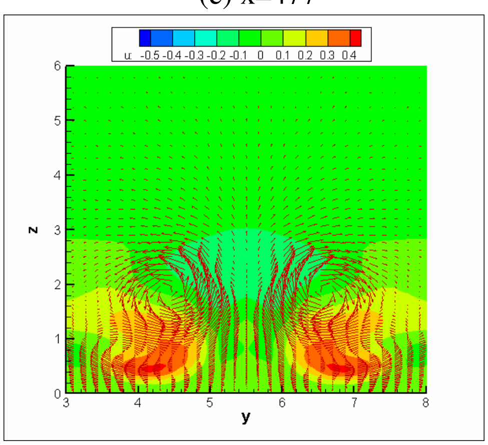
(d) x=479



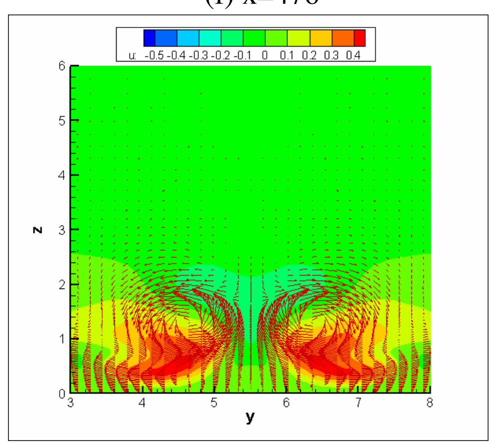
(e) x=477



(f) x=476



(g) x=475



(f) x=474

Fig 4 Contours of velocity disturbance u in the (y , z) plane together with velocity vector field (v , w) in t=7T

Ⅳ Conclusions

Understanding the ring-like vortices formation and their roles in the positive spikes formation is very important to investigate the turbulence production mechanism occurred at late and super late stages of transitional boundary layer. In this paper, we have performed a direct numerical simulation for the boundary layer flow over a flat plate in a March number of 0.5. The numerical results show clearly the formation process of ring –like vortices. The positive spikes which appeared in the near wall region are formed by strong downward motions induced by ring–like vortices. Superimposition of two downdraft motions induced by the first and second ring – like vortices result in maximum streamwise velocity disturbance.

Acknowledgements

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