Parallel DNS for Flow Separation and Transition around Airfoil

Li Jiang and Chaoqun Liu[*]

Department of Mathematics
University of Texas at Arlington
456 PKH, Box 19408, Arlington, TX 76019-0408, USA

Direct numerical simulation (DNS) for flow separation and transition around a NACA 0012 airfoil with an attack angle of 4^0 and Reynolds number of 100,000 is performed by MPI parallel computation. The details of the flow separation, formation of the detached shear layer, Kelvin-Helmoholtz instability (inviscid shear layer instability) and vortex shedding, interaction of non-linear waves, breakdown, and re-attachment are obtained and analyzed. Though no external disturbances are introduced in the baseline case study, the self-excited mechanism is observed, which may reveal the origin of the disturbance for airfoil with attack angle. The power spectral density of pressure shows the low frequency of vortex shedding caused by the Kelvin-Helmoholtz instability still dominates from the leading edge to trailing edge. The simulation shows that the nonlinear wave interaction and breakdown is driven by the generation and growth of the stream-wise vortex which leads to the deformation, stretching, and eventually breakdown of the shedding prime vortex.

Intruduction

Flow transition in separation bubbles is a classic topic and has been studied for many years (Boiko et al, 2002). However, most of work were focused on flow around a hump placed on a flat plate (Musad et al, 1994) or for a blunt leading edge (Yang & Voke, 2001). Flow separation and transition around an airfoil with attacked angle is rarely found in literature due to its complexity. The linear stability theory (LST; see Drazin & Reid, 1981) is mainly a local analysis with assumption of parallel base flow. The parabolized stability equations (PSE; see Bertolotti, 1992) assumes a steady base flow with no elliptic part. These assumptions do not apply for the case of flow separation and transition around airfoil with attack angle where no steady base flow exists and the transition process is dominated by an elliptic process especially in the late stages. Though it is true that the LST and PSE cannot provide a correct prediction for the case, the Kelvin-Helmoholtz instability mechanism in a separated shear layer, which is obtained by inviscid stability theory, still dominates in the early transition stage.

Boundary layer separation and transition exist in many engineering flows around wings and blades. When an adverse pressure on a laminar boundary layer over a surface is strong enough, the laminar boundary layer separates from the surface. Separation and transition in these types of flows are strongly coupled. The instability at the separation zone is widely accepted as dedicated by the Kelvin-Helmholtz mechanism. Transition takes place owing to nonlinear breakdown of spatially growing traveling waves in the separated free shear layer (Yang & Voke, 2001). When the shear layer becomes turbulent, the detached shear layer may reattach to the surface, creating a separation bubble and forming attached turbulent boundary layer. Obviously, the length of the bubble is closely related to when and where the transition takes place. On the other hand, the size of the bubble could directly effect the flight characteristics of the airfoil and the efficiency of the turbine machine. Understanding of the separation and transition mechanism is of great importance in improving design in aircraft and turbo-machinery.

In this work, DNS is used to simulate this transition process to explore the mechanism of flow separation and transition around airfoils. The full compressible Navier-Stokes equations in the generalized curvilinear coordinates are solved using LU-SGS implicit method. The sixth-order centered compact difference scheme is used for spatial derivatives. High-order compact

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[*] E-mail: cliu@omega.uta.edu

filter is employed to reduce numerical oscillation. Parallel computing based on Message Passing Interface has been utilized to improve the performance of the code. Numerical simulations are performed for a NACA0012 airfoil at attack angle of 4^0. The flow and computational conditions are listed in Table 1. Here, U_∞ is the free stream velocity and C is the chord length of the airfoil. The spanwise length is set as $L_y = 0.1C$. Grid is uniform in the spanwise direction and stretched in the wall-normal direction. C-grid is used in the (x, z) plane. Grid distributions in the (x, z) plane and on the airfoil surface are shown in Fig. 1. The computational domain is divided into N subdomains in x direction when N processors are used.

Table 1. Flow and computational conditions.

Re=$U_\infty C/\upsilon$	Ma_∞	**AOA**	$N_x \times N_y \times N_z$	Δx^+	Δy^+	Δz^+
10^5	0.2	4^0	$1200 \times 32 \times 180$	< 13	**<15**	< 1

(a) Grid in (x,z) plane

(b) Grid on the airfoil surface

Fig. 1. Grid distribution (one out of three grid points is shown).

Computational Results

This case has been running on SGI 2000 with 24 processors for around 2000 CPU hours and the time integration has reached $t = 1.282C/U_\infty$. Mean values are obtained by performing averaging in the spanwise direction and in time over a period of $0.5C/U_\infty$.

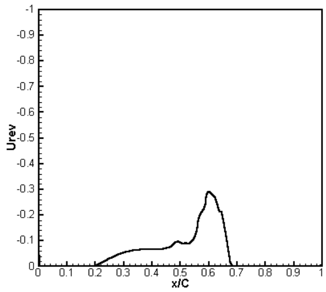


Fig. 2. Mean reverse flow distribution on the suction side, $U_{rev} = \min(\overline{u})$.

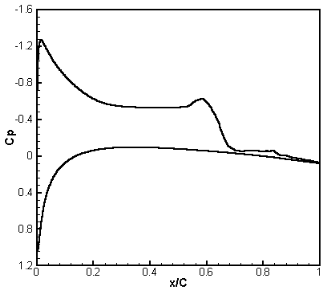


Fig. 3. Mean pressure coefficient.

Fig. 2 shows the maximum reverse flow in the wall normal direction along the suction surface. The separated zone appears form $x/C = 0.22$ to $x/C = 0.85$, where the separated laminar boundary evolves into reattached turbulent boundary layer. Fig. 3 shows the mean pressure coefficient. The flattened region indicates the separation of the boundary layer.

According to our observation, the acoustic waves generated near the trailing edge travel upstream and excite the shear layer near the separation point and the induced fluctuations then grow and travel downstream. The detached shear layer becomes unstable via the Kelvin-Helmholtz instability mechanism and the rapid growth of the instability wave leads to the transition to turbulence. Mean velocity profiles and RMS fluctuation velocity profiles are depicted in Fig. 4. The turbulent velocity profile is found after the reattachment. Transition is observed to take place from $x/C = 0.5$ to 0.8 in the separation region near the reattachment point, where the instability waves grow rapidly and cause the breakdown. The RMS fluctuation streamwise velocity profiles at different locations are displayed in Fig 4 (b). The first location ($x/C = 0.2$) is very close to the separation point. The peak appears at about the center of the boundary layer. At the following two locations, the fluctuations grow and two peaks show up. From $x/C = 0.5$, the fluctuations grow rapidly and three peaks are found at some locations. This evolution is related to the sudden amplification of the upstream perturbations due to the existence of the inflected velocity profile.

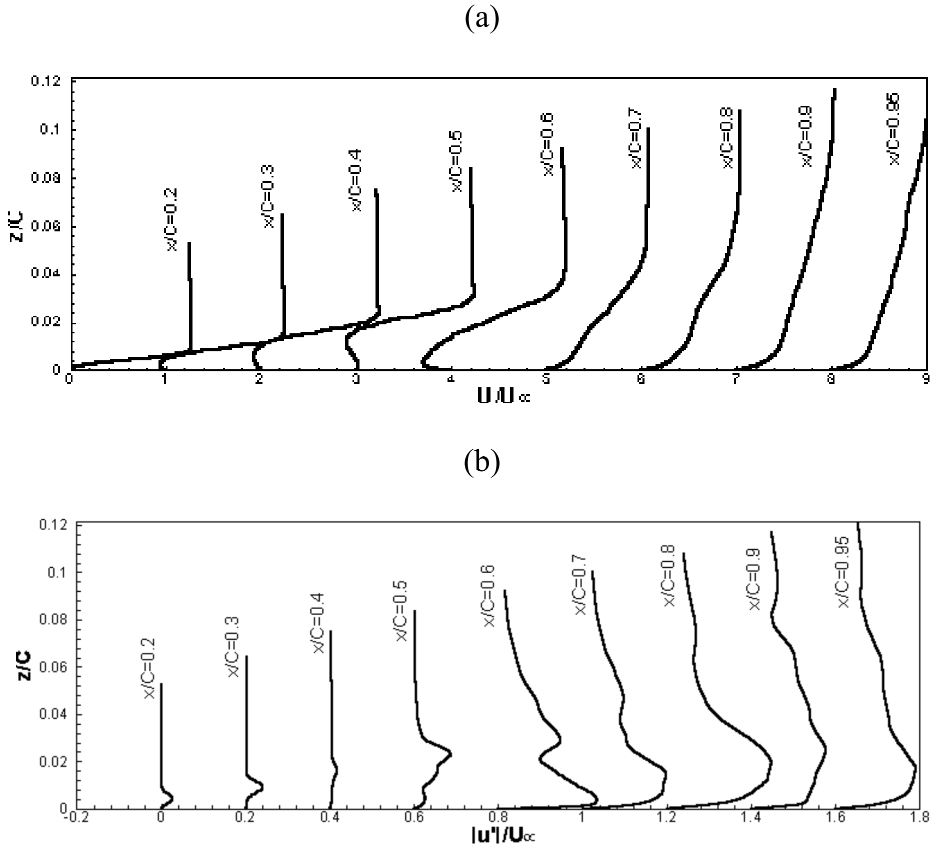
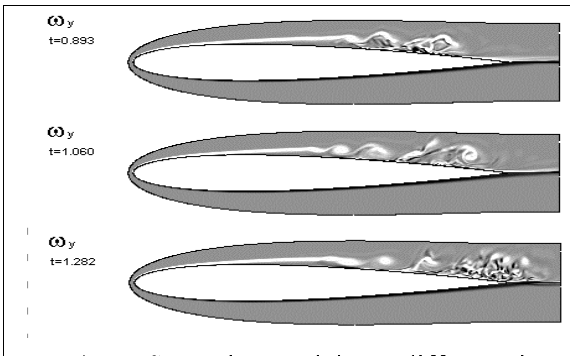
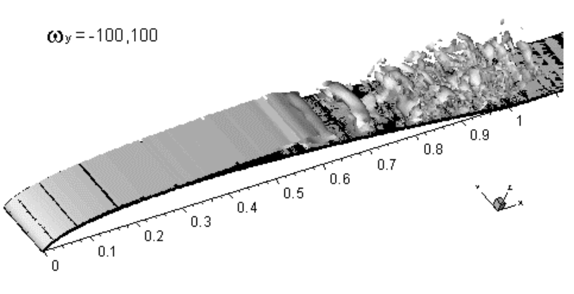


Fig. 4. Mean velocity profiles (a) and RMS fluctuation velocity profiles (b).

Fig. 5 shows contours of the instantaneous spanwise vorticity in the middle (x,z) plane. The rolling-up of the separated shear layer and the ejection of coherent structures are clearly seen. The isosurfaces of instantaneous spanwise vorticity in three time steps are plotted in Fig. 6. The transition process and breakdown of the rolling-up shear layer are clearly demonstrated. The boundary layer becomes fully turbulent after flow reattaches.

 **Fig. 5.** Spanwise vorticity at different time.	 **Fig. 6.** Instantaneous spanwise vorticity isosurface at t=1.127

Reference

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