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Insight into separation induced transition in laminar separation flow over SD7003 airfoil

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ABSTRACT

The flowfield around SD7003 airfoil at Reynolds number of 60,000 and attack angle of 4° was simulated by the large eddy simulation, and the mechanism behind the evolution of laminar separation flow was analyzed by the proper orthogonal decomposition method. The present LES method utilized the implicit sub-grid-scale model. Based on the structured patched mesh, the numerical method adopted the AUSM scheme for spatial discretization and dual-time-step method for time marching. The numerical simulation clearly captured the flow structure characteristics of laminar separation, transition, and subsequent breakdown. And the unsteady flow field were utilized for the proper orthogonal decomposition analysis. The numerical results reveal that, the laminar separation flow contains the complex phenomenon of laminar separation, transition and reattachment, and the separation induced transition is caused by the multiple interaction of shearing vortex.

1. INTRODUCTION

Laminar separation phenomenon is the characteristic feature of airfoils at low Reynolds number condition. The formation and subsequent turbulent breakdown of laminar separation flow has long been known to be detrimental to the performance of airfoils, directly affecting endurance and degrading handling and stability of aircrafts. The laminar separation flow contains the complex phenomenon of laminar separation, transition and reattachment, and flow separation and transition are strongly coupled. Further insight into the complex flow structures and the mechanism of separation induced transition are of prominent value in academic, as well as great importance in improving designing and flow control method for airfoils.

The study of laminar separation flow over airfoils can be traced back to the 60s of the last century. Horton and Gaster proposed the classic laminar separation bubble model[1,2]. However, massive wind tunnel experiments and numerical simulations indicate the so-called laminar separation bubble is the time averaged result of a series of large scale vortices. Because the laminar separation flow is unstable and is easily disturbed by external factors, the in-depth study is of great difficulties for both experiment and computation. With the rapid improvement of computer performance and the development of numerical methods, the researchers on the phenomenon tend to utilize the high-fidelity methods of LES (Large Eddy Simulation) and DNS (Direct Numerical Simulation). Although the flow structure characteristics of laminar separation flow have been comprehensively studied, the deep understanding of flow evolution is insufficient and the mechanism of separation induced transition is still unclear.

In present study, large eddy simulation is carried out for the laminar separation flow past the SD7003 airfoil, and the proper orthogonal decomposition (POD) method is utilized to investigate the flow evolution based on the computed unsteady flow field.

2. NUMERICAL METHOD

The present numerical study focuses on the laminar flow past the SD7003 airfoil at the Reynolds numbers 6×10^4 and angle of attack 4°. The particular condition is selected for the typical laminar separation phenomenon, and there are computational and experimental results available for validation. The free stream Mach number is set to 0.2, the value at which compressibility can be ignored and computational efficiency can be improved.

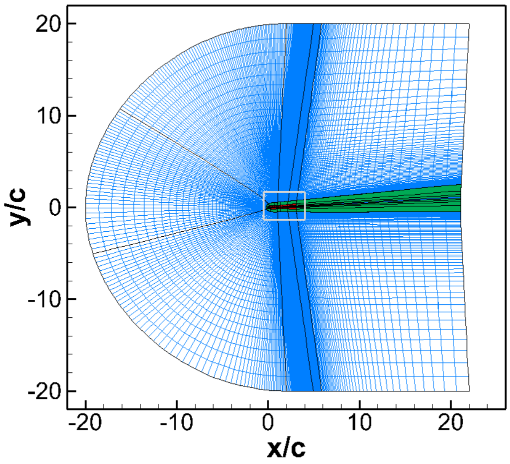
The present LES solves the three dimensional Favre averaged compressible Navier-Stokes equations, and utilizes the implicit subgrid model, which relies upon the numerical dissipation to model the impact of the sub-grid vortex on the solvable flow. Based on the finite volume discretization, the convective flux is constructed by the AUSM+ (Advection Upstream Splitting Method +) scheme. In order to improve the resolution and accuracy, the original variables on both edges of the grid unit are reconstructed by fifth order WENO scheme. The viscous flux is discretized by the second order central difference scheme. The dual time step method based on implicit LU-SGS scheme is utilized for time marching.

The patched structural mesh is utilized to discrete the computational domain, as is shown in figure 1. The entire computational domain is divided into three regions: key areas (red parts), transition regions (green), and peripheral regions (blue). The grid points are clustered in the laminar separation flow region, and the total number of grid units is 7,704,000. The three dimensional mesh over the suction surface of the airfoil satisfies the following criteria,

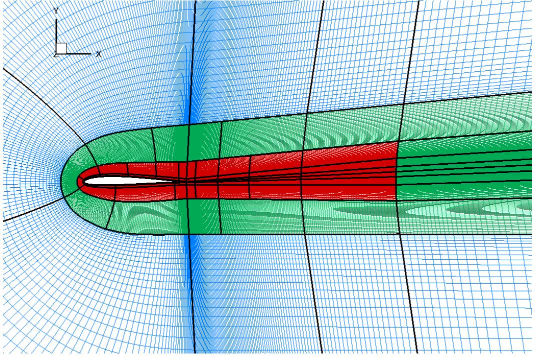
$$\Delta\xi^+ < 10, \quad \Delta\eta^+_{\min} < 0.5, \quad \Delta\zeta^+ < 5\,.$$

Where, $\Delta\xi$ is the stream wise grid spacing, $\Delta\eta_{\min}$ is the wall-normal minimum grid spacing, and $\Delta\zeta$ is the span wise grid spacing. Here the superscript plus denotes the normalized length valued based on the frictional velocity and kinematics viscosity at the wall. The unsteady complex flow structures can be well resolved by the present three dimensional LES method.

Free-stream conditions are prescribed with fixed dependent variables on the far-field boundary. The no-slip, adiabatic temperature condition are adopted on the airfoil surface. Period condition is set in the span-wise direction.



(a) global grids



(b) local grids near airfoil

Figure 1. Computational mesh for flow simulation

Proper orthogonal decomposition is a technique for extraction of a set of basic functions of the spatial variables that have maximum energy content. By the capture of the principal structures, the POD method can provide important insight into the complex flow. The present study utilized the Snapshot method proposed by Sirovich [3]. The present study select the three dimensional velocity as the dynamic variable. The flow data utilized for POD analysis is interpolated from the unsteady flow field.

The present study pays close attention to the laminar separation flow over the suction surface of the airfoil. The computational mesh for POD analysis is shown in Figure 2. The grid number in the stream wise and wall normal direction are 300 and 50, respectively, and the mesh is 0.15 chord length in span wise direction with 50 grid points equally distributed.

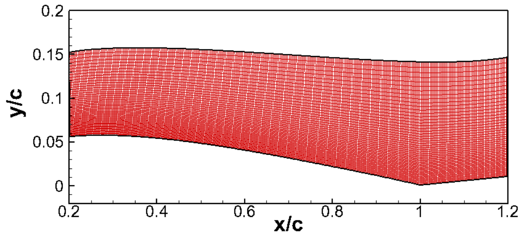


Figure 2. Computational mesh for POD analysis.

3. RESULTS AND DISCUSSION

3.1 Simulation validation

Firstly, the present LES simulation is validated by the comparison with computational and experimental data in reference [4]. The averaged pressure coefficients are compared in Figure 3, where ILES stands for Marshall's computed data.

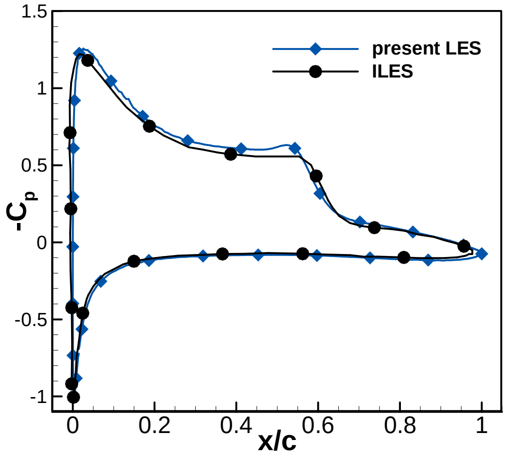
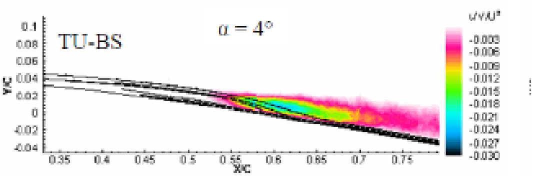
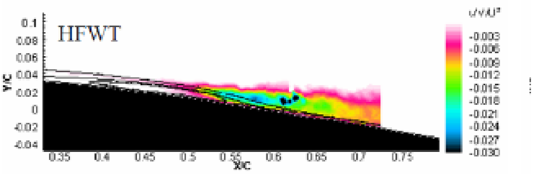


Figure 3. Comparison of pressure coefficient

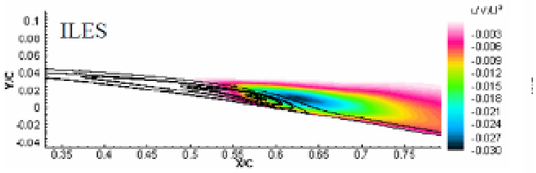
Computed Reynolds shear stress is compared with the experimental measurements and ILES computed data in Figure 4. Good agreement between computational and experimental data sets in terms of shape, magnitude, and extent of the fluctuating region are observed. The computed Reynolds shear stress by ILES and present LES is almost identical to each other. The differences between computation and experiments are attributed to the free stream turbulence intensity, and lower PIV imagery resolution for measurements. The large absolute value of Reynolds shear stress indicates the intense momentum exchange of vortices.



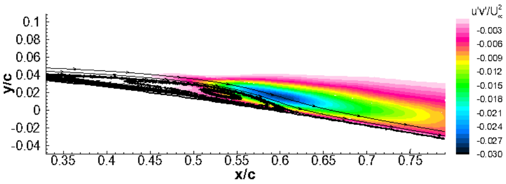
(a)TUBS wind tunnel



(b)HFWT water tunnel



(c)ILES



(d)present LES

Figure 4. Comparison of Reynolds stress

Table 1 shows the comparison of averaged location of separation, transition and reattachment with TU-SB and HFWT experimental measurements and ILES simulation. The location of separation and reattachment are measured from the averaged friction coefficient. The transition locations are determined by the criterion when the Reynolds shear stress reaches a value of 0.1% and exhibits a visible rise. The computed locations by the present LES are close to the ILES simulation of reference. Both fall in between the experimental measurements. The distinction from the experimental measurements is caused by the free stream turbulence.

Table 1. Comparison of locations of separation, transition and reattachment

Data Set	xs/c	xt/c	xr/c
TU-SB	0.30	0.53	0.62
HFWT	0.18	0.47	0.58
ILES	0.23	0.55	0.65
Present LES	0.20	0.52	0.62

3.2 Flow structures

Then the flow structure characteristics are analyzed by the present three-dimensional LES simulation. The iso-surfaces of the second invariants of the velocity gradient tensor ($Q = 0.01U_\infty^2 / c^2$) are shown in Figure 5, which are colored by the x-direction velocity. The Q-criterion provides a means of visualizing vortex cores and identifies turbulent structures. The figure shows that the flow separates from the airfoil surface and forms the two-dimensional spanwise vortices periodically. These vortices break up near the middle part of the airfoil and turn into hairpin-like vortices, and large scale vortex structures are generated in the wake region. The breakup of these vortices resembles a chain reaction.

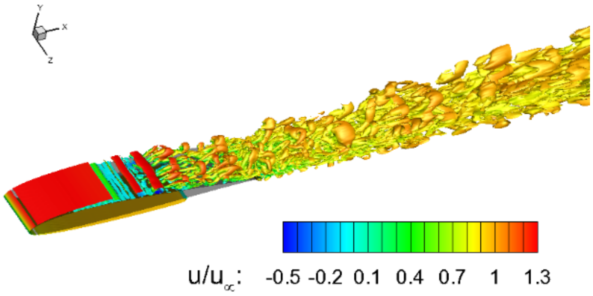


Figure 5. Q-isosurfaces of instantaneous vortex

Figure 6 shows the instantaneous spanwise vorticity at the middle (x,y) plane. The separated flow on the airfoil surface produces a strong velocity shear layer, which is unstable and causes dithering and confusion of the spanwise vorticity. The evolution of the separated vortices causes the large scale vortex structure in the wake region.

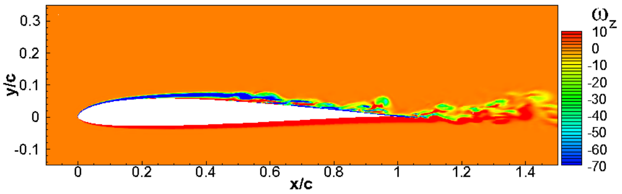


Figure.6 Instantaneous spanwise vorticity

Figure 7 displays the configuration of laminar separation bubble by the time and spanwise averaging. In the view of averaged flowfield, the flow separates from the airfoil surface and reattaches to the wall downstream, forming the laminar separation bubble.

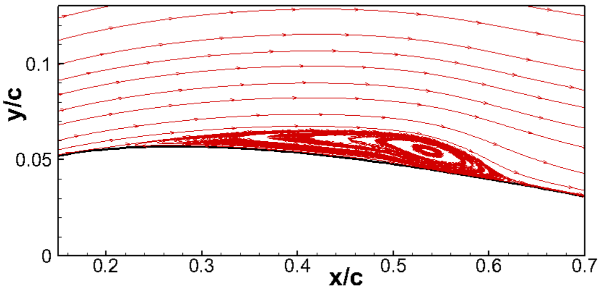


Figure.7 Averaged stream lines

3.3 Transition mechanism

The mechanism of the laminar separation induced transition is investigated in this section. From the averaged velocity vectors shown in Figure 8, it can be found that a recirculation zone exits over the airfoil surface and an inflection point is generated in the hyperbolic tangent-like profile. Hence, the initial spanwise coherent two-dimensional vortices are generally considered to be generated by the Kelvin-Helmholtz (K-H) instability.

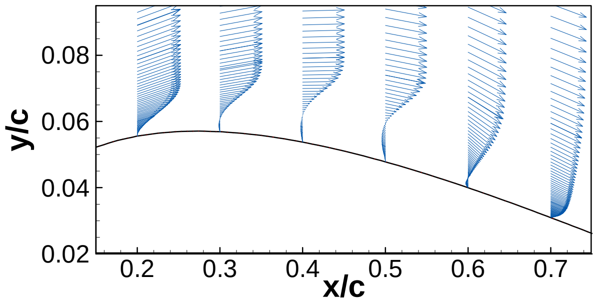


Figure.8 Averaged velocity vectors

Figure 9 shows the contours of the root mean square of the spanwise velocity with the averaged separation bubble. It can be found that upstream the location of x/c=0.5, the spanwise velocity fluctuation is near zero, which implies the flow remains laminar. Then transition occurs near the averaged attachment point, causing the three-dimensional flow structures. The rapid rise of spanwise velocity fluctuations indicates the appearance of three-dimensional motion and nonlinear interaction, which leads to breakdown and turbulence.

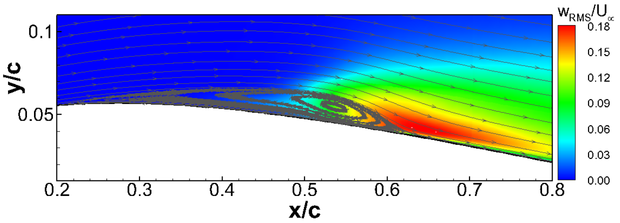
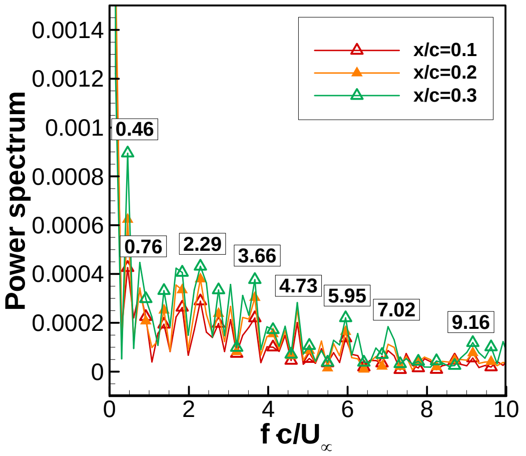
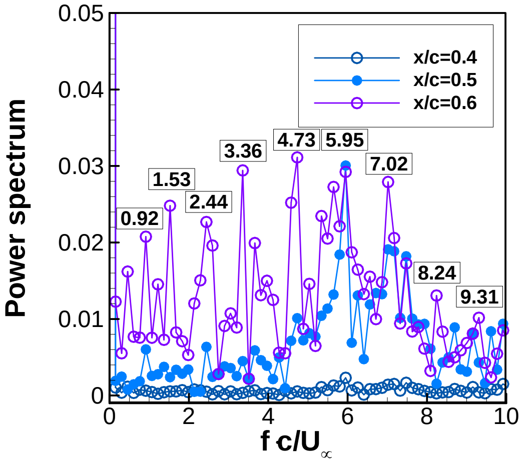


Figure.9 Root mean square of the spanwise velocity and averaged streamlines

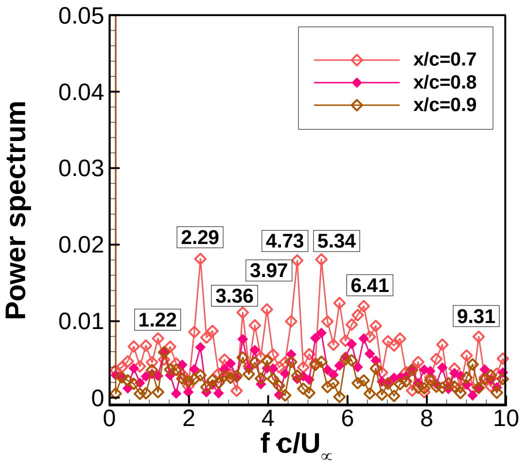
The power spectrum of wall pressure at different streamwise locations are compared in Figure.10. It can be seen that, the amplitude of pressure fluctuation is small upstream the location x/c=0.3, while at the location of x/c=0.6, the pressure fluctuates most forcefully. Besides, there are the obvious sum and duplication correlations between the characteristic frequencies, which indicates that the complex vortex system composes of multiple interactions of the vortices.



(a)x/c=0.1~0.3



(b)x/c=0.4~0.6



(c)x/c=0.7~0.9

Figure.10 Power spectrum of pressure at different location

The unsteady three-dimensional flow field is utilized for the POD analysis. The energy portions of POD modes are shown in Fig.11. The first mode captures about 60% of the total kinetic energy, while the kinetic energy contributions of other modes are much smaller.

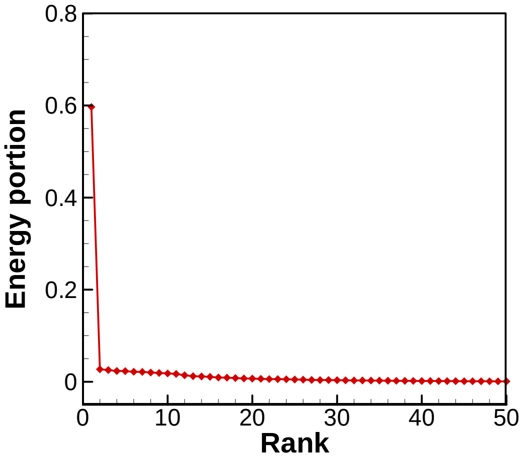
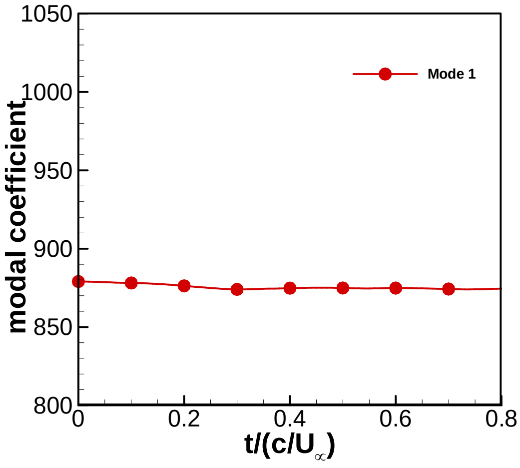


Figure.11 Energy portion of POD modes

The modal coefficients of the first nine modes are shown in Figure 12. The coefficient of first mode is invariant, the others are periodically oscillating with respect to time. Except for the first mode, the coefficients of dynamic mode are analogy in distribution in pairs, with a fixed phase deviation of 0.5π in time.



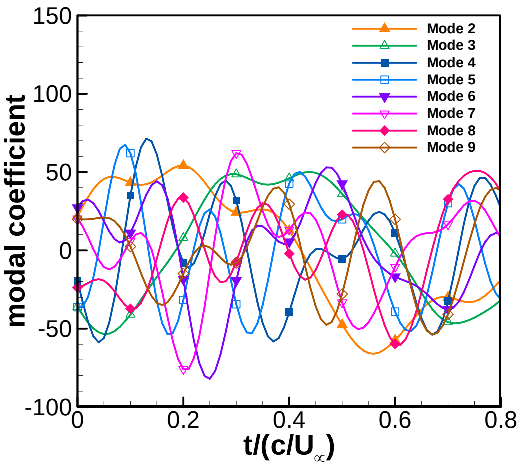
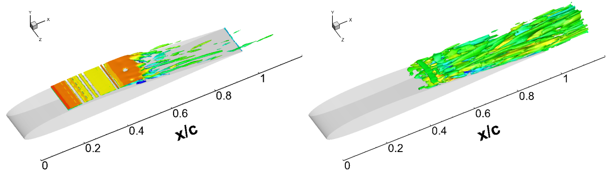
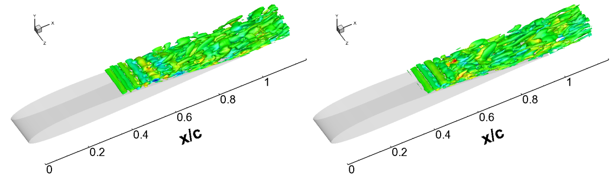


Figure.12 Time evolution of modal coefficients

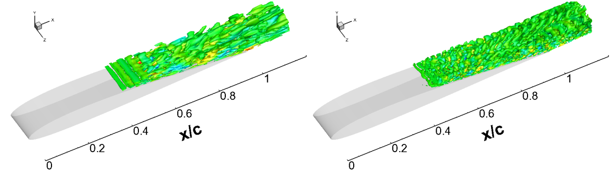
The POD modal bases are shown in Figure. 13. (The omitted bases are similar to the adjacent ones.) The first mode is the time averaged flow field, which is characterized by the two dimensional spanwise vortices. And the second to eighth modes represent the large scale coherent structures. The three dimensional pairing and merging process generate the lower and higher frequency flow structures, which are shown in the second mode and eighth mode. In the twentieth mode, only the high-frequency, small scale vortex are contained. This suggests that as the order of POD modes increase, the structures of vortex break down gradually. The above analysis suggests that the three dimensional flow structures are generated by the multiple interaction of shearing vortex, and break down to the small scale vortices gradually. That is how the flow separation induced transition phenomenon occurs.



(a)Mode 1 (b)Mode 2



(c)Mode 4 (d)Mode 6



(e)Mode 8 (f)Mode 20

Figure.13 POD modes with Q iso-surfaces

4. CONCLUSION

In this study, we conducted the LES simulations of the low Reynolds flow over the SD7003 airfoil, and utilized POD mode decomposition method to investigate on the transition mechanism. The numerical study predicts the flow structure characteristics and reveals the mechanism of separation induced transition. In the laminar separation phenomenon, the separated flow forms a free shear layer, which is unstable and rolls up to form the spanwise vortices, then these vortices pair and merge with each other to generate the three dimensional flow structures. The evolution of shear layer plays a key role in the laminar separation flow. The flow separates from the airfoil and forms a free shear layer, which is unstable because of the Kelvin-Helmholtz instability. The separated shear layer rolls up to form the spanwise vortices, then the adjacent vortices pair and merge into large scale vortex and generate three dimensional flow structures. It is concluded that the transition process is closely correlated to the separation flow. The multiple interactions of the separated vortices are proved to cause the separation induced transition.

ACKNOWLEDGMENTS

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