Numerical Simulation of Transitional Flow Past SD7003 Airfoil over a Range of Reynolds Number

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Abstract

In this work the transition characteristics of the low Reynolds number airfoil SD7003 for a wide range of Reynolds number ($6 \times 10^4 \leq Re \leq 7.5 \times 10^6$) at $4°$ and $8°$ angles of attack are analysed. The numerical analysis is carried out using the $\gamma - Re_\theta$ SST transition model avaliable in the in-house multiblock structured incompressible flow solution code 3D-PURLES. The transition onset, length of the laminar separation bubble and the areodynamic coefficeints predicted at $Re = 6 \times 10^4$ using the $\gamma - Re_\theta$ SST transition model is found to be in a good agreement with the available measurement data and other Implicit LES computations especially at $4°$

Keywords: Transition model, transition onset, laminar separation bubble, finite volume method, incompressible flow, pressure based solver.

1 Introduction

The Selig-Denovan(SD) 70003 is a low Reynolds number airfoil having 8.5% thickness with 1.4% camber and used for low Reynolds number aerodynamic applications. The formation of laminar separation bubble (LSB) and flow undergoing transition is the major characteristics of the SD7003 airfoil which effects its aerodynamic performance. In the literature, various numerical [1, 2, 3] and experimental [4, 5] results for transition onset and formation of LSB are available for SD7003 airfoil at lower Reynolds numbers ($Re \leq 8 \times 10^4$) mainly for two for angles of attack (α) *viz.* $4°$ and $8°$. Handling the transitional flows in one of the major challenge faced by the computational fluid dynamics (CFD) community. Different ways to numerically solve the transitional flows are available in literature. Starting from the empirical approach which is quite simple and straight forward. The major draw of this low fidelity approach is that it lacks generality and cannot be used for complex practical problems. The direct numerical simulation (DNS) approach which falls in the other end of the fidelity spectrum, in the recent years is gaining importance due to the advancement in high performance computing, high accuracy schemes and acceleration schemes. However, the DNS due its high demand of computational resource and time is used only for simple geometry of research interests that too at low Reynolds number. The large eddy simulation (LES) though is less expensive than DNS and applied to some fairly complex geometry is still not a viable designer tool. The Reynolds Averaged Navier Stokes (RANS) based approaches which can predict mean flow quantities reasonably accurate at a lower computational cost is extensively used as a designer tool. One of The recent approach to model flow transition in the framework of RANS is to solve additional transport equations in order to include the effects of transition on the flow field prediction. In this direction, Menter *et al.* [6, 7, 8] proposed a correlation based transition model which solves the transport equations for intermittency (γ) and momentum thickness based Reynolds number (Re_θ) for finding the transition onset. This γ - Re_θ transition model has three closure coefficients which were not disclosed initially and published simultaneously by Langtry and Menter [8] and Malan *et al.* [9]. The present paper discusses results obtained using $\gamma - Re_\theta$ SST transition model implemented in the in-house flow

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code 3D-PURLES (**3D P**ressure based **U**nsteady **R**ANS **LES** solver) for SD7003 airfoil at $\alpha = 4°$ and $\alpha = 8°$ in terms of transition onset, length of laminar separation bubble and aerodynamic coefficients for Reynolds number ranging between 6×10^4 and 7.5×10^6.

2 Mathematical Formulation

The Reynolds Averaged Navier Stokes (RANS) equations for unsteady incompressible flow in the coordinate-free form:

Mass conservation:

$$\bigtriangledown.\rho U = 0 \tag{1}$$

Momentum conservation:

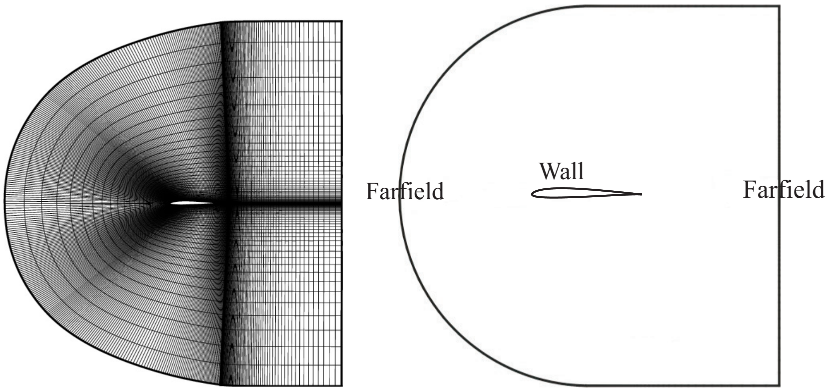
$$D_t \rho U = - \bigtriangledown P + \bigtriangledown.((\mu + \mu_t)(\bigtriangledown U + \bigtriangledown^t U)) \tag{2}$$

where μ and ρ are fluid viscosity and density, p and U are pressure and velocity vector, respectively. The eddy viscosity μ_t is evaluated using the $\gamma - Re_\theta$ SST model [8, 9]. The γ - Re_θ transition model implemented in the in-house code 3D-PURLES is same as that given by Langtry and Menter [8] except for the two correlation functions *viz.* $Re_{\theta C}$ and F_{length} which are adopted from Malan *et al.* [9]. However, based on our validation study carried out for the flat plate T3A test case [10], $Re_{\theta C}$ correlation has been suitably modified as given below

$$Re_{\theta C} = min\left(0.665\tilde{R}e_{\theta t} + 66.5, \tilde{R}e_{\theta t}\right) \tag{3}$$

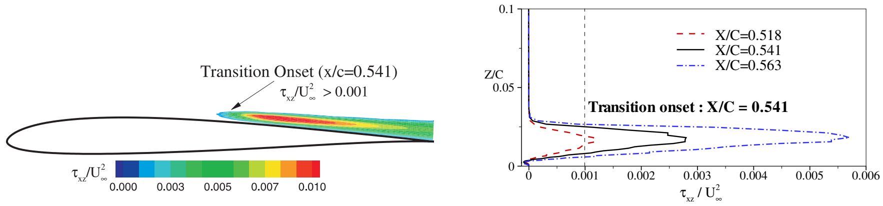
3 Results and Discussion

The simulations for the SD7003 airfoil are carried out using the $\gamma - Re_\theta$ SST model on a C-grid topology having 527×101 control volumes (Fig. 1(a)) with near wall $y^+ < 1$ and a third order accurate QUICK scheme for spatial discretization. The boundary conditions used for present simulations are shown in Fig. 1(b). In these simulations the level of free stream turbulence Tu is maintained to be 1% of the mean kinetic energy. The transition onset is determined using the Reynolds shear stress threshold criterion [4, 5] for angle of attack $4°$ and $8°$ as shown in Fig. 2. According to this criterion, the onset of transition is the point where the normalized turbulent (Reynolds) shear stress $(\frac{\tau_{xz}}{U_\infty^2})$ value exceeds more than 0.1%. The transition onset and the details of the laminar separation bubble obtained from the Reynolds shear stress threshold criterion and the sign of the surface skin friction coefficeint respectively are shown in Table 1. The table clealry indicates that the transition onset predicted by present simulation is in very good agreement with the measurement data of Radespial *et al* [5] as well as the ILES computations of Galbraith and Visbal [1] for $\alpha = 4°$. However for $\alpha = 8°$ the transition onset obtained by the computations in general are overpredicted as compared to the measurements with the present computation being closer. On the other hand, though the present computation could capture the separation point reasonably well has grossly overpredicted the reattachment point leading to an increase in the length of the LSB when compared to measurements and ILES data. Based on this validation, the $\gamma - Re_\theta$ SST model is used to simulate at higher Reynolds number in order to understand the effect of Reynolds number on the transition onset location, length of laminar separation bubble and aerodynamic coefficients at $4°$ and $8°$. The varaiation of transition onset and length of LSB is shown in Fig. 3, the transition onset as excepted [11] moves towards the leading edge with Reynolds number for both the angles of attack. The shift in the onset of transition with Re is much steeper for $4°$ when compared to $8°$. At $Re = 7.5 \times 10^6$, the transition onset location occurs very close to leading edge indicating the flow to be fully turbulent. Further it is observed that the transition onset location shifts upstream with angle of attack. On the other hand, a smooth fall in the length of the LSB with Reynolds number upto $Re = 7.5 \times 10^5$ for both the angles of attack is observed. The figure clealry indicates that the length of LSB reduces with Re and angle of attack. As anticipated, for both the angle of attack no laminar separation is observed at $Re = 7.5 \times 10^6$ as the flow is almost fully turbulent. Fig. 4 clearly shows that the trend of variation for lift coefficient (C_l) and drag coefficient (C_d) with Re for both the angles of attack is almost similar with C_l increasing and C_d decreasing with Reynolds number.

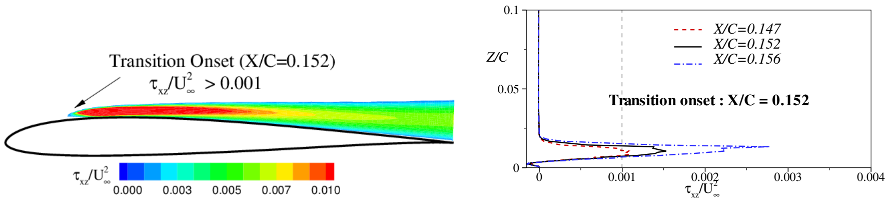


(a) C-grid (527×101) (b) Boundary conditions

Figure 1: Grid and boundary conditions



(a) $\alpha = 4°$

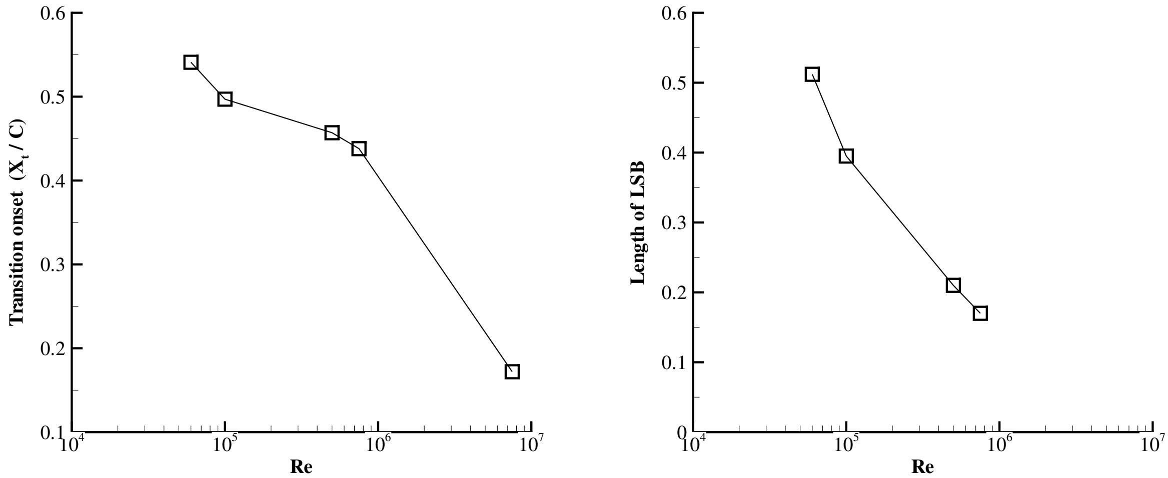


(b) $\alpha = 8°$

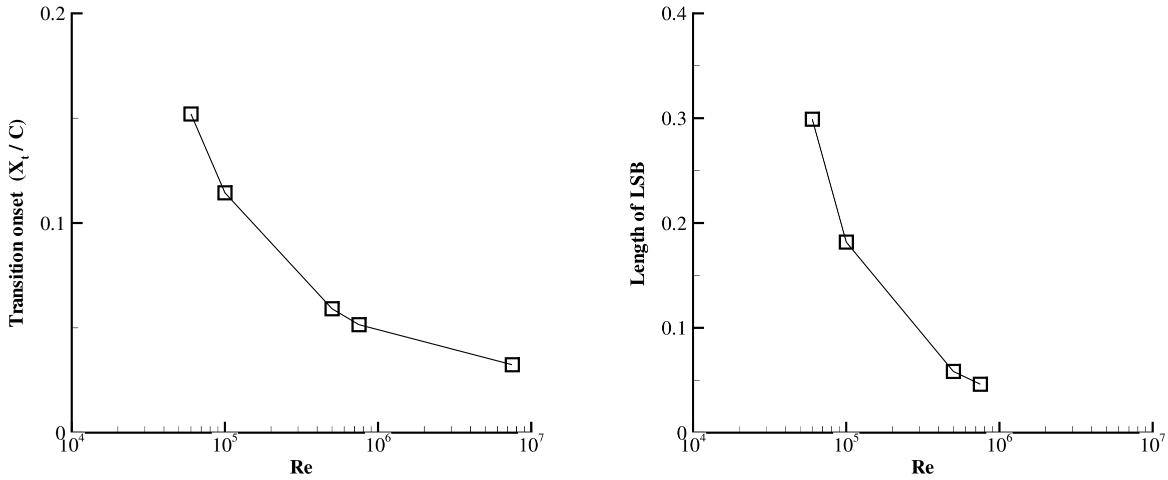
Figure 2: Reynolds shear stress contours and normal profiles for SD7003 airfoil at $Re = 6 \times 10^4$

Data set	Approach	$Tu\%$	Separation pt.		Transition onset		Reattachment pt.	
			$\alpha = 4°$	$\alpha = 8°$	$\alpha = 4°$	$\alpha = 8°$	$\alpha = 4°$	$\alpha = 8°$
Present computation	$\gamma - Re_\theta$ SST model	1.0	0.218	0.039	0.541	0.152	0.73	0.33
Galbraith and Visbal [1]	Implict LES	0	0.23	0.04	0.55	0.18	0.65	0.28
Radespial *et al* [5]	Experiments	0.08	0.30	0.06	0.55	0.14	0.62	0.18

Table 1: Transition and laminar separation bubble details for SD7003 airfoil at $Re = 6 \times 10^4$

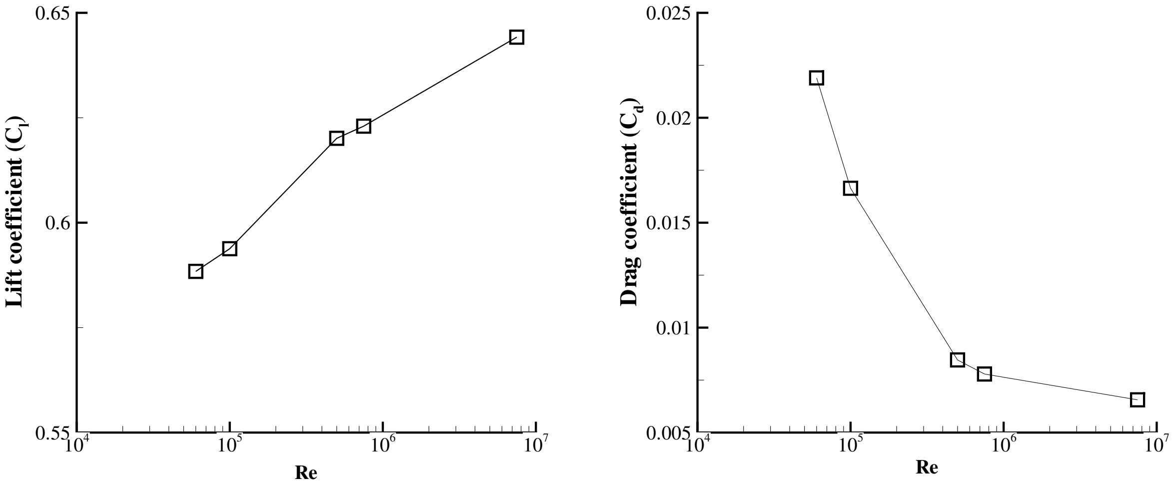


(a) $\alpha = 4^{\circ}$

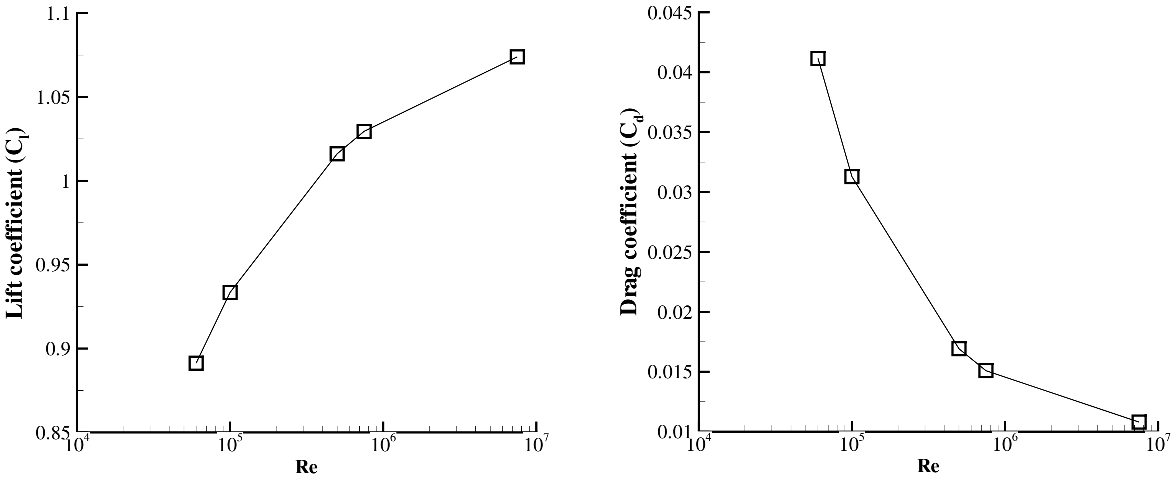


(b) $\alpha = 8^{\circ}$

Figure 3: Effect of Reynolds number on transition onset and length of LSB for SD7003 airfoil



(a) $\alpha = 4^{\circ}$



(b) $\alpha = 8^{\circ}$

Figure 4: Effect of Reynolds number on aerodynamic coefficients for SD7003 airfoil

4 Concluding Remarks

The transitional flow past SD7003 airfoil at higher Reynolds number regime is carried out using the in-house incompressible flow code 3D-PURLES. The capability of the $\gamma - Re_\theta$ SST model to predict transition onset and laminar separation bubble at high Reynolds number is demonstrated.

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