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CFD ANALYSIS OF SD 7003 AIRFOIL AT LOW REYNOLDS NUMBER WITH A LAIMINAR KINETIC ENERGY BASED TRANSITION MODEL

Mazharul Islam[1], Jiří Fürst[2] and David Wood[3]

[1]Department of Mechanical Engineering, Kulliyah of Engineering, International Islamic University Malaysia, Kuala Lumpur, Malaysia
[2]Department of Technical Mathematics, Faculty of Mechanical Engineering, Czech Technical University in Prague, Karlovonam Praha, Czech Republic
[3]Department of Mechanical and Manufacturing Engineering, Schulich School of Engineering, University of Calgary, Canada
E-Mail: mazharul@iium.edu.my

ABSTRACT

The characteristics of laminar separation bubbles (LSBs) on the SD 7003 airfoil have been extensively studied in the past at low Reynolds numbers. It has been found that the LSB is extensive, especially at airfoil at angle of attack (α) of 4º. To analyze separation, transition and reattachment of flow around SD 7003 airfoil effectively, Computational Fluid Dynamics (CFD) analysis can be performed with suitable transition models. In this article, a modified version of k-k_L-ω transition model, originally proposed by Walter and Cokljat [1], has been used with open source CFD tool OpenFOAM for analyzing SD 7003 at Reynolds number (Re) of 60,000. The article investigated k-k_L-ω transition model with two recently developed variants for analyzing SD7003 airfoil. These two variants are based on Pohlhausen and Falkner-Skan profiles to consider effect of pressure-gradient for natural transition. It has been found that both the variants under-predicted the lift coefficients and slightly over-predicted the drag coefficients. Both of the pressure-gradient sensitive variants gave better prediction of separation of the laminar BL. However, the reattachment locations were delayed significantly. Among the two variants, the Falkner-Skan based variant predicted the reattachment location slightly earlier than the Pohlhausen based variant and thus conforming better with different experimental and computational results.

Keywords: SD7003, airfoil, LSB, transition modeling, CFD, k-k_L-ω, OpenFOAM, pohlhausen, falkner-skan.

ACRONYMS AND ABBREVIATIONS

APG   adverse pressure gradient
BL   boundary layer
C_d drag coefficient
CFD   Computational Fluid Dynamics
C_f skin friction coefficient
C_l lift coefficient
C_m moment coefficient
C_p pressure coefficient
DGM   Discontinuous Galarkin Method
DNS   Direct Numerical Simulation
ILES   Implicit Large Eddy Simulation
LES   Large Eddy Simulation
LSB   Laminar Separation Bubble
PIV   Particle Image Velocimetry
RANS   Reynolds-average Navier-Stokes Equation
Re   Reynolds number
Tu   Turbulence intensities

INTRODUCTION

At low Re, flow over airfoils can exhibit LSBs which results from separation of the laminar boundary layer (BL) and subsequently reattachment as turbulent BL. The characteristic of LSB of the SD 7003 airfoil has been extensively studied in the past at low Reynolds numbers. Apart from different experimental methods [2], the SD 7003 has been investigated through diversified computational techniques [3]-[8] involving Direct Numerical Simulation (DNS), Large Eddy Simulation (LES), Reynolds-average Navier-Stokes Equation (RANS). Based on these previous research activities, transition points are approximately in the range of 40 to 60%. This fact necessitates that CFD analysis of SB 7003 should properly model or simulate the separation of the laminar BL and the subsequent development of the LSB for acceptable results.

Though transition phenomena of airfoils can be fairly accurately simulated with DNS and wall-resolved LES techniques, however, the number of cells and computational time required for these techniques are often prohibitive (Choi & Moin 2011) [9]. Because of this reason DNS and LES techniques are usually applied for selected specials cases at low Re which can be used for validation of RANS based results. CFD analysis with RANS models requires substantially fewer cells and computational time.

Over the year, diversified RANS-based models have been proposed by researchers to mimic characteristics of flows when they undergo through transition from laminar to turbulent. The main three classes of the transition models are: (i) linear stability theory based e^N models [10]-[14], (ii) local correlation based transition models [15], [16], and (iii) laminar kinetic energy based transition models [1], [17]. Each class of model has its strengths and weaknesses. However, for CFD analysis, the first class of models (i.e. e^N models) are considered impractical due to its need for non-local parameters. It should be noted that modern CFD codes are now-a-days used for unstructured grid through massively parallel operations in High Performance Computing (HPC) clusters. Due to this fact, now-a-days the local correlation based γ-$Re_{\theta t}$ [18] or laminar kinetic energy based k-k_L-ω [1] models are usually used for modeling transition and turbulence in CFD analysis. To strengthen the modeling capacity of k-k_L-ω model in flows with

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adverse pressure gradients (APG), different modifications (e.g. [19], [20]) have been proposed. For the present work, two recently developed pressure-gradient sensitive variants of k-k_L-ω model were investigated in OpenFOAM [21] for performing two-dimensional (2D) CFD analysis of SD 7003 airfoil at angle of attack (α) = 4º and Re=60,000. The obtained results are compared with experimental and computational results for validation purpose.

CFD ANALYSIS
OpenFOAM, which is a freely available opersource CFD toolbox, is widely used for different applications. For the present anlysis, a steady-state RANS solver called simpleFoam [22] is used. The other salient details of the OpenFOAM cases are presented in the subsequent headings of this section.

Computational domain and mesh
For transition modeling, preparation of mesh is more challenging. According to "Best Practice Guidelines for Using the Transition Model" which is included as an appendix in [23]- "Based on the grid sensitivity study the recommended best practice mesh guidelines are a max y^+ of 1, a wall normal expansion ratio of 1.1 and about 75 - 100 grid nodes in the streamwise direction". It was also noted in this useful guideline that additional grid points are most likely needed in the streamwise direction if separation induced transition is present.

To assess mesh sensitivity, several mesh sizes were investigated. However, finally three different meshes (termed as Coarse, Medium and Fine mesh in this article) were selected and analyzed through their results. Salient features of these three mesh sizes are shown in Table-1. The computational domains for airfoils are usually O-type or C-type. For airfoils with sharp trailing edges, the C-type mesh is preferred and thus used in this work. In Figure-1, the computational domain along with the Fine mesh is shown. Also, the mesh around the airfoil is shown for illustration purpose in Figure-2.

Transition and turbulence model
In this article, two different types of pressure gradient sensitive variants of modified k-k_L-ω transition and turbulence model are investigated. These variants are based on Pohlhausen and Falkner-Skan profiles. These two modifications introduced new threshold functions considering pressure-gradient flows at low turbulence intensities and they have already been tested for NACA 0012 (Re=600,000) and NACA 4415 (at Re=700,000) airfoils. These modifications have shown to improve the modeling capabilities of k-k_L-ω model for adverse pressure gradient (APG) flows at low Tu.
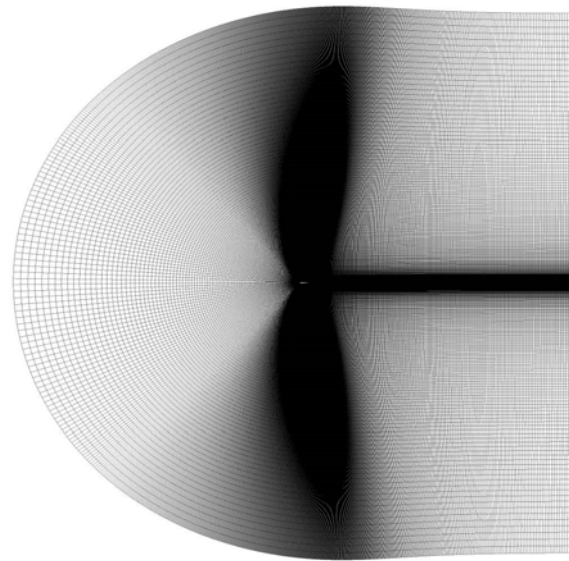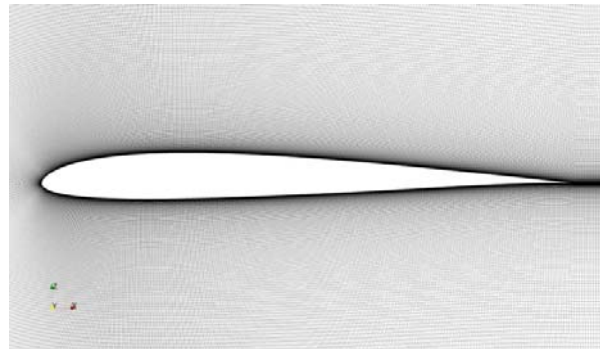

Figure-1. Computational domain with mesh.

Figure-2. Mesh around the SD 7003 airfoil.

Table-1. Salient features of the 3 meshes.

Parameter	Coarse	Medium	Fine
Number of Cells	223571	396506	519707
Type of Cells	hexahedra	hexahedra	hexahedra
Number of points on the airfoil surface	200	300	450
Number of points in the normal direction of the airfoil surface	80	120	180
Maximum y+ in the final iteration	0.911751	0.912573	0.913211

More information about these modifications can be obtained from (J. Fürst *et al*. 2015; Jiří Fürst *et al*. 2015) [20], [24]. Results from these variants of k-kL-ω model were compared with the original version (implemented in OpenFOAM). The main turbulence related parameters, which are k and ω, were determined for a turbulence intensity of 0.1%.

RESULTS AND DISCUSSIONS

For the three different cases with different mesh sizes, simpleFoam were run until the fluctuations of lift and drag coefficients (C_l and C_d) became low. To determine values of different coefficient (like C_l, C_d and C_m), average values over a range of iterations were determined.

Mesh sensitivity

Performing mesh sensitivity analysis is quite critical for a successful CFD analysis. To determine the mesh dependency of the results, OpenFOAM cases were run with different mesh sizes and three meshes (described in Table-1) were finally selected and analyzed in detail. In Table-2, three important aerodynamic coefficients (which are C_m, C_d and C_l) are shown for three mesh sizes: Coarse, Medium and Fine. It can be clearly seen from this table that values are identical for C_d and slightly different for C_l and C_m values between the meshes. It can also be seen from Figure-3 that the pressure coefficients are also almost identical for the three mesh sizes.

Table-2. Moment, drag and lift coefficients for 3 mesh sizes.

Mesh	C_m	C_d	C_l
Coarse	-0.0403	0.0195	0.5151
Medium	-0.0403	0.0195	0.5159
Fine	-0.0402	0.0195	0.5160

Skin friction coefficient

In Figure-4, skin friction coefficient (C_f) obtained from three variants of model are compared with LES and XFOIL results. It can be seen from this figure that both of the variants were able to model LSB better than the original model. However, though both the variants predicted the separation location satisfactorily, but the reattachment location was delayed significantly. As the present 2D study is done with a steady-state RANS (which has inherent shortcomings) solver of OpenFOAM, it is not possible to match the other two results shown in the figure which were obtained from highly computationally expensive LES techniques completely.
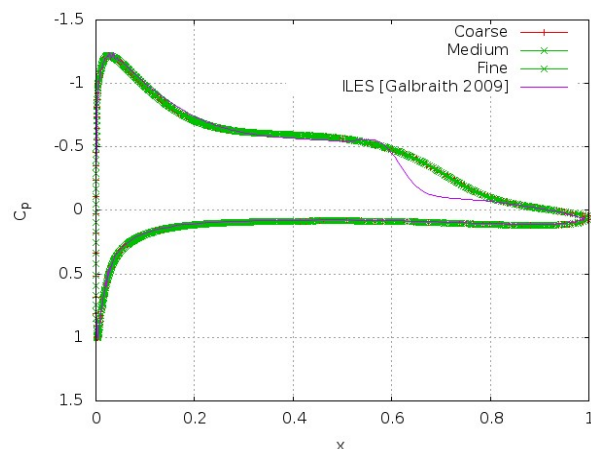
Separation and reattachment locations

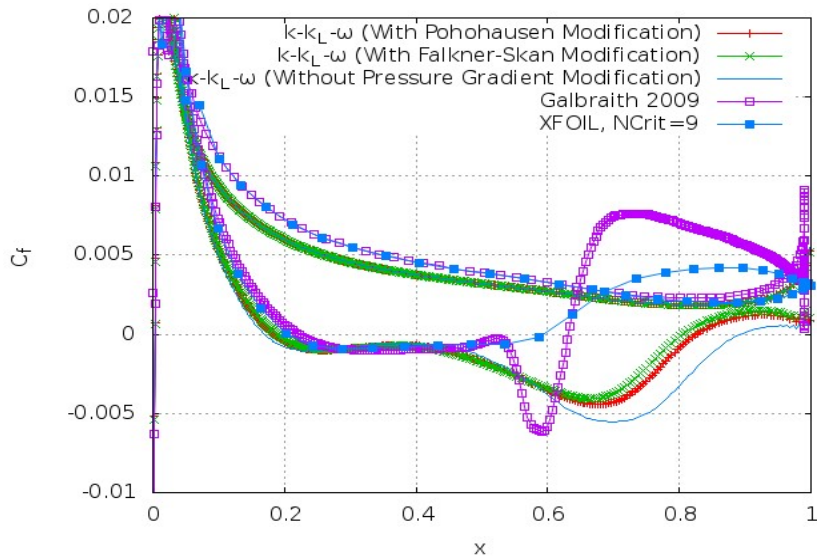Table-3 represents separation and reattachment locations according to different types of experimental and computational methods. The experimental investigations were done with Particle Image Velocimetry (PIV). Though the results from LES and DNS are closer to the experimental results, RANS based modeling done in the present study is computationally much economical. As indicated earlier, the two variants are in better agreements with the experimental, DNS and LES results than the original k-k_L-ω model which demonstrate the effectiveness of considering pressure gradient sensitivity for natural transitions. It should also be noted that the original model predicted multiple values at which Cf=0. For the present study, only the first two values were considered as separation and reattachment locations for the sake of simplicity. The results from XFOIL, an effective tool for analyzing airfoils undergoing through natural transition, agrees better than all the three variants of the k-k_L-ω model with experimental and LES methods.

Aerodynamic coefficients

In Table-4, the three aerodynamic coefficients obtained from the three variants of k-k_L-ω model are compared with XFOIL, LES and experimental results. It can be seen that the C_d value obtained from the Falkner-Skan based variant of the model agrees quite well with the LES result. However, all the variants of the model underpredicted the lift coefficients which can be attributed to the inaccurate transition modeling capability of the present analysis performed with steady-state RANS based solver of OpenFOAM.

Figure-3. Comparison of C_p for three mesh sizes.

Figure-4. Comparison of skin friction coefficients (C_f).

Table-3. Comparison of separation and reattachment locations for sd 7003 at re=60,000 and $\alpha = 4°$.

	Method	Free-stream turbulence (%)	Separation location (x/c)	Transition	Reattachment location (x/c)
Experimental					
IAR Tow Tank by Ol *et al*. [2]	PIV	0	0.33	0.57	0.63
TU-BS Low-Noise Wind Tunnel by Ol *et al*. [2]	PIV	0.1	0.3	0.53	0.62
AFRL Free-Surface Water Tunnel by Ol *et al*. [2]	PIV	~ 0.1	0.18	0.47	0.58
CFD – DNS					
Discontinuous Galarkin Method DNS by DeWiart *et al*. [3]	DNS/DGM		0.209		0.654
CFD – LES					
Discontinuous Galarkin Method by Uranga *et al*. [4]	ILES/DGM		0.210		0.650
Discontinuous Galarkin Method by DeWiart *et al*. [3]	ILES/DGM		0.207		0.647
Implicit LES by Galbraith and Visbal [6]	ILES		0.230	0.550	0.650
LES 3D by Yuan *et al*. [8]	LES 3D		0.250	0.490	0.600
LES Q2D by Yuan *et al*. [8]	LES Q2D		0.210	0.480	0.590
CFD – RANS					
k-kL-ω (Without Modification) - Fine Mesh	RANS	0.1	0.169		0.893
K-kL-ω (Falkner-Skan) - Fine Mesh	RANS	0.1	0.189		0.805
K-kL-ω (Pohlhausen) - Fine Mesh	RANS	0.1	0.184		0.825
Linear Stability Theory based					
XFOIL 6.99	e^N Method	0.07 (Ncrit 9)	0.206	0.548	0.593

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Table-4. Comparison of moment, drag and lift coefficients.

	C_m	C_d	C_l
k-k_L-ω (Without Modification) – Fine	-0.0463	0.0218	0.5223
k-k_L-ω (Folknar-Skan) – Fine	-0.0387	0.0188	0.5150
k-k_L-ω (Pohlhausen) – Fine	-0.0402	0.0195	0.5160
XFOIL (Ncrit = 9)	-0.0355	0.0199	0.6253
ILES by Galbraith and Visbal	-	0.021	0.59
Experiment by Selig et al. (Selig et al. 1995)[25]* at Re=61,400	-	0.0166	0.6038

* Interpolated for α = 4º

CONCLUSIONS

Two recently developed pressure-gradient sensitive variants of k-k_L-ω model are investigated for SD7003 airfoil at low Reynolds number where the flow is dominated by a large LSB. Both the variants under-predicted C_l values and slightly over-predicted the C_d values. And, both of these variants gave better prediction of separation of the laminar BL but the reattachment location was delayed significantly. It has been found that the Falkner-Skan based variant predicts the reattachment location slightly earlier than the Pohlhausen based variant and thus conforming better with different experimental and computational results.

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