Passive flow control strategies for low Reynolds number airfoils

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Abstract. This study focuses on ameliorating the aerodynamic performance of an airfoil in low Reynolds number regime by implementing a passive flow control technique to suppress the effects created by the bubble bursting which holds significance in enhancing the aerodynamic performance of SUAVs which fall under this regime. A numerical study is conducted for the flow over E387 airfoil at a Reynolds number $10^5$ to investigate the effects of the implementation of the passive flow control configuration on the laminar separation bubble dynamics. It is noted that orientation, thickness, inlet location, and configuration of the passive flow control passage had imposed significant effects on lift and drag coefficients generated by the airfoil. A significant drag reduction was achieved when the airfoil is implemented with a slot oriented at 30° that has a converging exit which resulted in the rise of the airfoil’s aerodynamic efficiency.

1. Introduction
In low Reynolds number regime, even due to a slight adverse pressure gradient, the formation of the laminar separation bubble is encountered on an airfoil. The bursting phenomenon of the separation bubble is detrimental to the aerodynamic performance of the airfoil used in SUAVs that fly in this regime. With an increase of incidence or a reduction in speed, the separated shear layer may fail to reattach and the short bubble may burst to form either a long bubble or an unattached free shear layer [1]. O’Meara et al. [2] observed that with an increase in the angle of attack, the laminar separation point is moved forward without any significant change in the length of the bubble. Hence, various active and passive flow control techniques are being adopted to improve the performance of the airfoils or wings in low Reynolds numbers regime. A numerical study by L. Huang et al. [3] shows that in low Reynolds numbers blowing on NACA0012 at downstream locations decreased the drag and a suction jet near the leading edge increased the lift. A. V. M. Kumar et al. [4] studied that constant and periodic heat sources at the lower nose of the NACA0012 have reduced drag. Sang Hoon Kim et al. [5] utilized a single synthetic jet to get an increase in lift and decrease in drag when the velocity of the synthetic jet is thrice the free stream velocity at higher angles of attack. The laminar separation bubble was eliminated by synthetic jet at 0° angle of attack in an experiment conducted by M. Gul et al. [6]. A numerical study done by Xie et al. [7] on S809 airfoil with slot had increased the lift and slightly decreased the drag produced at higher angles of attack. Based on the research conducted above on flow control techniques, this study focusses on enhancing the aerodynamic performance of an airfoil in low Reynolds number regime by implementing a passive flow control technique. A numerical study is conducted to investigate the aerodynamic performance of E387 airfoil when implemented with a passive flow control configuration in $10^5$ Reynolds number.
2. Numerical setup

The S809 airfoil implemented with a slot from the Xie et al. [7] paper is validated at a Reynolds number $10^6$ and E387 airfoil implemented with various slot passages is considered for the numerical study at $0^\circ$ angle of attack and Reynolds number $10^5$ while the chord of the airfoil is considered as 0.305m which falls under the range of typical chord length of SUAVs. A structured C-H mesh domain having dimensions 19.67 times the airfoil chord length is generated in ANSYS ICEM CFD 2019 R1 with appropriate cell growth rate and biasing of nodes toward the airfoil surface ensuring that wall $y^+$ is less than 1 as shown in figure 1. ANSYS FLUENT 2019 R1 employing transient pressure-based solver with double precision is used for performing numerical simulations. Transition – SST (4 equations) turbulence model is used for predicting boundary layer physics and laminar separation bubble dynamics accurately. The no-slip wall boundary condition is set for the airfoil surfaces, the inlets of S809 and E387 airfoils are specified with velocities 47.8929ms$^{-1}$ and 4.8755ms$^{-1}$ respectively, both their outlets are specified with 0 Pa gauge pressure and the turbulent intensity is set to 0.11%. All the residual values are set to 0.0001 and the simulations are run for a flow time of 4s.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** The Computational Structured C-H Mesh for the flow field around (b) S809 airfoil (c) S809 airfoil with slot, (d) E387 airfoil, (e) E387 airfoil with 0.002 m thick slot oriented at 30\(^\circ\), and (f) E387 airfoil with the same slot having a converging exit in ANSYS ICEM CFD.

3. Numerical Validation

Numerical simulation results of S809 airfoil is validated with experimental results [8] and are compared with the results obtained by Xie et al. [7]. It is observed that the numerical results that are run with Transition SST turbulence model closely matched with the experimental results following a similar trend of a dip and rise in lift coefficient at higher angles of attack compared to the results from Xie et al. [7]
paper which used SST-κ-ω turbulence model (2 equations eddy viscosity) as shown in figure 2. Numerical simulations of S809 airfoil implemented with slot suggest that upon addition of the slot there resulted in a rise in the drag and fall in the lift. Numerical simulation results and experimental results [9] of E387 airfoil are observed to be closely matching with each other as shown in figure 3.

![Figure 2](image1.png)

**Figure 2.** The plots showing Lift curve and Drag polar for the flow past S809 airfoil for $R_e = 10^6$ obtained from numerical simulation results, experimental results [8], Xie et al. [7] paper and numerical simulations obtained for S809 airfoil with slot.

![Figure 3](image2.png)

**Figure 3.** The plots showing Lift curve and Drag polar obtained from numerical simulations and experimental data [9] of the flow past an E387 airfoil at $R_e = 10^5$.

4. Results and discussion

Numerical simulations are performed at $10^5$ Reynolds number for the flow past E387 airfoils implemented with 0.003 m thick slots oriented at 12.97°, 30°, 60° and 90° w.r.t chord line with all their inlet locations at 0.1c from the leading edge on the airfoil’s pressure surface at 0° angle of attack. The E387 airfoil with 12.97° slot orientation, the slot cuts through the laminar separation bubble while bubble bursting takes place for the airfoils with remaining slot orientations. The numerical results suggest that there is a loss in lift coefficient upon addition of the slot of any orientation to the airfoil.
With increasing slot orientation from 30° to 90°, both the lift and drag coefficients generated by the airfoils kept decreasing as shown in table 1. The airfoil with the slot oriented at 90° has very little flow passing through the slot and it produced the least amount of both drag and lift coefficients among the airfoils. Although the airfoil with the slot oriented at 30° generated the highest drag coefficient, it generated the least amount of loss in the lift coefficient as compared to that of the airfoils with other slot orientations and hence this slot orientation is considered for the subsequent simulations.

**Table 1.** Time-averaged Lift and Drag coefficients generated for the flow past E387 airfoils with 0.003 m thick slots oriented at 12.97°, 30°, 60° and 90° respectively at α=0°, t = 4 s and Re = 10^5.

| Slot orientation | 12.97° | 30°   | 60°   | 90°   | No slot |
|------------------|--------|-------|-------|-------|---------|
| **c_l**          | 0.29762| 0.34961| 0.29762| 0.28561| 0.37630 |
| **c_d**          | 0.01948| 0.02478| 0.01728| 0.01208| 0.01574 |
| **c_l / c_d**    | 15.278 | 14.109 | 17.223 | 23.627 | 23.903  |

Numerical simulations are performed at 10^5 Reynolds number for flow past E387 airfoil implemented with 0.001 m and 0.002 m thick slots oriented at 30° with their inlet location at 0.1c from the leading edge on the airfoil’s pressure surface at 0° angle of attack. The slot exit geometries for both airfoils are made smooth for facilitating gradual turning of the flow to obey the Coanda effect. The 0.001 m thick slot passage is too slender to let any flow into it. Thus, results obtained for this slot thickness are almost identical with the results of an airfoil without any slot passage. The airfoil with the 0.002 m thick slot is considered for the subsequent simulations as it has relatively improved the aerodynamic efficiency of the airfoil as compared to that of 0.003 m thick slot as shown in table 2.

**Table 2.** Time-averaged Lift and Drag coefficients generated for the flow past E387 airfoils implemented with slots oriented at 30° having various thicknesses at α=0°, t = 4 s and Re = 10^5.

| Slot thickness | 0.003 m | 0.002 m | 0.001 m | No slot |
|----------------|---------|---------|---------|---------|
| **c_l**        | 0.34961 | 0.34358 | 0.34114 | 0.37630 |
| **c_d**        | 0.02478 | 0.02145 | 0.01562 | 0.01574 |
| **c_l / c_d**  | 14.109  | 18.232  | 23.914  | 23.903  |

Numerical simulations performed on the E387 airfoil implemented with a 0.002 m thick slot oriented at 30° which is shifted rightward from slot inlet position 0.1c to 0.15c from the leading edge on the airfoil’s pressure surface, suggest that there is a slight increment in the lift coefficient as compared to the airfoil whose slot is not shifted, but the lift coefficient generated is still around 6.8% lower than that of the airfoil without slot. Although reduction of slot thickness has reduced the drag coefficient, the shifting of the slotted passage only increased the drag coefficient even further as compared to the airfoil whose slot is not shifted, which resulted in a decrease in aerodynamic efficiency as shown in table 3.

Numerical simulations were performed for the E387 airfoil implemented with a 0.002 m slot oriented at 30° whose exit is modified into a converging passage to facilitate the acceleration of flow at the slot exit. Despite this modification generated a lower lift coefficient as compared to the airfoil without slot, a 13.43% reduction in drag coefficient was achieved as shown in table 3, which resulted in a considerable improvement in aerodynamic efficiency of the airfoil.

When the E387 airfoil is implemented with a slot which is shifted rightward to the inlet position 0.15c from the leading edge on the pressure surface of the airfoil and the slot’s exit is modified into a converging passage, the numerical simulation results suggest that the lift coefficient generated is nearly same as that of the airfoil with a converging exit alone and the drag coefficient generated is nearly same as that of the airfoil without slot as shown in table 3.
5. Conclusions

1. Numerical simulations are executed for the E387 airfoils implemented with various passive flow control configurations to investigate their aerodynamic performances. The orientation, thickness, inlet location, and configuration of the passive flow control passage had imposed significant effects on the lift and drag coefficients generated by the airfoil. The loss in the lift coefficient is encountered upon the addition of any slot configuration to the airfoil.
2. The airfoil implemented with a slot oriented at 30° generated the highest lift coefficient among airfoils with other slot orientations.
3. While a 0.001 m thick slot is too slender to let any flow into it, a 0.002 m thick slot has improved the aerodynamic efficiency of the airfoil than that of a 0.003 m thick slot.
4. The gradual turning of the flow coming out of the slot was facilitated by smoothening of the slot exit geometry to obey the Coanda effect.

| Table 3. Time-averaged Lift and Drag coefficients generated for the flow past E387 airfoils with shifted slot with converging exit, shifted slot, slot with converging exit and for the flow past E387 airfoil with unmodified slot, all slots are oriented at 30° and have thickness 0.002 m at α=0°, t = 4 s and Re = 10^5. |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                                | Shifted slot    | Converging slot exit | Shifted slot with converging exit | Unmodified slot | No slot |
| cl                             | 0.35063         | 0.32475           | 0.32434         | 0.34348         | 0.37630         |
| cd                             | 0.02338         | 0.01363           | 0.01568         | 0.02145         | 0.01574         |
| cl/cd                          | 17.192          | 27.414            | 20.951          | 18.232          | 23.903          |

Figure 4. Computed Velocity contours obtained from numerical simulations for the flow past (a) E387 airfoil implemented with a 0.002 m thick slot with its inlet located at 0.1c and oriented at 30°, (b) when the slot inlet is shifted to 0.15c, (c) with a converging slot exit, and (d) when the slot inlet is shifted to 0.15c and with a converging exit at α=0°, t = 4 s and Re = 10^5.
5. Upon modifying the slot’s exit into a converging passage, a maximum of 13.43% reduction of drag coefficient leading to a considerable rise in aerodynamic efficiency of the airfoil by 14.69% was achieved.

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