A 2D Simulation of the Flow Separation Control over a NACA0015 Airfoil Using a Synthetic Jet Actuator

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Abstract. The present study aims to investigate numerically the flow control possibility using a synthetic jet actuation over a bi-dimensional NACA0015 airfoil manoeuvring at a highly turbulent flow (8.9e10 Reynolds to chord number). The 2-D flow behaviour was computed using the ANSYS Fluent commercial code. The so-called Reynolds Averaged Navier-Stokes (RANS) approach has been tested for one (Spalat-Allmaras S-A) and two (K-ε) transport equations for the turbulence modelling. Both present a weakness to predict the stall angle effectively. The S-A lift coefficient slope seems to be the closest to the experimental data. The synthetic jet control exhibits an extraordinary lift coefficient enhancement at high Angles Of Attack (AOA) but seems to be less obvious at low AOA, where the flow is still attached. A synthetic jet of a Strouhal (St = 2) and momentum (Cμ of 0.56%), delays the stall onset from 15 to 19deg with enhancing the lift coefficient by 40%. The actual work has been enriched by studying the effect of the jet’s frequency and momentum on the lift temporal signal. Also, the interaction between the mean flow and the synthetic jet structures topology was undertaken.

1. Introduction

Despite the huge advancement reached in the aero/hydrodynamic fields, the boundary layer instability remains one of the most challenging purposes facing scientists and engineers. Aiming usually to delay or eliminate the boundary layer separation, unless otherwise for spoilers or speed brakes- in order to enhance the aerodynamic performances at the same wing body geometry. Postponing the separation onset can be traduced by a lift increase, drag reduction and a stall delay. These three latter lead to deal with huge issues in both civilian and military domains.

In the civilian aviation, the economic and environmental issues are more and more strict, reducing the drag goes together with a fuel consumption reduction and therefore more green flights. While, the military sector looks for higher air superiority and tactic ability. Both can be increased by enhancing the aircraft’s manoeuvrability and shortening the take-off and landing required distance.

According to the energy expended to set a flow control, Gad-el Hal et al. [1] classified the control strategies into two main kinds. A passive control requiring any auxiliary power to be used (ex: vortex generators) and an active control which requires contrary to the first one an external power to be set
(ex: suction/blowing actuators). Even if the named control strategies reached a high-efficiency level, they are usually fed from the engine compressed air, ex: the MiG21 can reduce his approach speed by 40 km/h using a continue blowing control. That requires a complex piping apparatus and constitutes an additional load for the engines. Also in the case of an engine failure, pilots may lose the lift force when the most needed.

Nowadays, research focus on how to enable continuous suction or blowing technics to save on the actuator energy by reducing the injected rates. Continuous control has become alternative or pulsed. At a first approximation, one can say that a synthetic jet is generated by a succession of blowing and suction phases. The mean jet resulting does not bring any additional fluid from where they named as a Zero Net Mass Flux ZNMF technic. Technically, we find plenty of solutions enabling the generation of this type of jet. Devices driven by piezoelectricity, electrostatic, thermal or acoustic can be small enough to be accommodated within the controlled body and have a localised action. However, they cannot provide a high-speed ejection, particularly when their membranes are activated at frequencies away from their resonance frequency. The thing that has delayed the use of this type of actuators compared to their counterpart based on a simple mechanical principle as carried out by Gilarranz et al [2].

It was found that the actuator geometry scale and the fluid characteristics are key points in the ring or pair vortex formation in a ZNMF. Several studies aim to parameterize its generation criteria. A number of dimensionless parameters governing the production and evolution of the SJA are carried out. Glezer et al [3], and Smith and Glezer [4] started by proposing two independent parameters. The first one relative to the blown fluid column size named the stroke length ratio. The second one based on the blowing stroke Reynolds number. Utturkar et al [5], and Holman et al[6] found that the ratio $\frac{V_l}{V_s}$ of the self-induced velocity in a vortex generation at the blowing stroke $V_l$ and the mean velocity at the suction stroke $V_s$ must be greater than a known value $K$ (dependent to the ZNMF) to avoid the vortex reversibility to the actuator during the suction stroke. They proposed the following:

$$\frac{V_l}{V_s} \sim \frac{1}{St} = \frac{Re u_0}{St} > K \tag{1}$$

Where, $St = (\frac{2\pi Re u_0}{L})^{1/2}$ is the Stokes number and $St = \frac{2\pi f D_0}{u_0} = \frac{2\pi}{L}$ is the Strouhal number. Thereby the Strouhal number used in the present study found to be relative to the vortex shedding is based on the flow field and not on the actuator scale.

For a ZMNF interacting with a mean flow boundary layer -the case usually met in the flow control applications- the momentum amount released by the SJ to this latter is found to be exceptionally essential for the control efficiency. Different definitions of the momentum coefficient can be found in the literature McCormick [7], Amitay et al [8], Tuck and Soria [9] and Seifert et al [10]. In the present study we take the momentum coefficient as defined in Gilarranz et al [2]’s work:

$$C_m = \frac{e(\rho u_{max})_{jet}}{c(\rho u^2)_{so}} \tag{2}$$

Where, $e$ is the slot diameter and $c$ is the airfoil chord length.

In the present work, the commercial software ANSYS FLUENT is used to solve the steady Reynolds-Averaged Navier-Stokes (RANS) equation for a highly turbulent flow over the two-dimensional NACA0015 airfoil under two turbulent model closure (S-A) and (K-ε). Once the turbulence model was chosen, the synthetic jet control technic is computed and then compared to the experimental data. Further topology analyses are made concerning the mean flow-synthetic jet interaction.

2. Problem position

The stall phenomenon is more or less an abrupt loss of the lift force due to the huge flow separation. Even if the stall onset is usually encountered at reduced speeds, it can occur practically at any flow velocity and depends on other parameters as the flight configuration, the load factor and the meteorological parameters. Aiming to simulate the synthetic jet actuation ability to postpone the stall’s
occurrence, a 2D NACA 0015 was chosen because of its symmetry, making the validation easy at a zero Angle Of Attack AOA from one hand and its abundance in the literature, on the other.

The same experimental apparatus carried out by Gilarranz et al [11] was reproduced to facilitate the computing validation. The airfoil is an NACA 0015 with 375 mm chord-wise, dotted by a 2 mm diameter synthetic jet actuator SJA, fitted at 12% its chord. The Reynolds number Re of 8.96 \(10^5\) is reached at a free stream velocity of \(U = 35\text{m/s}\).

3. Computation procedures

The flow behaviour over the airfoil is estimated by resolving the Reynolds Averaged Navier-Stokes (RANS) equations using the commercial software (ANSYS Fluent) based on the finite volume method. The flow is supposed to be steady, viscous and two-dimensional. We assume that the flow is incompressible as the velocities encountered are far below the sound’s speed maintaining the air density constant. (Mach number \(M \leq 0.3\)). The energy equation is decoupled, as there is no heat transfer. As the air is a light gas, we can easily neglect the volume forces and the air weight. The RANS equations constitute an open system due to the new random variables resulting from the averaged quantities. This requires additive equations to solve the system. In the present work, two turbulence first order models – well described in the literature - were used for the system closure. The first one at one transport equation called Spalart-Allmaras S-A and the second one is at two transport equations called K-\(\varepsilon\).

For an external flow as over an airfoil, it is beneficial to define the boundaries as far as possible from the body geometry to enhance the far field boundary condition accuracy. A constant velocity defines the inlet condition. The different AOA are obtained in each case by varying the inlet velocity components. The wing body is defined by its adherence and set as wall condition. The control parameters are introduced by setting a modulated speed as a User Defined Function UDF to the SJA section (2 mm) at 12% of the upper surface using a moving wall condition. The controlling flow will be normal to the airfoil chord, sinusoidal in time and constant in the space. The jet speed is defined as follow:

\[
v(x, y) = (0, U_{\text{max}} \sin(\omega t))
\]

While the flow is considered incompressible, as said before, it is more convenient to resolve the partial differential equations using the Fluent’s coupled algorithm based on the pressure. The second order upwind scheme was used to interpolate the convection terms of momentum and turbulence. In which concern the pressure-velocity coupling, the algorithm SIMPLE is used. The resolution convergence can be acceptable for all the simulations, where all the residual quantities go below a \(10^4\) order with a stabilisation of the calculated aerodynamic coefficients.

4. Grid generation

After importing the airfoil geometry into the software Gambit, the computational domain is defined and filled using a quadrangular structured 2D ‘C grid’ (“quad-map” for Gambit) by imposing the same discretization for all segments facing. This for all the simulations carried out. One notes that the airfoil discretization is performed accordingly to the profile curvature. The boundary layer is generated by a front mounted to ensure a sufficiently fine grid near the walls where the higher pressure gradients are located. The blockings are so meshed by defining the number of elements and the geometric reasons at each face. Once the ratio height-width allows, the mesh becomes coarser to alleviate the computational requirements. To reach an optimal computational accuracy, three grids were tested for both turbulence models while looking out the grid-to-solution dependency and the value of \(y^+\).

|     | Coarse | Medium | Fine |
|-----|--------|--------|------|
| S-A | 83     | 24     | 5    |
| K\(\varepsilon\) | 70     | 28     | 9    |

Table 1. \(y^+\) values obtained at a Re of 8.96 \(10^5\) for both K-\(\varepsilon\) and S-A models for a 18 900, 26 300 and 37 400 quadrilateral cells.
Simulations were done for each two degrees from 0 till 22 deg AOA using the coarse grid for the $K\varepsilon$ and the fine grid for the S-A turbulence model which correspond respectively to the relatively high value 70 of $y^+$ and the moderately low value of 5. For a zero AOA, both turbulent models present a perfect symmetry between the suction and pressure surfaces with a zero lift coefficient as expected from the NACA0015 bilateral symmetry independently to the grid.

Figure 1 shows how the upper surface $Cp$ superposes perfectly on the lower surface one and highlights the high depression near the leading edge. Then, the softening of the depression along the chord with the airfoil thickness decrease. This applies to both turbulence models. Curves coincide on the whole airfoil except at the leading edge where the stop pressure is the exception. This difference is important in view of the simplicity of this test case. The problem is due probably to the fact that the mesh is not refined enough at the leading edge.

For validation purposes, the lift coefficient is plotted in the Figure 2 for both S-A and K-$\varepsilon$ against the Gilarranz et al [11]’s experimental one.

For small AOA (lower than 7deg) the two models match perfectly with the experimental data. When the airflow starts separate (higher than 7deg AOA) both simulations experience a slight gap from the experimental values. This latter becomes more and more remarkable for the nearby stall AOA.

![Figure 1](image1.png)  ![Figure 2](image2.png)

**Figure 1.** Pressure Coefficient $Cp$ at zero AOA for both S-A and K-$\varepsilon$.

**Figure 2.** Lift coefficient validation, both S-A and K-$\varepsilon$ plotted against the Gilarranz et al [11] data.

**Table 2.** Simulation validation parameters

| Models | Stall AOA | $C_{l_{max}}$ | $\frac{C_{l_{num}} - C_{l_{exp}}}{C_{l_{exp}}}$ | $\frac{C_{l_{num}} - C_{l_{exp}}}{C_{l_{exp}}}$ | Slope Behaviour |
|--------|-----------|----------------|---------------------------------|----------------|-----------------|
| Experiment | 12.6 | 1.01 | | | |
| S-A | 15 | 1.03 | 1.9% | 0.01 | Identical |
| K-$\varepsilon$ | 18 | 0.96 | 4.9% | 0.05 | Different |

Table 2 summarises the different validation parameters, where $\alpha$ designs the AOA. Both models display a stall delay prediction with a module variation. These differences between the experimental data and the numerical simulations show that the current RANS methods cannot simulate the airfoil stall properly. However, in the present study, authors opt for the S-A model for all SJA controlled cases. Because it offers the lowest stall angle variation and a typical thick airfoil lift coefficient behaviour, contrary to the K-$\varepsilon$ presenting a double jump behaviour, which usually characterises the
thin airfoils. The pulsed slot of the SJA has been defined as a 2 mm skin segment at 12% of the chord. A new grid is generated by refining the mesh near the slot and conserving the previous y+ and distortion conditions.

5. Results

5.1. Aerodynamic coefficients

The SJA control strategy combines both suction and blowing control mechanisms. It against the flow separation by energising the boundary layer and therefore, overcomes the adverse pressure gradient. That can be realised at the different control cycles by adding a momentum to the weak boundary layer. At the suction cycle, the lower momentum is aspired into the actuator cavity shifting, therefore, the higher momentum closer to the airfoil surface. Then, at the blowing period, the actuator releases the same flow amount, now at higher momentum. In addition, the system frequency creates vortices cores leading to enhance the mixture region between the inner (weak) region and the outer (energised) region. This makes the boundary layer more turbulent and thereby, effectively energises it.

Figure 3 shows a ($St = 2, C\mu = 0.56\%$) SJA control effect on the NACA0015’s lift coefficient. The flow control does not seem to bring any positive effect at the low AOA. Until 8 deg AOA, where the flow is mainly attached to the wing body, the two curves remain slightly superposed. For the higher AOA, when the separation is more obvious and affects more the flow patterns, the control strategy enhances the lift coefficient dramatically by energising the boundary layer and therefore delaying the separation occurrence. Under the present actuation parameterisation, the lift coefficient knows an extraordinary jump of about 40% from 1.01 to 1.44 for the airfoil without and with control respectively. This can be traduced practically by a higher load and action range. The stall onset is also postponed from 15deg to 19deg, giving thereby four more exploitable degrees allowing to higher manoeuvrability.

Once reaching the $Cl_{max}$, The two cases present different slide slope. The basic airfoil smoothly stalls as expected from a thick airfoil as the NACA0015. Here the flow separation starts from the trailing edge and overtakes the leading part when pitching to further AOA. In contrary, the controlled airfoil experiences a different behaviour. It abruptly stalls and loses his lift similarly to the leading edge stalls usually encountered for the medium aerofoils. These stalls are characterised by forming a bubble just after the leading edge. The size this latter does not vary too much with the AOA increase until it bursts under the action of the high adverse pressure leading to a more aggressive stall. The SJA control does not provide a significant effect on the lift enhancement for the AOA greater than 19 deg. This at least for the present parameterization.

In Figure 4 the drag coefficient is plotted against the lift one for both controlled and not cases. Two domains are easily distinguished. For the lower AOA, the drag force is mainly composed of a parasitic drag. The SJA makes the boundary layer more turbulent. It, therefore, procures a higher drag level without any consistent lift gain.

For higher AOA leading to a $Cl > 0.75$, the induced drag amount increases significantly for both airfoils. The flow separation leads to an additive drag clearly noticed for the uncontrolled airfoil. This extra drag supposed to result from the wake blockage and the vortex cores shedding can be largely reduced by delaying the flow separation onset, and therefore the SJA succeeds to reduce the drag coefficient dramatically. This can be explained by the fact that a laminar boundary layer induces a lower friction drag than a turbulent one. However, the latter resists more to the separation. Thus, for a separated laminar boundary layer, the viscous drag is much greater than if the boundary layer is turbulent and remained attached.
Figure 3. SJA effects on the lift coefficient at Re of 8.96 $10^5$.

Figure 4. SJA effects on the aerodynamic performance, Drag coefficient vs. Lift coefficient.

5.2. Topological analysis of the flow created by the actuator

Figure 5a shows how the flow separates over the NACA0015 at 15deg AOA. The separation is clearly a trailing edge separation as presented by the streamlines and it causes the airfoil stall as noticed from the lift coefficient in the section above. Figure 5b illustrates the ability of the current control to eliminate the flow separation all over the suction surface. The flow establishment delays then the stall occurrence and procures higher lift force with lower drag.

For better understanding of the control phenomenon, this section undertakes the interaction (free stream-synthetic jet) by limiting to the streamlines pattern at the different actuator phases focusing on the evolution of the vortex topology.

Under the same control settings as the section above, at 15deg AOA Figures 6 show the near slot vortex development over one control cycle.

For, $t = T / 8$, the synthetic jet starts blowing in an attached boundary layer in the y direction as shown in (Figure 6a). The incoming flow enters in a collision with the synthetic blown detaching the boundary layer locally, and rolling a pretty strong vortex, located just downstream of the slot. The upstream counter-clockwise vortex expected to be noticed seems to be annulled by the boundary layer having a clockwise vorticity.

For, $t = T / 4$ as the synthetic jet intensifies until its maximum, the first vortex moves aft away from the slot, while growing as its size reaches approximately ten times the slot diameter $10 e$ of length, and $5 e$ in height releasing enough space for a second vortex generation. Upstream of the slot a strong shear zone is visible. The flow plunges to the wall just before being thrown up under the influence of the jet blowing giving birth to a new vortex structure as Figure 6b expresses.

In which concern the blow reducing phase ($t = 3T / 8$), as the border between the latter vortex and the jet still intense is strongly sheared and unstable, it creates a third vortex structure extending almost to the body skin. The last two vortices are weaker and smaller compared to first one generated (Figure 6c).

For $t = T / 2$, the vortex structures continue moving away from the slot. While the free stream is driving these structures downward, it tends to stretch them while still creeping to the wall (Figure 6d).

Contrary to the first half-period, the suction phase is manifested only by one behaviour. It is the place of the boundary layer reattachment near the slot (Figures 6 e & f) and the different vortex convection along the upper surface. The dominant element of this flow is the primary vortex, which is the largest and one whose life is the longer.
5.3. Synthetic jet control parameterisation

Synthetic jets are a parietal source of momentum to which the length and the time scales characteristics are controlled. This feature becomes remarkable in view to achieve a flow control since it becomes possible to combine the influence of two physical quantities, namely the time scale by an alternative excitation ($St$) and a spatial size by a momentum ejection rate ($C_\mu$). It is common to delay the flow separation by simple boundary layer suction or momentum injection, but if we can provide an alternative jet having a frequency near those of the large unstable coherent structures. This may promote the boundary layer mixing and therefore increases the momentum amount added thereto, which can delay much more efficiently the separation phenomenon. Below will assessed the effect of the two parameters on the lift coefficient separately.

**Figure 5.** streamline pattern for a 15deg AOA flow: a) uncontrolled, b) a $St = 2$, $C_\mu = 0.56\%$ SJA control
5.3.1. Jet frequency effect. In order to distinguish the jet frequency effect on the control mechanism, various dimensionless excitation on $St$ are introduced while holding the $C_\mu$ at 0.56%.

Figure 7 shows the lift coefficient temporal reaction to four control frequencies $St$: 0, 0.2, 0.8 and 2. The lower control frequency seems incapable to fix the lift signal and other frequencies not related to the SJA appear as a mean flow coherent structures generation. Once the SJA reaches to lock the lift temporal as for a $St$ of 0.8 and 2, the lift averaged value remains slightly the same while the signal amplitudes are proportionally shrunk according to the excitation frequency.

5.3.2. Jet momentum effect. Once the reduced operating frequency of the synthetic jet is fixed, the effect of its momentum is investigated. The blown momentum $C_\mu$ is changed by varying the maximum jet amount ($U_{\text{max}}$). Three pic speeds $U_{\text{max}}$ were tested: of $U$, $U/2$ and $U/4$ which correspond respectively to a $C_\mu$ of 0.53%, 0.13%, 0.03%.

Figure 8 shows how the lift temporal demurs mainly random for a $C_\mu$ of 0.03% where no frequency locking is noticed and the peak to peak amplitudes remains significant. This attests a control failure under this SJA parameterisation. Higher speed control $U_{\text{max}}$ leads imperatively to a signal lock into the control excitation frequency. A proportional relation is to highlight between the temporal lift...
amplitudes and the momentum injected while the averaged lift remains invariant. The $C_\mu$ of 0.13% which seems optimally controlling the present flow (15deg AOA) is not able to do the same at 19deg AOA where the 0.53% jet does. Higher AOA generate greater wake and larger structures, which require higher momentum to be locked.

![Figure 7. Lift coefficient temporal signal for different $St$ excitation control.](image)

![Figure 8. Lift coefficient temporal signal response to a various SJA momentum $C_\mu$.](image)

6. Conclusion

The interaction of a synthetic jet with a turbulent boundary layer "Re = 8.96 $10^5$" developed over an NACA0015 was simulated over a range of 20 degrees of incidence and compared to a similar experimental apparatus data. The S-A turbulent model expressed a greater agreement with experimental data compared to the K-\varepsilon model. It provides a closer lift slope with a certain gap. These variations proportional to the AOA, probably result from the RANS limitations, including the loss of the turbulent information by averaging. The SJA control was able to expand spectacularly the flight domain, where it shifted the critical stall angle from 15deg to 19deg with a lift gain exceeding 40% accompanied by a significant drag reduction.

A control parameterization was based on the frequency and jet speed dimensionless respectively on $St$ and $C_\mu$. It concludes a proportional relationship between the jet momentum and the lift signal amplitudes. Contrary, the control frequencies react inversely with the temporal peak-to-peak values. Thus, it can be concluded in the current state of research that is quite difficult to design a unique grid of SJA capable of controlling the flow at different flight configurations. This is the consequence of the jet aerodynamic parameters dependence and also its position and orientation, the slot shape, the jet modulation, the $Re$ and the $Mach$ number and the airfoil geometry.

Perspectives are to enhance the SJA effectiveness furthermore. In this sense, the focus on a reactive smart control having the ability to vary the jet proprieties depending on the main flow state. It is well known from the bibliography that a boundary layer requires less momentum to be kept attached than to reattach from a separated state. Similarly for the frequencies required.

7. References

[1] Gad-el Hak, Mohamed & Bushnell, Dennis M 1991 Separation control: review. *Journal of Fluids Engineering* 1991; 113 (1), 5-30.

[2] Gilarranz J, Traub L, Rediniotis O. A new class of synthetic jet actuators—part I: design, fabrication and bench top characterization. *Journal of fluids engineering*. 2005; 127(2):367-76.

[3] Glezer A, Amitay M, Honohan AM. Aspects of low-and high-frequency actuation for aerodynamic flow control. *AIAA journal*. 2005; 43(7):1501-11.
[4] Smith BL, Glezer A. The formation and evolution of synthetic jets. *Physics of Fluids* (1994). 1998; 10(9):2281-97.

[5] Utturkar Y, Holman R, Mittal R, Carroll B, Sheplak M, Cattafesta L. A jet formation criterion for synthetic jet actuators. *AIAA paper*. 2003; 636:2003.

[6] Holman R, Utturkar Y, Mittal R, Smith BL, Cattafesta L. Formation criterion for synthetic jets. *AIAA journal*. 2005; 43(10):2110-6.

[7] McCormick D. Boundary layer separation control with directed synthetic jets. *AIAA paper*. 2000; 519:2000.

[8] Amitay M, Honohan A, Trautman M, Glezer A. Modification of the aerodynamic characteristics of bluff bodies using fluidic actuators. *AIAA paper*. 1997; 2004.

[9] Seifert A, Darabi A, Wyganski I. Delay of airfoil stall by periodic excitation. *Journal of Aircraft*. 1996; 33(4):691-8.

[10] Tuck A, Soria J, editors. Active flow control over a NACA 0015 airfoil using a ZNMF jet. *15th Australasian fluid mechanics conference*, 2004.

[11] Gilarranz J, Traub L, Rediniotis O. A new class of synthetic jet actuators—part II: application to flow separation control. *Journal of fluids engineering*. 2005; 127(2):377-87.