MODELING OF TANGENTIAL SYNTHETIC JET ACTUATORS USED FOR PITCHING CONTROL ON AN AIRFOIL

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Abstract. *Pitching moment control in an airfoil can be achieved by trapping concentrations of vorticity close to the trailing edge. Experimental work has shown that synthetic jet actuators can be used to manipulate and control this trapped vorticity. Two different approaches are used to model the action of tangential-blowing synthetic jet actuators mounted near the trailing edge of the airfoil at different angles of attack: a detailed model and Reynolds stress synthetic jet (RSSJ) model. The detailed model resolves the synthetic jet dynamics in time while the RSSJ model tries to capture the major effects that the synthetic jet induces in the flow by modeling the changes in the Reynolds stress induced by the actuator. In the RSSJ the effects of the synthetic jet actuators are modeled as local momentum sources based on numerical results from the detailed model. While the RSSJ model reduces the complexity of the simulation (geometry and boundary conditions) in comparison with the detailed model, it only captures the average behavior of the synthetic jet, and requires extensive data to be calibrated. Numerical results are focused on the actuation effects on the vorticity field and the aerodynamic properties. Both models along with the Computational Fluid Dynamics (CFD) computations in which they are embedded are validated against wind tunnel data acquired by Dr Ari Glezer's group at Georgia Tech. The synthetic jet models have been developed to simulate closed loop flow control of the pitching and plunging of the airfoil, and to this end the RSSJ model is particularly useful since it reduces the cost of simulating the long-term evolution of the system under control.*

Keywords: *Tangential synthetic jet; Pitching control; Synthetic Jet modeling*

1. INTRODUCTION

During the last decade, there has been a growing interest in small active flow control devices that affect the flow field and modify forces and moments over lifting surface, particularly for low-Reynolds number applications such as Unmanned Aerial Vehicles (UAV). Extensive experimental work has demonstrated that the synthetic jet actuators are an effective way to modify the aerodynamic properties of a lifting surface by manipulating the vorticity near the trailing edge (Amitay *et al.*, 1999) (Parekh *et al.*, 2003) (DeSalvo and Glezer, 2004) (DeSalvo and Glezer, 2007) (DeSalvo and Glezer, 2005) (DeSalvo *et al.*, 2002), giving the potential to replace conventional control surfaces such as flaps, spoilers and deflectors (Amitay *et al.*, 2001). A synthetic jet actuator placed on a lifting surface is capable of modifying the streamlines around a body, as if the shape had been modified, making the synthetic jet useful for the manipulation of the aerodynamic properties of a body. Dr Glezer's group at Georgia Tech has shown that synthetic jet actuators are an effective way to enhance the lift and modify the moments of wings and airfoils (DeSalvo and Glezer, 2004). Effective control has been achieved with actuation frequencies an order of magnitude larger than the natural shedding frequency of the body (Amitay *et al.*, 2001). The development and implementation of CFD models for this synthetic jet application complements the experimental work already done at GA Tech, providing detailed information about the controlled flow. In recent years, CFD has played an important role in flow control problems of low-Reynolds number aerodynamic applications. The majority of the CFD research in low-Reynolds number applications is towards separation control at high angle of attack so that little work has been done towards the simulation to modify aerodynamic properties at low angle of attack (Vadillo and Agarwal, 2006). This paper is focused on computational modeling of tangential synthetic jets used to modify the aerodynamics properties (in particular lift and moment) of an airfoil.

This research is part of the AVOCET (Adaptive VOrticity Control Enabled flighT) project[1], which main objective is to design and build closed-loop flow control with synthetic jet actuators for small scale Unmanned Aerial Vehicles (UAVs). The baseline for this numerical study is the experimental set-up used for the AVOCET project which consists on a 18-in-chord modified NACA4415 airfoil model with two tangential actuators mounted near the trailing edge (see Fig. 1). These actuators have a characteristic height of $\approx 4 \times 10^{-3}$m and an effective jet outlet of 4×10^{-4}m. The Reynolds number based on the chord length and free stream velocity ($U_\infty = 30m/s$) is $\approx 9 \times 10^5$. Figure 1 also shows a detail of the modified airfoil trailing edge, in which is clear that there is an increment in the airfoil thickness close the the trailing edge in comparison to the unmodified (dashed line). More details about the experimental set-up can be found on references: (Brzozowski and A.Glezer, 2002) (Brzozowski *et al.*, 2008) (Muse *et al.*, 2008).

Numerical simulation of synthetic jets is still an active research field in particular because of the wide range of spatial

[1] `http://www.avocet.gatech.edu/`

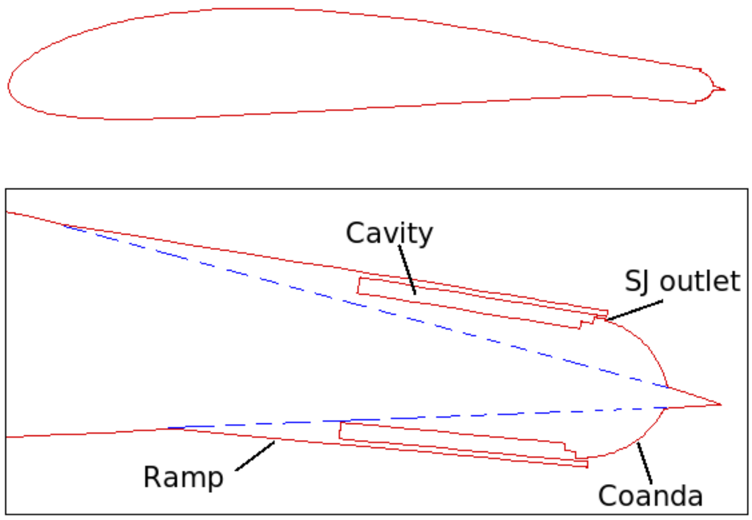

Figure 1. Modified NACA 4415 profile with trailing edge detail.

and temporal scales involved in such a simulation. Several types of models of synthetic jets can be used in simulations of controlled flow: detailed models, reduced-order models (ROM) or a simple periodic surface boundary condition (Rumsey, 2008). One of the important characteristics of synthetic jet actuators used in this numerical study, is the fact that they are tangential. The simulation and modeling of a tangential synthetic jet implies an extra difficulty since such a model would be highly dependent on modeling the interaction with the wall and with the cross flow (Touber and Moser, 2006). In this numerical study two synthetic jet models are presented: detailed model and a new Ad hoc model called Reynolds Strees Synthetic Jet (RSSJ).

2. COMPUTATIONAL TOOLS AND MODELS

2.1 CFD code and turbulence model

CDP[2] an unstructured grid incompressible flow solver was used as the basic CFD tool in this study. CDP was developed at the Center for Integrated Turbulence Simulations (CITS) at Stanford University and it has been widely used in a variety of fluid flow problems becoming one of the state of the art unstructured LES codes (Moin and Apte, 2004). One important characteristic of this CFD code is that is a nearly energy conserving solver (Mahesh *et al.*, 2004), which makes it very attractive for reliable simulations of turbulent flows. But using LES in an aerodynamic application (such as this numerical study) can be expensive in particular close to the airfoil surface (Spalart, 2009) (Spalart, 2000), which is why a hybrid RANS/LES model called Delayed Detached Eddy Simulation (DDES) model(Spalart *et al.*, 2006) was implemented on CDP. DDES is a modification of the Detached Eddy Simulation (DES) model (Spalart *et al.*, 1998) to improve its performance in thick boundary layers and shallow separation regions. In its standard implementation, DDES is based on the Spalart-Allmaras (SA) model which is a one equation turbulence model. DDES implementation on CDP showed satisfactory results in unmodified airfoils and also in unactuated cases with modified airfoil profiles (Lopez *et al.*, 2007) (Jee *et al.*, 2008) (Lopez, 2008).

2.2 Synthetic jet models

Synthetic jet models used in the CFD community can be group in three categories: detailed models, reduced-order models and a simple periodic surface boundary condition. A detailed model resolves all the spatial and temporal scales of the synthetic jet actuator, and are normally fully three dimensional, though they can be simplified to two dimensions. In such models the flow in the synthetic jet cavity is included in the computational domain, and the actuation frequency is resolved temporally, making it expensive. Nevertheless, this is one of the most used synthetic jet models(Rumsey, 2008) (Holman *et al.*, 2005). Reduced-order models (ROM) simplify the physics of the synthetic jet actuator (reducing the complexity of the simulation) and are suitable for flow control applications. For tangential synthetic jet applications, an ROM model has to include the jet-wall interaction which can be difficult to model (Touber and Moser, 2006). Finally, a simple periodic surface boundary condition model is simply the application of a periodic inlet/outlet boundary condition at the synthetic jet outlet, without representing the details of the cavity (Mittal and Cattafesta, 2008). Though this model is

[2] `http://www.stanford.edu/group/cits/research/combustor/cdp.html`

attractive, it is highly dependent on the details of the imposed velocity profile at the synthetic jet outlet. In this study, two different models were used in the simulation of the synthetic jet actuators: a detailed time-resolved synthetic jet model and a synthetic jet model based on an empirical Reynolds stress field induced by the actuator.

2.2.1 Detailed model

This model consists of resolving the spatial and temporal detail of the synthetic jet by imposing an inflow/outflow boundary condition in one of the cavity walls. Though the cavity deformation is not modeled, zero net mass flux is ensured in this model. In order to simulate the diaphragm oscillation, a specified normal velocity

$$U_n = A \sin 2\pi F^+ T \tag{1}$$

was imposed on the left boundary of the cavity (see Fig. 2). In Eq. (1), A represents the amplitude of the boundary condition and it is determined by the experimental velocity at the synthetic jet outlet which is about $\approx 40m/s = 1.333U_\infty$. Here, F^+ is the non-dimensional frequency (based on the chord length and the free-stream velocity) and it is set to 31.242 which for the experimental conditions is a frequency of 2050 Hz. T represents the non dimensional time i.e. $T = tU_\infty/c$ and the time step used in this model was $3 \times 10^{-4}c/U_\infty$ to ensure ≈ 100 samples per actuation cycle. This constraint in the time advancing limits the CFL number to ≈ 9 which is very low for the semimplicit formulation used in CDP.

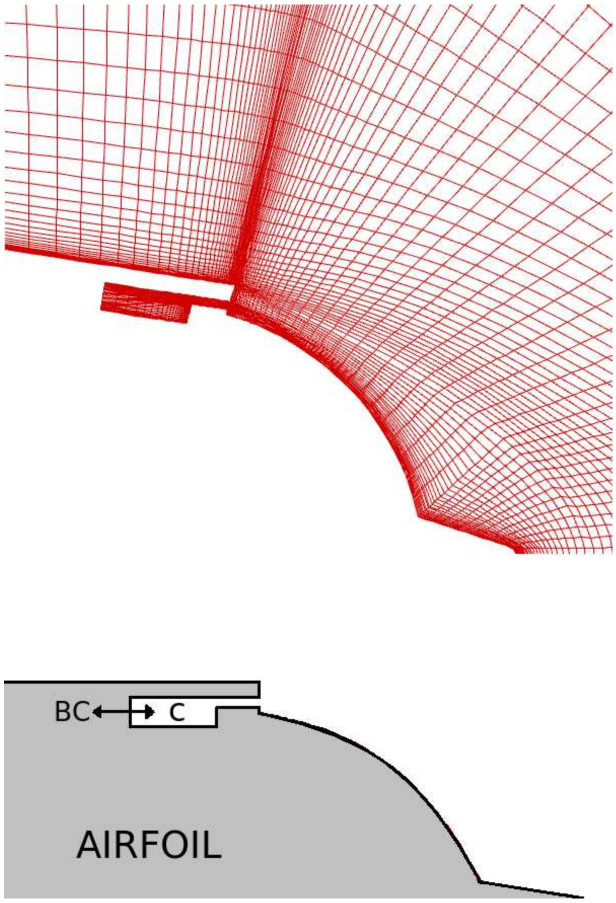

Figure 2. Geometry of the synthetic jet cavity (c) with mesh and detail of the boundary condition (BC)

2.2.2 Reynolds Stress Synthetic Jet (RSSJ) model

This ad hoc model is based on the fact that the actuation frequencies are high in comparison to relevant flow time-scales, which can be inferred from the fact that in order to achieve effective flow control the difference between the characteristic flow frequency and the actuation frequency must be about one order of magnitude (Kutay *et al.*, 2007). The time stepping in the detailed model is limited by the actuation frequency, so in order to be able to advance faster in time a model based on the averaged Reynolds stress field induced by the synthetic jet is proposed. The averaged Reynolds stress field of the synthetic jet can be obtained from computational results of the detailed model. Figure 3 (left) shows the time averaged difference of the $\overline{u'u'}$ Reynolds stress component between flows with the actuator on and off for the suction side actuator. It is clear that the Reynolds stress field is concentrated in spots or blobs, which is important to parametrize the

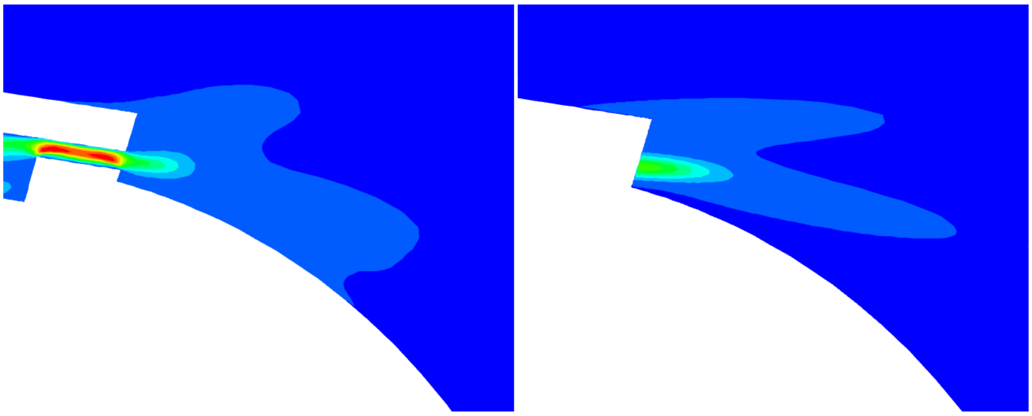

Figure 3. Averaged difference of the $\overline{u'u'}$ Reynolds stress component at $\alpha = 0°$, $Re = 9 \times 10^5$. Detailed model(left) and RSSJ model (right)

Reynolds stress field arising/induced by the jet. This parametrization was done by using simple mathematical exponential functions to mimic the computational (detailed model) Reynolds stress field e.g:

$$\overline{u'u'} = \sum_{i=1}^{n} \Gamma_i e^{\hat{x} \cdot M_i \hat{x}} \tag{2}$$

In this example, the parametrized $\overline{u'u'}$ component of the Reynolds stress field is composed from n different exponential functions. n depends on the number of spots (blobs) of $\overline{u'u'}$ needed, for example from Fig. 3 three spots are enough to mimic the $\overline{u'u'}$ field obtained from the detailed simulations. In equation 2, Γ_i determines the $\overline{u'u'}$ spot strength, $\hat{x}$ is a vector of position in space $\left(\begin{array}{cc} x - X_i & y - Y_i \end{array} \right)$, where X_i and Y_i are the location of the center of the spot of $\overline{u'u'}$. Finally, M_i is a matrix given by

$$M_i = \begin{pmatrix} \cos\theta_i & -\sin\theta_i \\ \sin\theta_i & \cos\theta_i \end{pmatrix} \begin{pmatrix} \lambda_i & 0 \\ 0 & \omega_i \end{pmatrix} \begin{pmatrix} \cos\theta_i & \sin\theta_i \\ -\sin\theta_i & \cos\theta_i \end{pmatrix} \tag{3}$$

Where λ_i and ω_i control the $\overline{u'u'}$ spot size while θ_i controls the orientation. Once all the components of the Reynolds stress are parametrized, its divergence is taken and then this result is introduced as a momentum source in the Navier-Stokes solver (Lopez, 2008). For a given Reynolds number, the magnitude of the different numerical parameters (Γ_i, λ_i, ω_i and θ_i) of the RSSJ model not only depend on the jet strength but also on the angle of attack. Figure 3 (right) shows the idealized $\overline{u'u'}$ using three spots ($n = 3$) and with a set of numerical parameters adequately calibrated to match the detailed $\overline{u'u'}$. This model uses a time step of $\approx 1.5 \times 10^{-3} c/U_\infty$ i.e. five times larger than the time step used in the detailed model. This speed up is relevant for future controlled dynamic simulations in which the detailed model is computationally expensive.

3. NUMERICAL RESULTS

Computational results are mainly focused on spanwise averaged vorticity field close to the trailing edge and integrated aerodynamic properties in particular lift (C_l) and moment (C_m) coefficients. Experimental and computational results showed that the effect of actuation of the drag (C_d) coefficient is negligible (DeSalvo and Glezer, 2005) (Lopez, 2008).

3.1 Effects on the vorticity field

Figure 4 shows the time averaged vorticity contours close to the suction side actuator in which it is clear that the average effect of the synthetic jet is to bend the shear layer (formed at the end of the actuator ramp) towards the actuator coanda surface. This bending of the shear layer has been observed experimentally (see Fig. 4) and is associated with lift enhancement due to a local reduction of the pressure(Brzozowski *et al.*, 2007). While the details of the near actuator mean streamlines are a bit different in the experiments and computations, the amount by which the extend streamline deflected is about the same. Another important change brought on by the actuation is the strength of the trapped vorticity close to the trailing edge.

Figure 5 shows the time averaged vorticity field in the near wake with either the suction side or the pressure side actuators activated. For suction side actuation, the near wake shows a downwash compared to the unactuated case consistent with the experimental results (Muse *et al.*, 2008). For the pressure side actuator the near wake shows an upwash, which has also been observed in previous experimental work(Muse *et al.*, 2008). Similar results and observations were obtained for the RSSJ model (not shown) (Lopez, 2008).

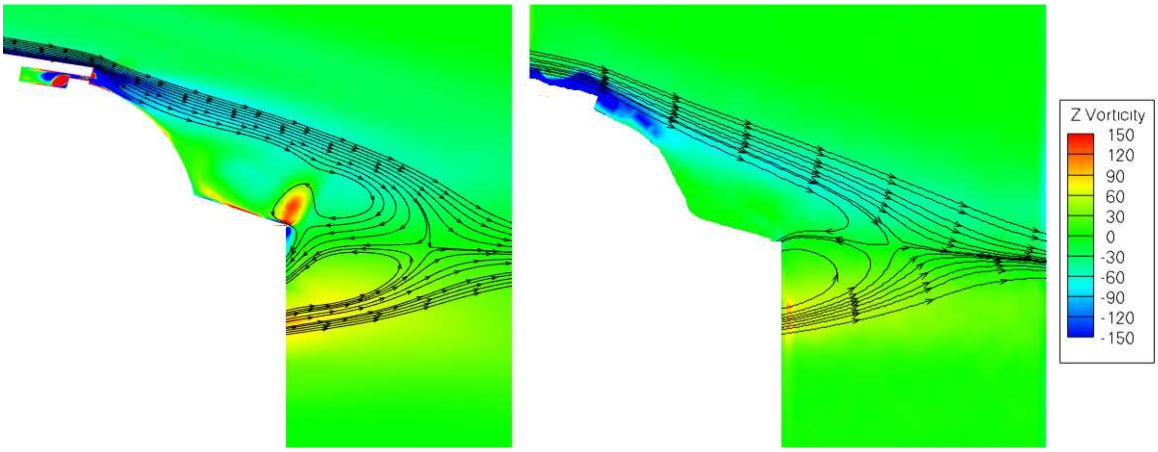

Figure 4. Time averaged vorticity field including streamlines for the suction side actuator. Computational (left) and experimental PIV (right)

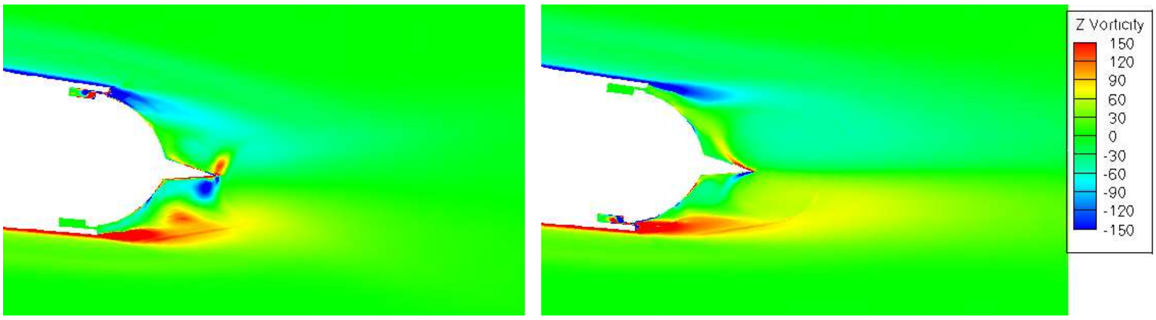

Figure 5. Computational time averaged vorticity field in the near wake ($\alpha = 0°$). SS actuation (left) and PS actuation (right)

3.2 Effects on the aerodynamic properties

Figure 6 (left) shows the evolution of C_m at angle of attack of $0°$ for the detailed model in which the actuator is active after 7.5 convective time units. When the suction side actuator is active, there is an increase in the pitch down moment, on the other hand there is a pitch up when the pressure side actuator is active. Figure 6 (right) shows the effects of the actuator on the C_l for the same simulation, when the suction side actuator is active there is a reduction of the lift coefficient, while there is an increase when the pressure side actuator is active, similar observations were reported in the experimental measurements at Georgia Tech. Another important observation is the change in the dominant frequencies in the evolution of the aerodynamics properties, before and after the actuation. For the detailed model, before actuation, the shedding frequency is dominant, but with actuation, it is the actuation frequency that is dominant.

Figure 7 shows the evolution of C_m (left) and C_l (right) for the RSSJ model. The conditions for these simulations are the same as the detailed model i.e: $Re = 9 \times 10^5$ and $\alpha = 0°$. Clearly, lift enhancement and moment reduction result from suction side actuation while lift reduction and moment enhancement arise with pressure side actuation. Though the magnitude of C_m and C_l fluctuations are significantly smaller in the RSSJ model, the average values of the aerodynamic properties are consistent between RSSJ and detailed models. In these plots, the dominant frequency after actuation corresponds to the shedding frequency, not the actuation frequency, as was the case in the detailed model. RSSJ model eliminates the actuation frequency, so that the time step used in this model is higher than the detailed model. This high frequency elimination makes RSSJ model attractive for dynamic simulations in which there is a difference greater than 3 orders of magnitude between the actuation and maneuvering frequencies.

Figure 8 shows the variation of the time-averaged pressure coefficient (C_p) along the airfoil due to full actuation at an angle of attack of $0°$. Actuation influences the pressure distribution, especially at the trailing edge where a spike in the pressure is induced by the actuation. The increment of C_p at full actuation, for both the suction and pressure side actuators, at $\frac{x}{c} = 0.95$ (position of the actuators) is about 0.9 relative to the unactuated case. Similar results were reported by DeSalvo et al (DeSalvo and Glezer, 2007) with the same actuators but on a different airfoil. This local reduction of the pressure is associated with the trapped vorticity and with a flow acceleration close to the trailing edge.

The actuator effectiveness is measured by computing the increase or decrease of the the aerodynamic properties of the airfoil, in particular the change in moment and lift coefficients (ΔC_m and ΔC_l respectively). Figure 9 shows ΔC_m and ΔC_l for both models and a comparison with the experimental results in the range of $-2°$ to $6°$ at full actuation. A

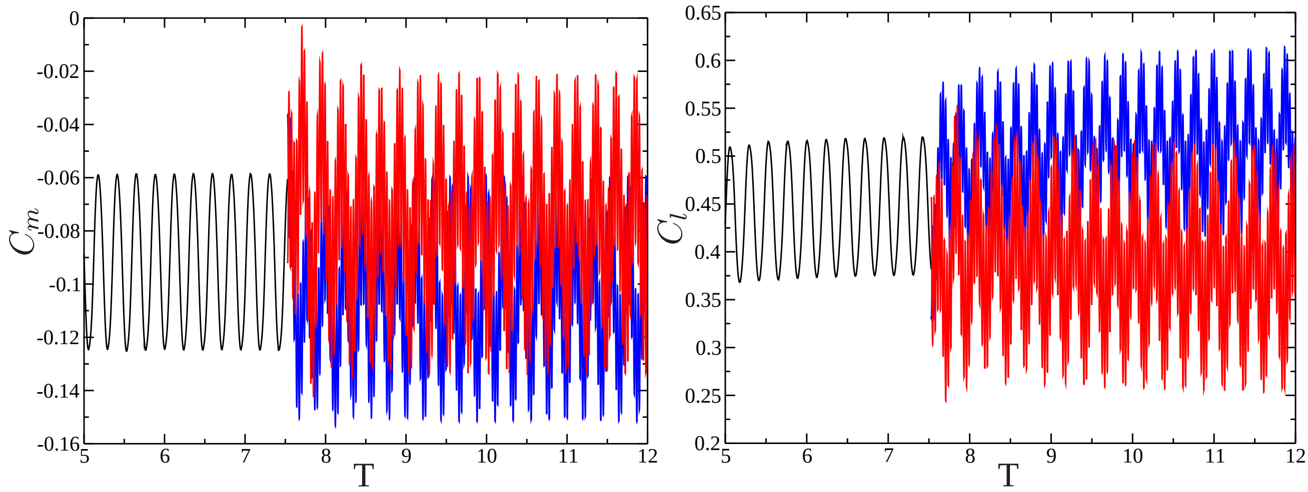

Figure 6. Evolution of aerodynamic properties - Detailed model. (No act – SS – PS –)

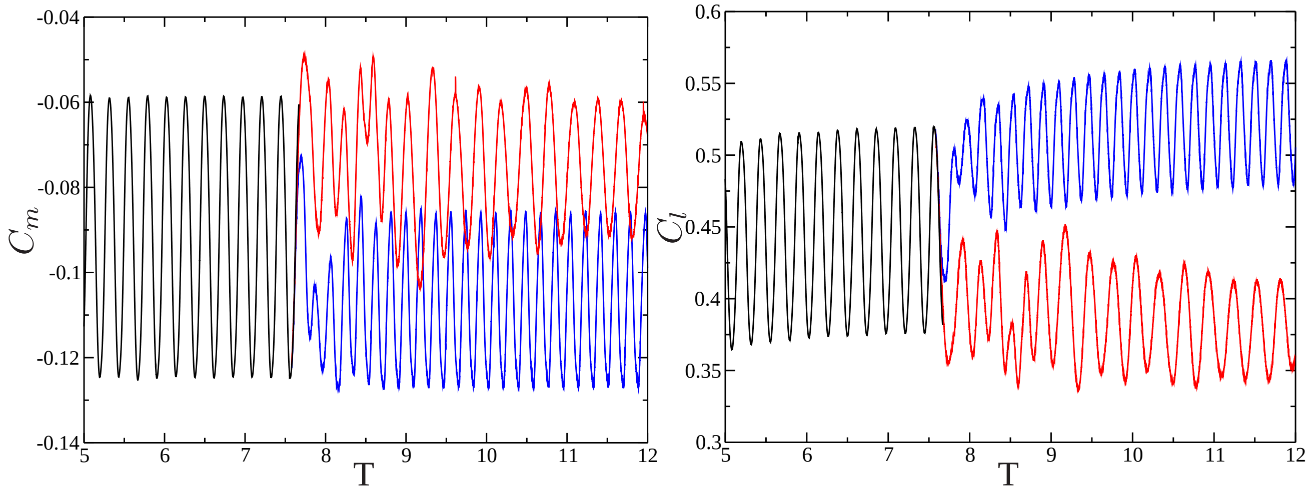

Figure 7. Evolution of aerodynamic properties - RSSJ model. (No act – SS – PS –)

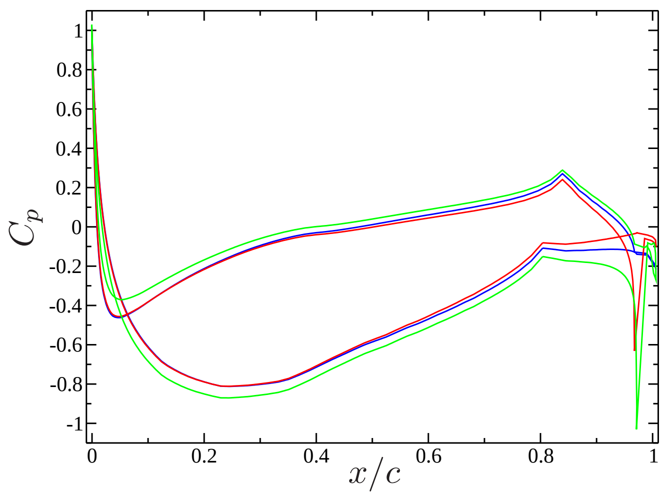

Figure 8. Pressure coefficient at $\alpha = 0^\circ$. (SS – PS – no act –)

very good agreement was achieved between the RSSJ model and the detailed model not only in the trends but also in the magnitude of the effectiveness. Even though the calibration of the RSSJ model was done for 0°, 6° and -6°, the model performs well at intermediate angles of attack like -2° and 3°. The performance and parametrization of the detailed and RSSJ models could be improved by more precisely matching the experimental data.

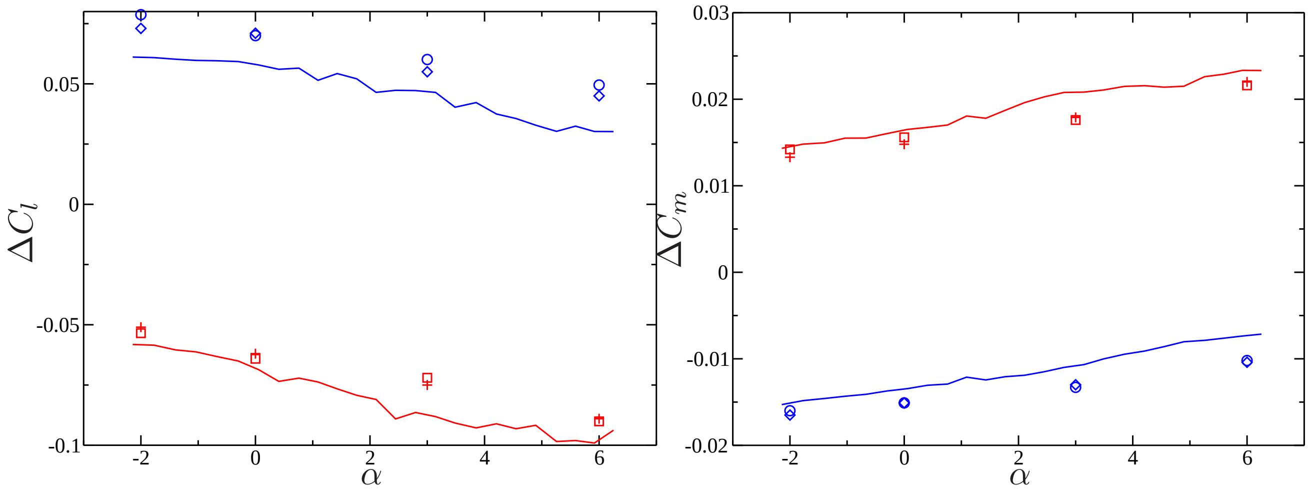

Figure 9. Actuator effectiveness. (SS exp — PS exp— SS detailed model ○ PS detailed model + SS RSSJ model ◇ PS RSSJ model □)

4. CONCLUSIONS

A computational study of an airfoil (modified NACA4415) with tangential synthetic jet for pitching control was presented. Numerical results demonstrated the effects of the synthetic jets in the flow (specially in the trapped vorticity) and in the aerodynamic properties of the airfoil.

Results from the detail model show the effects of the actuator on the aerodynamic properties of the airfoil (in special C_l and C_m). Full actuation of the SS actuator increases the pitch down moment and reduces the lift force, while the PS actuator reduces the pitch down moment and increases the lift force. Trapped vorticity close to the trailing edge of the actuator affects the pressure distribution along the airfoil, this change in the C_p allows the manipulation of the aerodynamic properties of the airfoil. In the time average near wake it is observed that the SS actuation downwashes the near wake (close to the trailing edge) while the PS actuation upwashes the near wake in comparison with the unactuated case. Both actuation affects the topology of the vortical structures observed in the time averaged vorticity field.

While the RSSJ model reduces the complexity of the simulation (geometry and boundary conditions) in comparison with the detail model, it just captures the average behavior of the synthetic jet. The detail model fully captures the dynamics of the synthetic jet actuator but it increases the complexity of the simulation due to the cavity geometry and extra boundary conditions. The most important advantage of using the RSSJ model instead of the detail model is that it uses a time step 5 times greater than the detailed model. This observation is consistent with the fact that the time stepping in the detail model is limited by the synthetic jet frequency while the time stepping in the RSSJ model is limited by stability/accuracy of the numerics. RSSJ model is attractive for flow control simulations with synthetic jets, in which there is a difference of more than 3 orders of magnitude between maneuvering time scale and the actuation time scale. While the RSSJ model was developed for a tangential synthetic jet, the methodology used in this study can be extended to normal synthetic jet actuators

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