43rd AIAA Aerospace Sciences Meeting and Exhibit, January 10-13, Reno, Nevada

Numerical Study of Resonant Interactions and Flow Control in a Canonical Separated Flow

Rajat Mittal* and Rupesh B. Kotapati†
Department of Mechanical and Aerospace Engineering
The George Washington University, Washington DC 20052

and

Louis N. Cattafesta III‡
Department of Mechanical and Aerospace Engineering
University of Florida, Gainesville FL 32611

A novel numerical configuration has been devised in order to investigate active control of separated airfoil flows in a comprehensive and systematic manner. The configuration consists of a flat plate at zero degrees angle-of-attack in a freestream on which a separation bubble of prescribed size is created at a prescribed location through blowing and suction on the top boundary of the computational domain. Numerical simulations of this configuration show that these canonical separated airfoil flows exhibit three distinct characteristic time scales corresponding to the shear layer, the separation zone and the wake vortex shedding. The vortex dynamics associated with these distinct phenomena are described. Preliminary simulations of this flow subjected to zero-net-mass-flux perturbation are also presented.

I. Introduction

ZERO-net-mass-flux (ZNMF) devices (e.g., synthetic jets) have emerged as versatile actuators with potential applications ranging from thrust vectoring of jets (Smith and Glezer 2002) to turbulence in boundary layers (Rathnasingham and Breuer 1997, 2003; Lee and Goldstein 2001) and active control of separation (Wygnanski 1997; Smith *et al*. 1998; Amitay *et al*. 1999; Crook *et al*. 1999). Separation control, especially in the context of wing stall delay and control, has generated considerable interest in the active flow control community. The versatility of these actuators is primarily due to the following three factors:

1. They provide unsteady forcing that is more effective than steady forcing.
2. Since the jets are synthesized from the working fluid, complex fluid circuits are not required.
3. Actuation frequency can usually be tuned to a particular flow configuration.

Research on these actuators has primarily been directed towards understanding the associated flow physics with the objective of identifying "optimal" forcing schemes and below we summarize our view of the outstanding issues in this area.

A. Flow Physics of ZNMF-Based Separation Control

The key control parameters in a ZNMF device are the jet frequency f and jet velocity V_J. The former is usually non-dimensionalized as $F^+ = f / f_n$ where f_n is some natural frequency in the uncontrolled flow. The latter is non-dimensionalized by U_∞. Note that V_J is some characteristic measure of the jet velocity, such as the peak or an

---

* Associate Professor, mittal@gwu.edu, Senior Member AIAA.
† Doctoral Student, rupesh@gwu.edu, Student Member AIAA.
‡ Associate Professor, catman@mae.ufl.edu, Associate Fellow AIAA.

average velocity. As expected, control authority varies monotonically with $\bar{V}_J / U_\infty$ (Seifert *et al*. 1993, 1996, 1999; Glezer and Amitay 2002; Mittal and Rampunggoon 2002) up to a point where a further increase would perhaps completely disrupt the boundary layer. Thus, there is little possibility of extracting an "optimal" value of this parameter. On the other hand, control authority has a highly non-monotonic variation with F^+ (Seifert and Pack 2000; Greenblatt and Wygnanski 2003; Glezer *et al*. 2003) and this not only suggests the presence of rich flow physics and multiple flow mechanisms but also reveals the potential of optimizing the actuation scheme with respect to this parameter. Here we discuss various issues pertinent to the flow physics of separation control.

Experiments have shown that accelerated transition to turbulence of a laminar boundary layer does not play a pivotal role in ZNMF based separation control (Seifert *et al*. 1996, Glezer *et al*. 2003). One key mechanism that is identified in ZNMF based active separation control is the formation of large-scale vortical structures in the separated shear layer due to oscillatory forcing, which entrains outer high-momentum fluid into the boundary layer, thereby delaying separation or even reattaching a separated flow. Control schemes that harness this mechanism are usually built on a sequence of propositions and we critically evaluate these propositions in order to highlight sources of ambiguity and provide guidance for the proposed research.

Proposition 1: The dynamics of a separated flow over an airfoil are dominated by the characteristic frequency of the separation region, f_{sep}.

Critique: Contrary to Proposition 1, in addition to f_{sep}, there are other naturally occurring frequencies that can play an important role in the dynamics of the flow. To examine this further, it is useful to classify the types of separation encountered for typical airfoils, and the subsequent discussion is drawn from classical work on stall classification by McCullogh and Gault (1951), Chang (1976), and more recent work on temporal dynamics of stalled airfoil flows by Zaman *et al*. (1989), Broeren and Bragg (1998), Bragg *et al*. (1993, 1996), and Wu *et al*. (1998). Based on these previous studies, one can consider the following three situations with regards to separation control as shown in figure 1. Case A represents attached flow at low angle-of-attack (AOA) where the boundary layer on the suction side develops under an adverse pressure gradient but does not separate. Such a flow has one dominant time-scale characterized by the inverse of the wake shedding frequency f_{wake} which, according to Roshko (1954) scales as $f_{wake} \sim U_\infty / W_{wake}$.

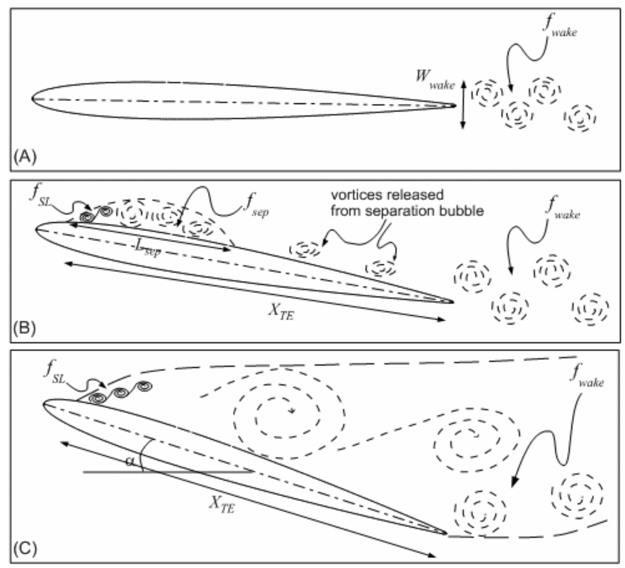

Figure 1: Characterization of possible frequency scales in separated flows.

In direct contrast to Case A is the situation at high AOA, namely the post-stall Case C where separation occurs near the leading-edge and the flow does not reattach (in the mean) to the airfoil surface. This flow behaves like that past a bluff body and is consequently subject to two frequency scales, f_{SL} and f_{wake}, where the former is the natural vortex rollup frequency of the shear layer and the latter is again the frequency corresponding to vortex shedding in the wake. The question may be asked as to whether such a local, convective instability mechanism is important given the global, absolute instability of the wake. The answer is a most definite "yes" as shown in a number of experimental investigations of bluff-body wakes (Kourta *et al*. 1987; Williamson *et al*. 1995; Wu *et al*. 1996; Prasad and Williamson 1996). An extensive survey of the literature in this area reveals that only Wu *et al*. (1998) have considered both f_{SL} and f_{wake} in their analysis. In contrast, other studies of post-stall separation control account for f_{wake} but do not consider f_{SL} (He et al. 2001; Miranda *et al*. 2001; Chen and Beeler 2002). Finally, a majority of studies that have examined massively separated flow past airfoils/flaps (for example Siefert *et al*. 1993, 1996, Wygnanski 1997) consider only a single frequency corresponding to the separation region, f_{sep}, which is not necessarily the same as either f_{wake} or f_{SL}.

Finally Case B corresponds to the situation where separation occurs at some location downstream of the leading edge, and the separated shear layer may or may not reattach before the trailing edge. For instance, on some thin airfoils (like the NACA 0012), stall is manifested through the appearance of a small separation bubble near the leading edge (Chang 1976). On the other hand, open separation zones near the trailing-edge can be found on thicker airfoils (Chang 1976, Greenblatt and Wygnanski 2003) and on the exposed portion of low pressure turbine (LPT) blades (Mittal *et al*. 2001; Postl *et al*. 2004). If the flow reattaches before the trailing edge, there are potentially three frequency-scales: f_{wake}, f_{SL}, and f_{sep}, the frequency scale corresponding to the separation "bubble." The resonant interaction between these processes is a strong function of the distance between the separation location and the trailing edge, X_{TE}. It also depends on whether the separation bubble extends to the trailing edge or closes far upstream of it. In fact, when the separation bubble is "open" (i.e., reattachment does not occur), the flow is similar to Case C except that the separation point is not fixed at the leading edge. Mittal *et al.* (2001) examined the scaling of the frequencies for a PAK-B, LPT blade via large-eddy simulations (figure 2) and indeed found that the wake plays a role in determining the dynamics of suction-side separation.

In summary, f_{sep} is only one of three potentially naturally occurring frequencies in a separated airfoil flow. It is quite possible that nonlinear interactions determine the evolution of these disturbances (Wu *et al*. 1998). However, our understanding of the dynamics of these processes is quite limited.

Proposition 2: $f_{sep} \sim U_\infty / L_{sep}$ where L_{sep} is a characteristic length of the separation region.

Critique: For a shear layer that separates from and then reattaches to a solid surface (as in Case B above) the presence of a near-wall reversed flow region permits upstream propagation of disturbances and fundamentally alters the stability characteristics of the shear layer. In such cases, the separation region frequency indeed scales as $f_{sep} \sim U_\infty / L_{sep}$. In fact, analysis of separated flow past a wall mounted tab (Auld and Mittal 1999) and flow past a normal flat plate with a wake splitter (Najjar and Vanka 1993) indicates a universal value of $f_{sep} L_{sep} / U_\infty \approx 0.27$ when L_{sep} is defined as the distance between the separation point and the center of the mean recirculation bubble. It is plausible that in such cases f_{SL} "locks-on" to f_{sep} through subharmonic resonance (Ho and Huang 1982).

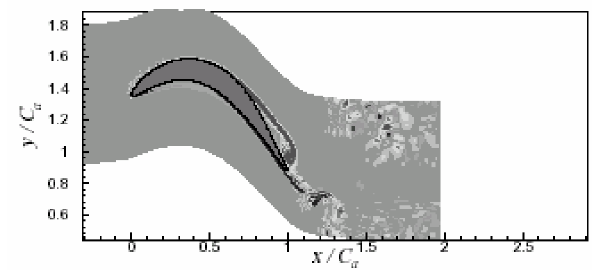

Figure 2: LES of flow over a LPT blade showing trailing edge separation (Mittal *et al.* 2001).

The wake shedding, however, is active for all cases and, due to its global effect, probably plays some role in the dynamics of the flow. The scaling for Kármán vortex shedding is $f_{wake} \sim U_\infty / W_{wake}$ (Roshko 1954), which is fundamentally different from that of f_{sep} above because the wake width W_{wake} appears as the fundamental length scale here. In many studies (Wu *et al*. 1998; Miranda *et al*. 2001) W_{wake} is assumed to be equal to $c \sin\alpha$ where c is the airfoil chord length. In cases where the separation extends over a significant portion of the airfoil (or a flap), it has been customary to assume $L_{sep} = c$ (Bar-Sever 1988; Seifert *et al*. 1993; Ravindran 1999; Wygnanski 2000; Darabi and Wygnanski 2002; Funk *et al*. 2002; Postl *et al*. 2004), but this might significantly overestimate the correct length scale in cases where the wake vortex shedding dominates the dynamics.

For a shear layer that separates and does not reattach (as in Case C), the shear layer instability frequency f_{SL} plays an important role. This frequency scales more like that of a free shear layer, i.e. $f_{SL} \sim \bar{U} / \theta$, where $\bar{U}$ is the average velocity across the shear layer, and θ is the momentum thickness. In fact, Ho and Huerre (1984) have shown that $f_{SL}\theta / \bar{U}$ attains a nearly universal value of about 0.04. In the special case where such shear layers are part of a Kármán-type vortex shedding process, as would in fact be the situation in Case C, the above scaling can be reformulated as $f_{SL} = A \mathrm{Re}^B f_{wake}$ (Kourta *et al*. 1987; Williamson *et al*. 1995; Wu *et al*. 1996) where the Reynolds number accounts for the dependence of the frequency on the momentum thickness. For a circular cylinder, $A \approx 0.024$ and $B \approx 0.67$ (Prasad and Williamson 1996).

Proposition 3: Forcing at f_{sep} will elicit the largest response. Therefore, control is expected to be most effective when $F^+ = f / f_{sep} = f\, L_{sep} / U_\infty = O(1)$.

Critique: Based on the critique of the previous two propositions, it seems clear that the situation with regard to the optimal forcing frequency is not quite so obvious. Considering the fact that even if one were to account for the various definitions of F^+ that have been employed, there is a wide variation in the observed values of optimal F^+. For example, among studies that have defined $F^+ = f\, c / U_\infty$, optimal F^+ values ranging from 0.55 to 5.5 have been observed (Bar-Sevar 1988; Seifert *et al*. 1993; Ravindran 1999; Wygnanski 2000; Margalit *et al*. 2002; Darabi and Wygnanski 2002; Funk *et al*. 2002). Among studies that define $F^+ = f\, X_{TE} / U_\infty$, optimal values range from 0.5 to 2.0 (Seifert and Pack 1999; Greenblatt and Wygnanski 1999; Gilarranz *et al*. 2001). Finally, for studies that employ $F^+ = f\, L_{sep} / U_\infty$, optimal values range from 0.75 to 2.0 (Seifert *et al*. 1996; Pack and Seifert 2000; Pack *et al*. 2002). It may seem that the magnitude of the variation in optimal value of F^+ reported in these studies is not significant, except that in many cases the control authority of the ZNMF device varies considerably with small changes in F^+. For instance, Seifert *et al*. (1993) report a 25% variation in C_L as F^+ varies between 0.25 and 1.5, while Wygnanski (2000) found that the required C_μ increased by about 400% as F^+ varies between 0.25 and 1.5.

For post-stall applications similar to Case C in figure 1, Wu *et al*. (1998) have argued that the optimal control frequency should be a harmonic of f_{wake}, i.e. $F^+ = f / f_{wake} = m$, where *m* is an integer greater than 1. Due to the ability of the shear layer to respond to a broad range of frequencies, a suitable choice of m can allow both the vortex shedding and shear layer to lock-on to the forcing frequency or its superharmonic. Lack of consideration of the importance of f_{wake} and the associated resonant interactions in past studies (Siefert *et al*. 1993, 1996, 1999, Wygnanski 1997) might explain some of the spread in optimal F^+ and corresponding C_μ values reported in the literature.

Proposition 4: Since the point of separation is the most receptive point for a separating shear layer, forcing is most effective when applied in the vicinity of this point.

Critique: This is a physically sound proposition provided that direct control of the vortices generated by the shear layer is the primary objective of the flow control strategy. Indeed, in most studies such a placement of the actuator has been found to be quite effective and other studies have found that placement of the ZNMF device inside the separation region does not work (He *et al*. 2001; Chen and Beeler 2002). However, if the objective of the control strategy is to modify the wake vortex shedding, then placement of the actuator at the trailing edge is also a possibility as shown by Wu *et al*. (1998) and Miranda *et al*. (2001). This also opens up the interesting possibility of deploying two actuators, one upstream of the shear layer and one at the trailing edge to simultaneously modify both flow features. This possibility remains to be investigated.

Proposition 5: Forcing at $F^+ = f / f_{sep} = f\, L_{sep} / U_\infty = O(10)$ is most effective because high frequency forcing displaces the local streamlines of the cross flow and induces a "virtual" shape change (Honohan *et al*. 2000; Honohan 2003).

Critique: In order to examine the physical basis of this mechanism, it is instructive to focus on one particular set of experiments by Amitay and Glezer (2002) where ZNMF based separation control over a 24% thick unconventional airfoil with a circular leading edge has been investigated. The nominal chord Reynolds number is around 3×10^5 and the AOA is 17.5 ^{o}. They find that the natural shedding frequency in the separation region $f_{sep}\, c / U_\infty \sim 0.7$ and further show that forcing at $F^+ = f\, c / U_\infty = O(1)$ produces a 2× increase in lift and a 2.5× increase in lift-to-drag ratio. The resulting flow shows a well-ordered train of vortices that are formed in the separation region at a frequency that matches the forcing frequency. In contrast, for higher forcing frequencies with $F^+ \geq 10$, they find an almost 3× increase in lift and 3.2× increase in lift-to-drag ratio, which suggests that this type of control is superior to lower frequency actuation.

Glezer and coworkers argue that this phenomenon is based on a decoupling of the high $F^+ \sim O(10)$ frequency actuation from that of the global flow instability which occurs at approximately $F^+ = O(1)$. This produces a virtual surface modification downstream of the actuator, which displaces the streamlines and results in a localized favorable pressure gradient. This approach leads to a thinner boundary layer that is more resistant to separation. This suggests an almost quasi-steady effect of the ZNMF actuator at these high forcing frequencies, except that wake velocity power spectra show that forcing at this frequency produces a remarkably different power spectrum with a large inertial range that is completely absent in the baseline flow (Amitay and Glezer 2002). This result is clear indication that unsteady effects play a much more important role in high-frequency actuation than is explainable by a quasi-steady "virtual-aero shaping" effect.

An intriguing possible explanation for this unsteady effect presents itself if we consider the shear layer frequency f_{SL} for this flow. Using the scaling for a circular cylinder $f_{SL} = 0.0235\,\mathrm{Re}^{0.67}\, f_{wake}$ (Prasad and Williamson 1996) where the Reynolds number is based on the projected body dimension, $\mathrm{Re}_c \sin\left(AOA\right) = 80000$, gives $F_{SL}^{+} \approx 30$. Thus, although the high frequency forcing is "decoupled" from the large-scale vortex shedding in the separation region, the above analysis shows that there is a distinct possibility that it could be coupled with the smaller-scale shear layer instability.

Proposition 6: Curvature effects, previously thought to be of second-order importance compared to pressure gradient, are potentially very important in separation control applications.

Critique: Despite the fact that most practical applications of separation flow control involve geometries with curvature, relatively few studies have critically examined the role of curvature. Much of the novel work with respect to flow control has been done by Wygnanski and Fasel and their colleagues. Initial work by Neuendorf and Wygnanski (1999) investigated the effect of curvature on a steady two-dimensional wall jet versus its planar equivalent and gleaned the dominant effect of the radius of curvature in determining the length and velocity scales of the curved flow. More recently, Cullen *et a*l. (2002) reported on a series of detailed studies on the effects of wall curvature and pressure-gradient on a curved wall versus a flat surface and concluded that surface curvature, previously assumed to be a second order effect, can be quite important in a boundary layer near separation. Greenblatt and Wygnanski (2002, 2003) have examined the effects of leading-edge curvature on NACA 0012 and NACA 0015 on airfoil separation control effectiveness. They found that the combination of larger leading edge curvature and excitation downstream of the separation bubble rendered the NACA 0012 flow less receptive to excitation than the NACA 0015 under similar conditions. Their results emphasized that the effectiveness of the control was highly dependent on flow curvature, actuator placement, forcing amplitude C_μ and F^+. Indeed, the mechanism of NACA 0012 separation control was identified as flow attachment downstream of a leading-edge separation bubble without eliminating the bubble itself. This is similar to Case B in figure 1 discussed above. Their work shows both the potential importance of curvature but also reveals the practical difficulty of isolating curvature effects in an experiment. This is because the pertinent non-dimensional parameters include the ratio of momentum thickness to curvature, θ/R, and the Clauser parameter $\beta = \dfrac{\delta^*}{\tau_w}\dfrac{dp_e}{dx}$. Unfortunately, the two parameters are coupled by virtue of the shape factor $H = \delta^*/\theta$. In particular, while two flows may have the same dimensional pressure gradient dp_e/dx, they may in fact have different β. In practice, therefore, it is extremely difficult to isolate curvature effects.

Proposition 7: Amplitude modulation is superior to sinusoidal excitation.

Critique: Yet another curious issue is the effect of the form of the excitation signal. Researchers have used single sinusoids, low-frequency amplitude-modulated (AM) signals (Pack *et al*. 2002), burst mode signals, and various envelopes (Margalit *et al*. 2002). Pack *et al*. found that low frequency amplitude modulation (with F_{AM}^{+} ~1) of the high resonant frequency of a piezo-ceramic actuator required approximately 50% less momentum input to achieve the same performance gains. AM uses a signal of the form $u(t) = \left(dc + \cos\left(2\pi f_{AM} t\right)\right)\cos\left(2\pi f_c t\right)$, where $f_{AM} \ll f_c$. If the dc value is zero, then the resulting frequencies are $f_c \pm f_{AM}$. However, due to nonlinear flow dynamics (Wiltse and Glezer 1993), the low amplitude modulation frequency f_{AM} results and forces the flow. The carrier frequency f_c is usually chosen as the natural frequency of the actuator. Margalit *et al.* found that the burst mode with very small duty cycle was even more effective than amplitude modulation. These results suggest that the input signal waveform can be catered to target f_{wake}, f_{SL}, and/or f_{sep} in an effort to enhance nonlinear coupling. It also emphasizes that the dynamics of the actuator should not be ignored.

B. A Canonical Separated Flow Configuration

The previous section described some of the key outstanding technical issues in the area of active separation control (ASC) using ZNMF actuation. Past approaches to studying these issues have mostly employed conventional airfoil geometries where the flow separation is produced by varying angle-of-attack and/or freestream velocity. Although this approach is obviously grounded in practical reality, it is not the best one for a precise investigation and delineation of the various physical mechanisms that are potentially implicated in ASC. For instance, consider Case B in figure 1. As discussed previously, this is a complex flow with potentially three different naturally occurring frequencies. In order to examine the scaling of these frequencies as well as their potential nonlinear interactions, it would be extremely useful to separately prescribe the extent and location of the separation bubble as well as the Reynolds number. This is not possible through just variation of AOA and freestream velocity for an airfoil. Thus, a configuration is needed that (1) is simple and includes all the important features of a canonical separated airfoil flow, including leading edge boundary layer inception, suction side separation (open as well as closed separation), and a wake, which includes vortices from the suction and pressure sides; (2) allows independent prescription of the location and extent of the separation region as well as the Reynolds number.

It should be pointed out that some past studies have induced separation on a flat wall via modification of the upper boundary (Na and Moin 1998; Sohn *et al*. 1998; Postl and Fasel 2004). This methodology does allow for control over the location and extent of the separation bubble but does allow for LE and TE effects. This configuration also do not account for the pressure side boundary layer. We therefore propose a novel configuration that satisfies all of the above requirements and is amenable to both simulation and experimentation. The current paper focuses on the numerical simulation and the experimental component will be described in a future paper.

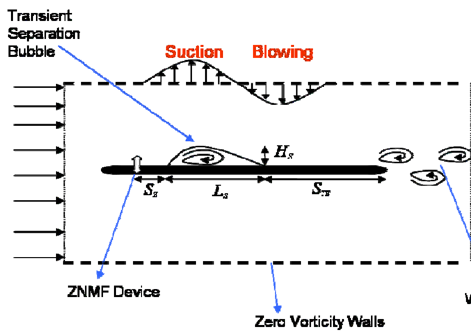

Figure 3: Flat plate with prescribed separation location via suction and blowing.

The configuration to be studied involves a thin flat-plate (chord length *c* and thickness *t*) with elliptic leading and trailing edges as shown in figure 3. Separation is induced on the upper surface of this plate by applying blowing/suction on the upper boundary of the computational domain as shown in the schematic. The technique of Na and Moin (1998) is adopted wherein the following boundary condition is prescribed on the upper wall:

$$u_y = G(x); \qquad \frac{\partial u_x}{\partial y} = \frac{dG}{dx}; \qquad u_z = 0$$

where $G(x)$ is the prescribed blowing and suction velocity profile, and the boundary condition on u_x ensures that no spanwise vorticity (ω_z) is produced due to the blowing and suction. The key aspect of this approach is that the function $G(x)$ allows us to prescribe the streamwise size of the separation region (L_{sep}) as well as its location. Thus, separation can be produced anywhere on the plate surface and can therefore reproduce any of the three separated flow situations discussed in the previous section. The above configuration can be employed to examine the nonlinear interactions between the shear layer, separation region, and airfoil wake in uncontrolled and ZNMF-based controlled versions of these flows. Note that the confounding effect of curvature is absent here, something that is not usually possible with conventional airfoil investigations. In the rest of the paper, we describe a set of simulations that examine both the uncontrolled and controlled flow in this configuration.

II. Simulation Results

A. Numerical Approach

A finite-difference based approach for computing flows with moving immersed solid three-dimensional boundaries on fixed Cartesian grid has been developed. The key feature of this method is that simulations with complex boundaries can be carried out on stationary non-body conformal Cartesian grids and this eliminates the need for complicated remeshing algorithms that are usually employed with conventional Lagrangian body-conformal methods.

The governing equations are the incompressible Navier-Stokes equations which are discretized using a cell-centered, collocated (non-staggered) arrangement of the primitive variables. The equations are integrated in time using the fractional step method. In the first step, the momentum equations without the pressure gradient terms are first advanced in time. In the second step, the pressure field is computed by solving a Poisson equation. A second-order Adams-Bashforth scheme is employed for the convective terms while the diffusion terms are discretized using an implicit Crank-Nicolson scheme, which eliminates the viscous stability constraint. The solution of pressure Poisson equation (PPE) is the most time consuming part of the solution algorithm. In the current solver an efficient multigrid methodology has been developed which is well suited for use in conjunction with the immersed boundary method. The solver is described in Bozkurttas *et al.* (2005).

B. Uncontrolled Flow

Two-dimensional simulations of this configuration using a 2% thick elliptic airfoil at a chord Reynolds number of 60,000 have been carried out. All simulations reported here have been carried out on a single 2.4 GHz, Pentium® 4 processor-based workstation. Figure 4 shows the baseline unseparated flow for this case and the contour plot of spanwise vorticity shows the presence of Kármán vortex shedding in the wake. Figure 5 shows the temporal variation of cross-stream velocity component at x/c = 0.25 (top), 0.5 (middle) and 1.25 (bottom) and it can be seen that even far upstream of the trailing edge, the global signature of the wake vortex shedding is present. The frequency of vortex shedding, when normalized with the momentum thickness of the wake and the freestream velocity, $f_{wake}\theta_{wake}/U_\infty$ gives a value of roughly 0.14 which is consistent with the scaling of Roshko (1954).

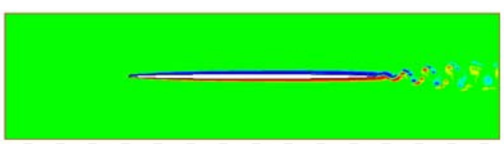

Figure 4: Simulation of flow past thin elliptic airfoil at zero angle of attack at Re_c = 60,000. Spanwise vorticity contour plot shows the Kármán vortex shedding in the wake.

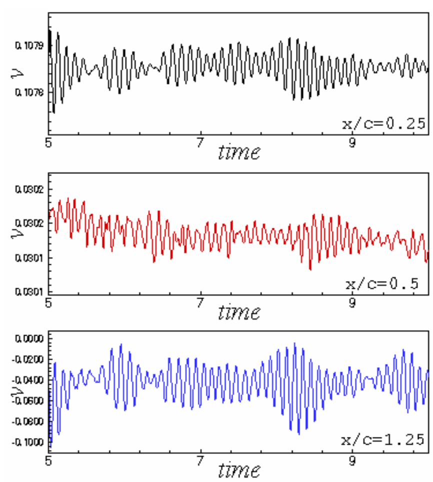

Figure 5: Temporal variation of cross stream velocity component at *x/c* = 0.25 (top), 0.5 (middle) and 1.25 (bottom)

This baseline case is subsequently subjected to sinusoidal blowing and suction on the top boundary to induce separation. Two different cases are simulated. The first one is of a closed mid-chord separation where the blowing and suction extends over $0.25 \le x/c \le 0.75$ and the second one is a case of trailing-edge separation where the blowing and suction extends over $0.50 \le x/c \le 1.00$. Fig. 6 shows pressure along a horizontal line above the top surface of the airfoil with adverse pressure gradient induced by blowing-suction on top boundary at two different locations. Examination of the mean flow shows that in the first case, a recirculation bubble of length $L_{sep} \sim 0.3c$ is created whereas in the second, the bubble length is $L_{sep} \sim 0.35c$.

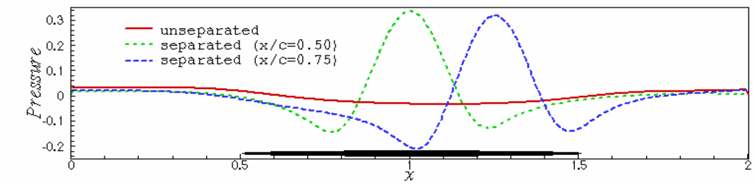

Figure 6: Pressure along a horizontal line above the top surface of the airfoil with adverse pressure gradient induced by blowing-suction on top boundary at two different locations (mid-chord and trailing edge). Nominal size of separation zone created $L_{sep} \sim 0.3c - 0.35c$.

Figure 7 shows a sequence of spanwise vorticity contour plots that show a flow rich in distinct vortical interactions. First, the boundary layer is seen to separate at the location where the suction becomes active ($x/c = 0.25$) and this separated shear layer immediately starts rolling up into small scale Kelvin-Helmholtz type vortices. Some of these vortices are seen to merge and form larger vortices and this leads to the formation of larger vortices in the separation region. At periodic intervals, one of these large vortices is released from the separation bubble and it travels downstream where it intermittently disrupts the Kármán vortex shedding in the wake. Thus, this one example clearly shows all of the features that we have claimed will be present in a canonical separated flow. Examination of temporal variation of flow variable allows us to extract the three distinct frequencies. Figure 8 shows the variation of cross-stream velocity component at the separation point ($x/c = 0.25$), at the center of the separation bubble ($x/c = 0.50$) and in the wake at $x/c = 1.25$. The first and second plots clearly show the presence of the high shear layer frequency as well as the lower separation bubble frequency which corresponds to the release of the vortex by the separation bubble. The third plot also clearly shows how the high frequency vortex shedding is disrupted periodically by the separation vortex. For this case, $f_{sep} L_{sep} / U_\infty$ is about 0.42. Furthermore, the shear layer frequency f_{SL} is about $7 f_{sep}$ where the vortex shedding frequency f_{wake} is about $19 f_{sep}$.

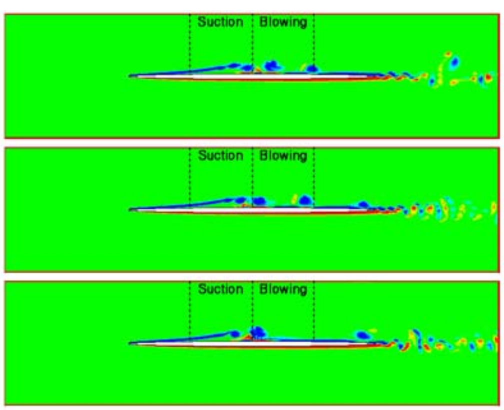

Figure 7: Vortex dynamics for case with induced mid-chord separation.

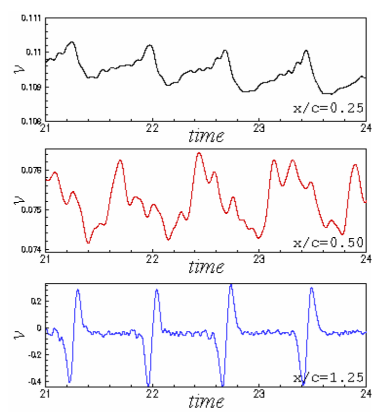

Figure 8: Temporal variation of cross-stream velocity component at x/c = 0.25 (top), 0.5 (middle) and 1.25 (bottom).

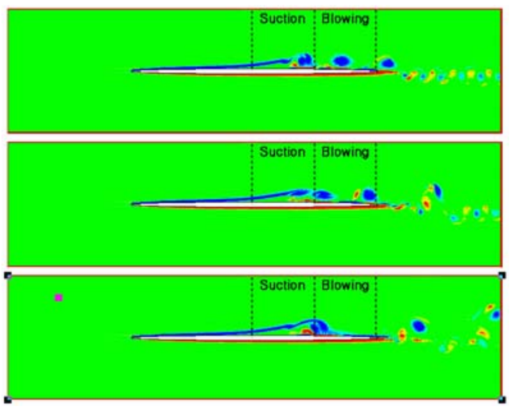

Figure 9: Vortex dynamics for case with induced mid-chord separation.

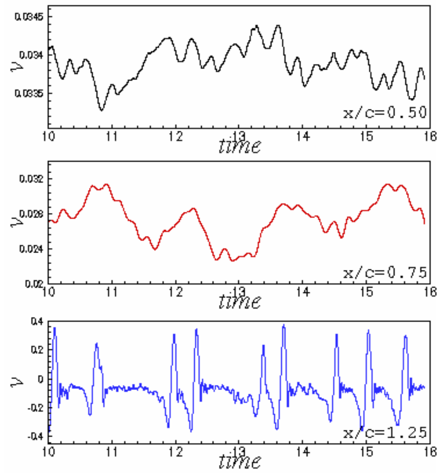

Figure 10: Temporal variation of cross-stream velocity component at *x/c* = 0.50 (top), 0.75 (middle) and 1.25 (bottom).

Figure 9 shows a sequence of spanwise vorticity contour plots for the second case and comparison with previous case illustrates the potential effect of separation bubble location on the flow. Overall the interaction between the three features of the flow (shear layer, separation bubble and wake) is qualitatively similar to that seen in the previous case. For this case, $f_{sep}L_{sep}/U_\infty$ is about 0.19 which is quite low and this is likely due to the effect of the wake on the separation dynamics. This underscores our earlier conjecture that $f_{sep}L_{sep}/U_\infty$ can be significantly different from unity depending on the flow configuration. The flow is clearly more chaotic (see figure 10) than the previous case and this is likely due to the interaction between the separation region and wake instabilities. Interestingly however, shear layer frequency f_{SL} is about $6f_{sep}$ which is similar to the previous case and the vortex shedding frequency f_{wake} is about $19f_{sep}$ which matches the previous case also. Therefore, there is some indication that the shear layer and wake seem to "lock-on" to the separation region frequency which itself seems to be modified by virtue of being near the wake. This again provides some validation to non-linear coupling that we have hypothesized is important in such flows.

C. Flow Control

Preliminary simulations of the mid-chord separation case subjected to ZNMF perturbations have been carried out. The effect of the ZNMF device is modeled by prescribing a localized oscillatory normal velocity just upstream of the separation point (location indicated by black line in figure 11 on the following page) on the top surface of the airfoil. Two different perturbation frequencies have been applied. The first one is a low frequency corresponding to $f_Z\, c/U_\infty = 2$ and the second one is a higher frequency which corresponds to $f_Z\, c/U_\infty = 20$. The velocity perturbation provided has a low amplitude of $0.1U_\infty$. Note that the first frequency is close to the natural separation frequency f_{sep} for this case whereas the second frequency is about twice the shear layer frequency for the uncontrolled case. The figure below shows the response of the separation zone to these two frequencies at one time instance. The low frequency forcing case shows a dramatic response wherein the separated shear layer essentially reattaches to the airfoil over a significant extent. On the other hand, the high frequency perturbation has a less noticeable effect on the separation process as is evident from the plot below. This is likely due to the fact that the perturbation frequency does not couple with either the separation or the shear layer frequency. Further simulations are being carried out currently to examine the response of this flow to a wide range of frequencies and these will be reported in the future.

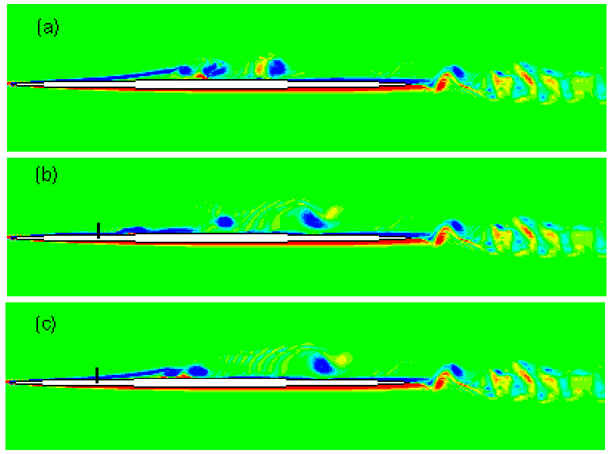

Figure. 11: Effect of ZNMF perturbation. (a) Uncontrolled flow (b) Low frequency perturbation (c) High frequency perturbation.

Acknowledgment

This research is supported by grants from U. S. Air Force Office of Scientific Research.

References

Amitay, M. and Glezer, A., "Controlled Transients of Flow Reattachment over Stalled Airfoils," *International Journal of Heat and Fluid Flow*, vol. 23, pp. 690-699, 2002.

Amitay, M., Kibens, V., Parekh, D. and Glezer, A., "The Dynamics of Flow Reattachment Over a Thick Airfoil Controlled by Synthetic Jet Actuators," AIAA Paper 99-1001, 1999.

Amitay, M., Pitt, D. and Glezer, A. "Separation Control in Duct Flows," *Journal of Aircraft*, vol. 39, no. 4, pp. 616-620, July-August 2002.

Auld, R. and Mittal R., "Numerical Simulation of Flow Past a Wall-Mounted Flap," *Bull. Amer. Phys. Soc.*, Division of Fluid Dynamics Meeting, New Orleans, LA, November 1999.

Bar-Sever, A., "Separation Control on an Airfoil by Periodic Forcing," *AIAA J.*, vol. 27, no. 6, pp. 820-821, 1988.

Bozkurttas, M., Dong, H., Seshadri, V., Mittal, R. and Najjar, F.M. "Towards Simulation of Flow Past Flapping Foils on Cartesian Grids. AIAA Paper 2005-0079, 2005.

Bragg M. B., Hienrich, D. C. and Khodadoust, A., "Low Frequency Flow Oscillation over Airfoils Near Stall," *AIAA J.*, vol. 31, no. 7, pp. 1341-1343, 1993.

Bragg, M. B., Hienrich, D. C., Ballow, F. A. and Zaman, K. B. M. Q., "Flow Oscillation over an Airfoil Near Stall," *AIAA J.*, vol 34, no. 1, pp. 199-201, 1996.

Broeren, A. P. and Bragg, M. B., "Low Frequency Flow Field Unsteadiness During Airfoil Stall and Influence of Stall Type," AIAA Paper 98-2517, 1998.

Chang, P. K., *Control of Separation*, McGraw–Hill, New York, 1976.

Chen F. –J., and Beeler, G. B., "Virtual Shaping of a Two-Dimensional NACA 0015 Airfoil Using Synthetic Jet Actuator," AIAA Paper 2002-3273, 2002.

Crook, A., Sadri, A. M. and Wood, N. J., "The Development and Implementation of Synthetic Jets for the Control of Separated Flow," AIAA Paper 99–3176, 1999.

Cullen, L., Nishri, B., Greenblatt, D. and Wygnanski, I., "The Effect of Curvature on Boundary Layers Subjected to Strong Adverse Pressure Gradients," AIAA Paper 2002-0578, 2002.

Darabi, A. and Wygnanski, I., "On the transient process of flow reattachment by external excitation," AIAA Paper 2002-3163, 2002.

Funk, R., Parekh, D., Crittenden, T. and Glezer, A., "Transient Separation Control using Pulse Combustion Actuation," AIAA Paper 2002-3166, 2002.

Gilarranz, J. L. and Rediniotis, O. K., "Compact, High-Power Synthetic Jet Actuators for Flow Separation Control," AIAA Paper 2001-0737, 2001.

Glezer, A. and Amitay, M., "Synthetic Jets," *Ann. Rev. Fluid Mech.*, 34:503–29, 2002.

Glezer, A. Amitay, M. and Homohan A. M., "Aspects of Low- and High-Frequency Aerodynamic Flow Control," AIAA Paper 2003-0533, 2003.

Greenblatt D. and Wygnanski, I. “Parameters Affecting Dynamic Stall Control by Oscillatory Excitation,” AIAA Paper 99-3121, 1999.

Greenblatt, D. and Wygnanski, I., “Effect of Leading-Edge Curvature and Slot Geometry on Dynamic Stall Control,” AIAA Paper 2002-3271, 2002.

Greenblatt, D. and Wygnanski, I., “Effect of leading-edge curvature on airfoil separation control,” *Journal of Aircraft*, vol. 40, no. 3, pp. 473-481, May-June 2003.

He, Y. -Y., Cary, A. W. and Peters, D. A., “Parametric and Dynamic Modeling for Synthetic Jet Control of a Post-Stall Airfoil,” AIAA Paper 2001-0733, 2001.

Ho, C. -M. and Huang, L. -S., “Subharmonics and Vortex Merging in Mixing Layers,” *J. Fluid Mech*., vol. 119, pp. 443-473, 1982.

Ho, C. -M. and Huerre, P., “Perturbed free shear layers,” *Ann. Rev. Fluid Mech*. 16, 365-424, 1984.

Honohan, A. M., Amitay, M. and Glezer, A., “Aerodynamic Control Using Synthetic Jets,” AIAA Paper 2000-2401, 2000.

Honohan, A. M., “The Interaction of Synthetic Jets with Cross Flow and the Modification of Aerodynamic Surfaces,” Ph.D. Dissertation, Georgia Institute of Technology, Atlanta, GA, 2003.

Kourta, A., Boisson, H. C., Chassaing, P. and Minh, H. H., “Non-Linear Interaction and Transition to Turbulenc in the Wake of a Circular Cylinder,” *J. Fluid Mech.*, vol. 181, 1987.

Lee, C. Y. and Goldstein, D. B., “DNS of Microjets for Turbulent Boundary Layer Control,” AIAA Paper 2001-1013, 2001.

Margalit, S., Greenblatt, D., Seifert, A. and Wygnanski, I., “Active Flow Control of a Delta Wing at High Incidence using Segmented Piezoelectric Actuators,” AIAA Paper 2002-3270, 2002.

McCullough, G. B. and Gault, D. E., “Examples of Three Representative Types of Airfoil-Section Stall at Low Speed” NACA TN 2502, 1951.

Miranda, S., Telionis, D. and Zeiger, M., “Flow Control of a Sharp Edged Airfoil,” AIAA Paper 2001-0119, 2001.

Mittal, R. and Rampunggoon, P., “On the Virtual Aero-Shaping Effect of Synthetic Jets,” *Phys. Fluids*, vol. 14, no. 4., pp. 1533-1536, 2002.

Mittal, R., Bonilla C. and Udaykumar, H., S., “Cartesian Grid Methods for Simulating Flows with Moving Boundaries,” *Computational Methods and Experimental Measurements XI*, ed. Brebbia, C. A., Carlomagno, G. M. and Anagnostopoulous, P., Halkidiki, Greece, May 2003.

Na, Y. and Moin, P., “Direct Numerical Simulation of a Separated Turbulent Boundary Layer,” *J. Fluid Mech.*, vol. 370, pp. 175-201, 1998.

Najjar, F. M., and Vanka, S. P., “Numerical Study of Separated-Reattaching Flow,” *Theoretical and Computational Fluid Dynamics*, vol. 5, pp. 291-308, 1993.

Neuendorf, R. and Wygnanski, I., “On a Turbulent Wall Jet Flowing over a Circular Cylinder,” *J. Fluid Mech*., vol. 381, pp. 1-25, 1999.

Pack, L. and Seifert, A., “Dynamics of Active Separation Control at High Reynolds Numbers,” AIAA Paper 2000-0409, 2000.

Pack, L., Schaeffler, N., Yao, C. and Seifert, A., “Active Control of Flow Separation from the Slat Shoulder of a Supercritical Airfoil,” AIAA Paper 2002-3156, 2002.

Postl, D., Gross, A. and Fasel, H. F. “Numerical Investigation of Active Flow Control for Low-Pressure Turbine Blade Separation,” AIAA Paper 2004-0750, 2004.

Prasad, A. and Williamson, C. H. K., “The Instability of the Separated Shear Layer from a Bluff Body,” *Phys. Fluids*, vol. 8, no. 6, pp. 1347-1349, June 1996.

Rathnasingham, R. and Breuer, K. S. “System Identification and Control of a Turbulent Boundary Layer,” *Phys. Fluids*, vol 9 (7), pp. 1867-1869, July 1997.

Rathnasingham, R. and Breuer, K. S. “Active Control of Turbulent Boundary Layers,” *J. Fluid Mech.*, vol. 495, pp. 209-233, 2003.

Ravindran , S. S. “Active Control of Flow Separation Over an Airfoil,” NASA/TM-209838, 1999.

Roshko, A. “On the Development of Turbulent Wakes from Vortex Streets,” NACA Report 1191, 1954.

Seifert, A., Bachar, T., Koss, D., Shepshelovich, M. and Wygnanski, I., “Oscillatory Blowing: a Tool to Delay Boundary-Layer Separation,” *AIAA J.*, vol. 31, no. 11, 1993.

Seifert, A., Darabi, A. and Wygnanski, I., “Delay of Airfoil Stall by Periodic Excitation,” *J. Aircraft*, vol. 33, pp. 691-698, 1996.

Seifert, A. and Pack, L. G., “Oscillatory Control of Separation at High Reynolds Numbers,” *AIAA J.*, vol. 37, no. 9, pp. 1062-1071, Sep. 1999.

Seifert A. and Pack L. G. “Separation Control at Flight Reynolds Numbers – Lessons Learned and Future Directions,” AIAA Paper 2000-2542, 2000.

Smith, B. L. and Glezer, A., “Jet Vectoring using Synthetic Jets,” *J. Fluid Mech.*, vol. 458, pp. 1-34, 2002.

Smith, B. L. and Glezer, A., “The Formation and Evolution of Synthetic Jets,” *Phys. Fluids*, vol. 10, no. 9, pp. 2281-2297, 1998.

Sohn, K. H., Shyne, R. J. and DeWitt, K. J., “Experimental Investigation of Boundary Layer Behavior in a Simulated Low Pressure Turbine,” ASME Paper 98-GT-34, 1998.

Williamson, C. H. K., Wu, J. and Sheridan, J., “Scaling of Streamwise Vortices in Wakes,” *Phys. Fluids*, vol. 7, no. 10, pp. 2307-2309, 1995.

Wiltse, J. M. and Glezer, A., "Manipulation of Free Shear Flows Using Piezoelectric Actuators," *J. Fluid Mech.*, vol. 249, pp. 261-285, 1993.

Wu, J., Sheridan, J., Hourigan, K. and Soria, J., “Shear Layer Vortices and Longitudinal Vortices in the Near Wake of a Circular Cylinder,” *Exp. Therm. Fluid Sci.*, vol. 12, pp. 169-174, 1996.

Wu, J. -Z., Lu, X. -Y., Denny, A. G., Fan, M. and Wu, J. -M. “Post-Stall Flow Control on an Airfoil by Local Unsteady Forcing,” *J. Fluid Mech.*, vol. 371, pp. 21-58, September 1998.

Wygnanski, I., “Boundary Layer and Flow Control by Periodic Addition of Momentum,” AIAA Paper 97-2117, June 1997.

Wygnanski, I., “Some New Observations Affecting the Control of Separation by Periodic Forcing,” AIAA Paper 2000-2314, 2000.

Zaman, K. B. M. Q., McKenzie, B. J. and Rumsey, C. L., “A Natural Low Frequency Oscillation Over Airfoils Near Stalling Conditions,” *J. Fluid Mech.*, vol. 202, pp. 403-442, 1989.