PHYSICS OF FLUIDS VOLUME 14, NUMBER 4 APRIL 2002

BRIEF COMMUNICATIONS

The purpose of this Brief Communications section is to present important research results of more limited scope than regular articles appearing in Physics of Fluids. Submission of material of a peripheral or cursory nature is strongly discouraged. Brief Communications cannot exceed four printed pages in length, including space allowed for title, figures, tables, references, and an abstract limited to about 100 words.

On the virtual aeroshaping effect of synthetic jets

R. Mittal
Department of Mechanical and Aerospace Engineering, The George Washington University, Washington, DC 20052

P. Rampunggoon
Department of Mechanical Engineering, University of Florida, Gainesville, Florida 32611

(Received 9 October 2001; accepted 3 January 2002; published 7 March 2002)

The ability of synthetic jets to form large mean recirculation zones in a crossflow is investigated using numerical simulations. It has been suggested that this so-called virtual aeroshaping effect is one mechanism through which synthetic jets affect separation reduction. Here the interaction of a two-dimensional synthetic jet with a flat-plate Blasius boundary layer is simulated and we examine the effect that key flow parameters have on the formation of these mean recirculation zones. The current simulations also suggest a simple scaling for this effect which could prove useful in the design and deployment of these devices.
[DOI: 10.1063/1.1453470]

The synthetic jet has emerged as a versatile microactuator with potential applications ranging from separation[1–3] and turbulence,[4] control to thrust vectoring,[5] and augmentation of heat transfer and mixing.[6] Among all these applications, the use of these devices for active control of separation has been studied quite extensively, and in a number of experimental studies,[1–3] it has been demonstrated that synthetic jets can indeed reduce the extent of separation over bluff as well as streamlined bodies. Despite these successful demonstrations, it is fair to state that the physical mechanisms through which synthetic jets accomplish this reduction in separation are not completely understood.

Separation over an airfoil is typically an unsteady process that is accompanied by the formation of large-scale vortex structures in the separated shear layer.[7] The characteristic frequency of formation of these vortex structures is $O(U_\infty/L_s)$ where L_s is the length of the separation zone and U_∞ the freestream velocity. There is broad consensus[1,8] that synthetic jets operating in this frequency range tend to promote and amplify the formation of the vortex structures in the separation region. These vortex structures entrain high momentum, freestream fluid into the separated flow region and this promotes the early reattachment of the separated boundary layer. In the case where the boundary layer is laminar at separation, synthetic jets operating at much higher frequencies could also lead to earlier transition in the boundary layer. Since a turbulent boundary layer is more resistant to separation, earlier transition to turbulence can delay the separation. Both of the above mechanisms are not unique to synthetic jets but have indeed been well known in the context of active separation control for quite some time.[7,9,10]

In addition to these two mechanisms, the unique characteristics of the flow produced by a synthetic jet interacting with a crossflow have also led researchers to suggest other flow features/mechanisms that might play a role in separation reduction in flows where these actuators are employed. One of these is the so-called "virtual aeroshaping" effect. It has been suggested[1,11] that due to the zero net mass flux constraint, synthetic jets are capable of forming recirculation bubbles in the mean external flow and these can be significantly larger in size than the jet orifice/slot size. It has further been suggested that these large bubbles effectively modify the shape of the body, consequently altering the pressure gradient and the extent of separation. This capability of synthetic jets is extremely desirable since it would potentially allow for "on-demand" virtual morphing of the wing section.

However, two issues have to be addressed in order to put our understanding of this virtual aeroshaping effect on a firm footing. First, although previous studies have hypothesized the presence of large mean recirculation bubbles in these flows, conclusive evidence that such bubbles actually exist has not been readily available. Second, even if the formation of these recirculation bubbles can be confirmed, it remains to be clearly demonstrated how separation reduction can be attributed to this feature. Valuable effort in both these issues has recently been made by Honohan *et al.*[12] who have studied the formation and effect of such bubbles in flow past streamlined and bluff bodies. The current Brief Communication addresses the first issue, namely, confirming the pres-

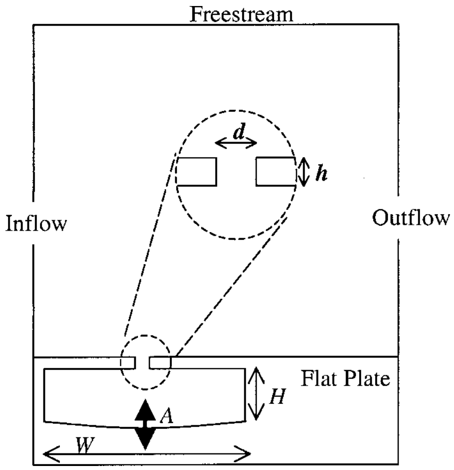

FIG. 1. Schematic of the synthetic jet model and computational domain employed in the current study. Drawing is not to scale.

ence of such features and establishing the conditions required for their formation. In doing so, a simple scaling law is extracted that relates the size of the mean recirculation bubble to the characteristics of the flow.

The virtual aeroshaping effect is examined here through numerical simulations. A relatively simple, two-dimensional model of a synthetic jet interacting with an external flow is employed. The model is shown in Fig. 1 and consists of a synthetic jet with a rectangular cavity (of width W and height H) flush mounted beneath a flat plate. The bottom boundary of the jet cavity is a moving boundary in the computation and is intended to accurately mimic the motion of the vibrating diaphragm. The vertical motion of the diaphragm is given by $Y(x,t)=A(x)\sin(\omega t)$ where ω is the angular frequency of the diaphragm motion and $A(x)$ its mode shape. In the current simulations, a mode shape corresponding to the fundamental mode of a membrane clamped at both ends is employed. The slot through which the flow is ingested and expelled has width d and height h.

The numerical solver employed here is described in detail in Ye *et al.*[13] and Udaykumar *et al.*[14] This solver simulates incompressible, viscous, unsteady flow in domains with complex, immersed, moving boundaries on a stationary Cartesian mesh. The spatial discretization is based on a finite-volume method which employs a second-order accurate, central-difference scheme and a second-order accurate, fractional step method is used for advancing the equations in time. The tracking of the moving boundary on the stationary, nonconformal Cartesian mesh is accomplished through the use of an Eulerian–Lagrangian approach in conjunction with special compact interpolation functions that allow for the imposition of the boundary conditions on the immersed boundary. For further details on the numerical methodology including validation and accuracy tests, the reader is referred to the two papers mentioned above.

With regard to the external flow, the computational domain has to be truncated to a finite extent in all directions and appropriate boundary conditions applied at these computational boundaries. For the external crossflow, a canonical Blasius flat-plate boundary layer profile (with freestream velocity U_∞, boundary layer thickness δ and momentum thickness θ) is imposed at the left inlet boundary. Thus, here we examine the interaction of a synthetic jet with a laminar, flat-plate boundary layer. The right boundary of the domain is the exit boundary and a nonreflective boundary condition[15] is employed here which allows vortical structures to convect out of this boundary with minimal reflections. At the top boundary, homogeneous Neumann velocity and pressure boundary conditions are employed and these allow the freestream to adjust to the presence of the synthetic jet without any spurious restrictions. This choice of boundary conditions coupled with the use of a relatively large ($80d \times 100d$) computational domain ensures that the results are relatively insensitive to the domain size. This is demonstrated conclusively by recomputing the flow with a different domain size.

A nonuniform Cartesian grid is employed in the current simulations wherein the region around the jet slot is provided with the finest resolution and the grid is stretched slowly in all directions in the external flow domain. The lips of the slot are effectively rounded with a radius of $\Delta/2$ where Δ is the local grid spacing. All results presented here are on a dense 600×220 mesh for which the grid spacing in the region around the slot is $0.05d$. This mesh was chosen after a careful grid refinement study wherein the highest Reynolds number computation in the current study ($\mathrm{Re}_\delta=400$; see definition below) was recomputed on a mesh with 50% higher resolution in the vicinity of the slot than the nominal 600×220 mesh. Comparison of the results (see Fig. 4) on the two meshes indicated insignificant differences thereby demonstrating the grid independence of the computed results.

The flow in this configuration can be considered to be a function of the following nondimensional parameters (W/H), (d/h), S, $\overline{V_J}/U_\infty$, Re_δ, and δ/d where $S=\sqrt{\omega d^2/\nu}$ is the Stokes number of the flow through the slot, and $\mathrm{Re}_\delta=U_\infty\delta/\nu$ is the Reynolds number based on the boundary layer thickness δ and crossflow velocity U_∞. Instead of the boundary layer thickness, one can choose the momentum thickness as the characteristic length scale for the external boundary layer. However, since for the Blasius boundary layer, the ratio between the boundary layer and momentum thickness is a constant ($\delta/\theta\approx 7.53$),[16] the results can always be recast in terms of either length scales. In the above expressions, $\overline{V_J}$ is the mean jet expulsion velocity, i.e., jet velocity averaged over slot width d and the expulsion phase of the cycle. Thus, even this relatively simple flow configuration has a large parameter space which makes a comprehensive analysis of this flow configuration quite difficult. Our previous computations[17,18] have indicated that the external flow is only marginally affected by the parameters (W/H) and (d/h) and therefore, in the current study, these parameters were fixed at values of 5 and 1, respectively. In order to further limit the scope of the study, the Stokes number has been fixed at a value of 10. The remaining three parameters have been varied in the current study and the impact of varying these parameters on the virtual aeroshaping effect examined. In the current study, $\overline{V_J}/U_\infty$ is varied between 0.5 and 5.0. Furthermore, results reported here include two values of Re_δ (250 and 400), and two of δ/d (2 and 5). Flow for all

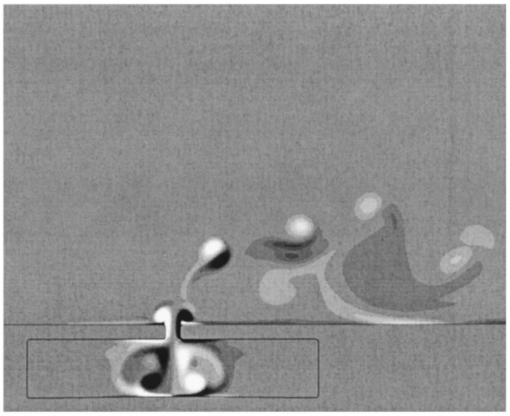

FIG. 2. Spanwise vorticity contour plot for case with $\delta/d=5$, $\overline{V}_J/U_\infty=3.75$, and $\mathrm{Re}_\delta=250$. Phase in cycle corresponds to maximum expulsion velocity and dark and light contours indicate clockwise and counterclockwise rotation, respectively.

cases presented here is simulated until it reaches a stationary state and statistics accumulated over a number of cycles beyond this time.

It should be pointed out that the investigation of Honohan *et al.*[12] suggests that the jet frequency plays an important role in the formation of the recirculation zone. In their experiments the Stokes number was varied from about 7 to 20 and quasisteady recirculation bubbles found for Stokes number greater than about 10. In these experiments, Re_δ and δ/d were kept fixed and only $\overline{V}_J/U_\infty$ and Stokes number S were varied. In the current study, only S is kept constant and therefore our results can be considered complementary to those of Honohan *et al.*[12]

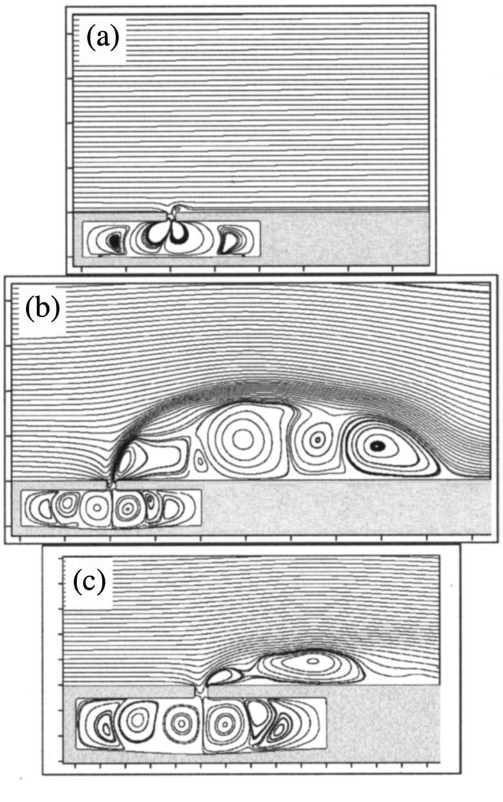

FIG. 3. Streamline of the mean flow for selected cases with $\mathrm{Re}_\delta=250$ (a) $\delta/d=5$, $\overline{V}_J/U_\infty=1.25$, (b) $\delta/d=5$, $\overline{V}_J/U_\infty=5.0$, (c) $\delta/d=2$, $\overline{V}_J/U_\infty=2.0$. Tick marks on the axes are a distance δ apart.

Figure 2 shows a spanwise vorticity plot corresponding to the $\delta/d=5$ case with $\overline{V}_J/U_\infty=3.75$ and $\mathrm{Re}_\delta=250$ at a phase in the cycle where there jet expulsion velocity is maximum and this plot shows the typical evolution of the vortex dipole in the presence of an external crossflow. The mean velocity for all cases has been computed and in Fig. 3, the streamlines corresponding to this mean velocity field are shown for three selected cases. Figures 3(a) and 3(b) both correspond to cases with $\delta/d=5$ but the mean jet velocity $\overline{V}_J/U_\infty$ is equal to 1.25 and 5 for these two cases, respectively. It can be seen that for $\overline{V}_J/U_\infty=1.25$, only a small recirculation bubble is formed in the vicinity of the jet slot. In contrast, with the higher jet velocity, a bubble which is significantly larger than the jet width is formed. The length of the recirculation zone is determined by examining the variation of the mean wall shear stress on the flat plate downstream of the jet and extracting from this, the location where the separation streamline attaches to the flat plate. Employing this procedure, the length of the recirculation zone (L_r) measured from the center of the slot for this highest jet velocity case is determined to be $35d$ or 7δ.

A second series of simulations have been carried out where δ/d and Re_δ are fixed at values of 2 and 250, respectively, and $\overline{V}_J/U_\infty$ varied systematically from 0.5 to 2.0. Figure 3(c) shows the streamline pattern corresponding to the mean velocity for the highest relative velocity jet in this series. For this case, the length of the recirculation zone (L_r) measured from the center of the slot is about $13d$ or 6.5δ. Finally, all of the above simulations were carried out at a fixed boundary layer Reynolds number of 250. Thus, in order to examine the variation of the flow with this parameter also, one more case with $\mathrm{Re}_\delta=400$, $\delta/d=2$, and $\overline{V}_J/U_\infty=1.25$ has been simulated. For this case, the length of the recirculation bubble is found to be about $4d$. Thus clearly, the ability of the synthetic jet to create large mean recirculation bubbles depends on the jet velocity relative to the external flow velocity. However, the above series of simulations also show that the thickness of the boundary layer relative to the slot width has a significant impact on the bubble size.

One of the main objectives here is to extract a scaling law that would relate the bubble size to the parameters of the flow. In order to accomplish this we have taken guidance from the previous study of Balachandar *et al.*[19] who studied the properties of the mean separation bubbles that form on the leeward side of bluff bodies. By balancing the forces on the fluid inside the mean recirculation region, they found that among other factors, the Reynolds stresses on the boundary of the bubble plays an important role in determining the size of the bubble. Furthermore, our preliminary simulations suggested that the bubble length increases with the jet momentum flux (which is effectively the vertical Reynolds normal stress at the lower boundary of the bubble) and decreases with increasing streamwise momentum flux of the boundary layer. Motivated by all of these considerations, it was decided to explore the scaling of the bubble size with the quantity $C_\mu=\overline{V}_J^2 d/U_\infty^2\theta$ that can be considered to be the ratio of

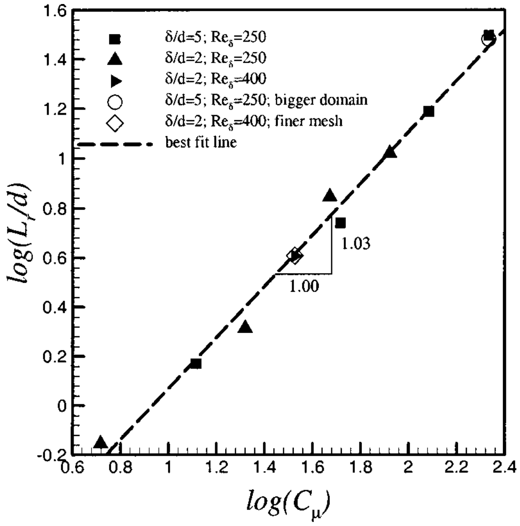

FIG. 4. Variation of log of normalized bubble length (L_r/d) with log of momentum coefficient (C_μ).

the jet momentum flux to the momentum flux associated with the external crossflow. Similar parameters have also been employed in the past in the context of active separation control[1,8] but have not specifically been related to the virtual-aeroshaping effect.

Figure 4 shows $\log(L_r/d)$ plotted against $\log(C_\mu)$ for the nine separate cases simulated here. In addition, for the case with the largest bubble [corresponding to Fig. 3(b)], the result of a simulation carried out on an external computational domain which is three times larger in each direction is also presented. Finally, for the highest Reynolds number case ($\mathrm{Re}_\delta = 400$) an additional simulation has also been carried out with a grid that has 50% higher resolution in the vicinity of the slot than the nominal mesh. Results of both these simulations show insignificant differences from the corresponding simulations carried out on the nominal domain and mesh, thereby demonstrating the adequacy of the chosen domain size and grid resolution. A least-squares linear fit has also been performed for the entire data and the slope of the line is determined to be 1.03. This provides strong indication that within at least the range of parameters investigated here, the normalized bubble length grows linearly with the momentum coefficient C_μ as defined above.

Thus the current study not only provides a clear demonstration of the ability of synthetic jets to form large mean recirculation bubbles, but also provides some insight into the physical process governing this formation process, i.e., the exchange of momentum between the jet and the external flow. Finally, the simple computational model employed here also gives some indication as to the regime where synthetic jets would have to operate in, in order to create large mean recirculation bubbles. The current study does not include effects such as three dimensionality, turbulence, compressibility, and pressure gradients in the external flow, all of which might have a modulating effect on the ability of the synthetic jets to form these mean recirculation bubbles. These effects need to be studied in the future using experiments and simulations.

ACKNOWLEDGMENTS

Support for this work has been provided by NASA under Grant No. NAG-1-01024 monitored by Susan Gorton. This work benefited from extensive discussions with Dr. L. Cattafesta and Dr. R. W. Mei on various aspects of synthetic jets.

[1] M. Amitay, V. Kibens, D. Parekh, and A. Glezer, "The dynamics of flow reattachment over a thick airfoil controlled by a synthetic jet actuator," AIAA Pap. 99-1001 (1999).

[2] A. Crook, A. M. Sadri, and N. J. Wood, "The development and implementation of synthetic jets for the control of separated flow," AIAA Pap. 99-3173 (1999).

[3] D. Smith, M. Amitay, V. Kibens, D. Parekh, and A. Glezer, "Modification of lifting body aerodynamics using synthetic jet actuators," AIAA Pap. 98-0209 (1998).

[4] C. Y. Lee and D. B. Goldstein, "DNS of microjets for turbulent boundary layer control," AIAA Pap. 2001-1013 (2001).

[5] B. L. Smith and A. Glezer, "Vectoring and small-scale motions affected in free shear flows using synthetic jet actuators," AIAA Pap. 97-0213 (1997).

[6] Y. Chen, S. Liang, K. Aung, A. Glezer, and J. Jagoda, "Enhanced mixing in a simulated combustor using synthetic jet actuators," AIAA Pap. 99-0449 (1999).

[7] M. Gad-el-Haq and D. M. Bushnell, "Separation control: Review," J. Fluids Eng. **113**, 5 (1991).

[8] A. Seifert, T. Bachar, D. Koss, M. Shepshelovich, and I. Wygnanski, "Oscillatory blowing: A tool to delay boundary layer-separation," AIAA J. **31**, 2052 (1993).

[9] F. B. Hsiao, C. F. Liu, and J. Y. Shyu, "Control of wall-separated flow by internal acoustic excitations," AIAA J. **28**, 1440 (1990).

[10] L. S. Huang and L. Maestrello, "Separation control over an airfoil at high angles of attack by sound emanating from the surface," AIAA Pap. 87-1261 (1987).

[11] E. Chatlynne, N. Rumigny, M. Amitay, and A. Glezer, "Virtual aeroshaping of a Clark-Y Airfoil using synthetic jet actuators," AIAA Pap. 2001-0732 (2001).

[12] A. M. Honohan, M. Amitay, and A. Glezer, "Aerodynamic control using synthetic jets," AIAA Pap. 2000-2401 (2000).

[13] T. Ye, R. Mittal, H. S. Udaykumar, and W. Shyy, "An accurate Cartesian grid method for viscous incompressible flows with complex immersed boundaries," J. Comput. Phys. **156**, 209 (1999).

[14] H. S. Udaykumar, R. Mittal, P. Rampunggoon, and A. Khanna, "A Cartesian grid method for incompressible flows with complex moving boundaries," J. Comput. Phys. **174**, 345 (2001).

[15] H-J. Kaltenbach, M. Fatica, R. Mittal, T. S. Lund, and P. Moin, "Study of flow in a planar asymmetric diffuser using large-eddy simulation," J. Fluid Mech. **390**, 151 (1999).

[16] H. Schlichting and K. Gersten, *Boundary Layer Theory* (Springer, New York, 1996).

[17] P. Rampunggoon, Ph.D. thesis, Department of Mechanical Engineering, University of Florida, Gainesville, Florida, 2001.

[18] Y. Utturkar, R. Mittal, P. Rampunggoon, and L. Cattafesta, "Sensitivity of synthetic jets to the design of the jet cavity," AIAA Pap. 2002-0124 (2001).

[19] S. Balachandar, R. Mittal, and F. M. Najjar, "Properties of the mean recirculation region in the waked of two-dimensional bluff bodies," J. Fluid Mech. **351**, 167 (1997).