Lattice Boltzman Method applied to Aerodynamic control on a low Reynolds airfoil with realistic synthetic jet geometries

Objective: The goal of the present study is to investigate the influence of cavity shape (as shown at University of Toronto)[1–3] on synthetic jets under a cross-flow over an airfoil. The work will focus on including cavity shape as a parameter important to the momentum transfer.

Background: A synthetic jet transfers linear momentum to the surroundings by alternately ingesting and expelling fluid from a cavity containing an oscillating diaphragm and has been shown to be a useful AFC device[4,5]. Compared with continuous jets, synthetic jet are low-weight, compact and do not require internal fluid supply lines[6–8]. A schematic diagram of a typical synthetic jet actuator is shown in Fig. 1, which also illustrates the primary structure and shows vortex pairs emanating from a nozzle while the SJA is in operation.

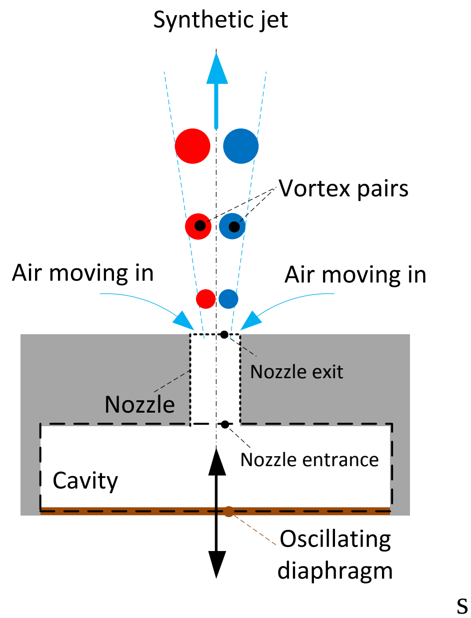

Fig. 1 Schematic diagram of a synthetic jet actuator.

A synthetic jet actuator typically has a nozzle or slot connected to a cavity in which a piezoelectric membrane oscillates. By oscillating the diaphragm, the working fluid is alternately ingested and expelled through the nozzle exit, forming a train of discrete vortical structures that impart linear momentum to the flow without net mass injection[9]. The ability of the vortex pairs to overcome the suction velocity during the ingestion stroke depends on its self-induced velocity, which in turn is a function of the vortex strength. The fact that no external fluid source is required combined with the availability of increasingly small vibrating diaphragms, e.g. piezo-electric disks, allows the design of extremely compact devices, even down to MEMS scales[10,11].

Recently, the influence of cavity shape on synthetic jet performance has been studied with numerical simulation or experiment. Bhapkar et al.[12] conducted an experimental study to investigate the effect of orifice cavity shape on resonance frequency and heat transfer characteristics of synthetic jets. The velocity measurement results showed that the resonance frequency was a weak function of cavity volume as the resonance frequency remains. Utturkar et al.[13] employed an incompressible flow model to study the flow in rectangular cavities where the aspect ratio and location of the oscillating diaphragm was varied. Cavities containing multiple oscillating diaphragms were also considered, where the oscillation amplitude was adjusted in order to maintain the same volume displacement in each case. The paper found that cavity shape and diaphragm placement had negligible impact on the actuator performance in both quiescent conditions or with cross-flow. Jain et al.[14] provided a detailed compressible simulation of an axisymmetric synthetic jet compared with the existing experimental and numerical results for the purpose of validation. A vibrating diaphragm was simulated as a moving boundary and was compared with other boundary conditions. They compared the standard cylindrical cavity to conical and parabolic shapes and the simulation results showed that cavity and orifice height did not affect the maximum exit plane velocity appreciably for the three shapes. However, Feero et al.[15] presented experimental measurements for three axisymmetric synthetic jets with different cavity shapes to examine jet performance, while holding constant cavity volume, nozzle length and nozzle diameter. The experimental results showed that synthetic jet performance was dependent on cavity shape.

The Lattice Boltzmann method (LBM) offers an effective and efficient method to simulate complex fluid flow, allowing easy implementation of boundary conditions and can be used for unsteady flows, phase separation, evaporation, condensation, cavitation, solute and heat transport, buoyancy, and interactions with surfaces can readily be simulated. Instead of solving the classical macroscopic Navier-Stokes (N-S) equations, as is done with traditional CFD methods, LBM solves for a limited number of interactions with small particles to determine the exchange of momentum and energy by simulating streaming and collision processes[16]. The LBM is based on constructing simplified kinetic models containing the physics of microscopic and mesoscopic processes so that averaging can recover macroscopic properties that obeys the continuum equations[17].

LBM also has been applied in the study on flow control including flow separation control, mixing control, and turbulence control, using a pair of synthetic jets (SJs). Wang et al.[18] studied active control of wakes and one-dimensional vortex-induced vibrations (VIVs) from a single circular cylinder using a pair of synthetic jets (SJs) at a low Reynolds number Re=100 using a lattice Boltzmann method based numerical frame work. Using a hybrid approach of the lattice Boltzmann method for flow field computations and a finite-difference model, Mautner[19] studied the modified main channel flow results for various wall jet geometries (derived from synthetic jets), jet inlet conditions, scaling issues and Reynolds numbers. Fu et al.[20] reported on the use of the lattice Boltzmann method, in conjunction with Large-Eddy Simulations, to study an interesting phenomenon related to the suppression of vortex shedding from circular cylinders with high accuracy coupled with computational efficiency. It had been observed in experiments that vortex shedding and separated shear layer from a cylinder could be drastically reduced by the injection of a fluid jet into the approach flow.

The application of LBM for fluid flow simulations is far less common than, *e.g.*, finite volume methods, however there is a significant body of findings in the literature that suggests that this method is more accurate and less computationally intensive compared to others. For this work, a 3-D simulation of synthetic jet cavities is conducted with the Lattice Boltzmann method. Based on the BGK model, the most popular model for the 3-D case, the D3Q19 model shown in Fig. 2, which consists of 19 distribution functions, was adopted[21].

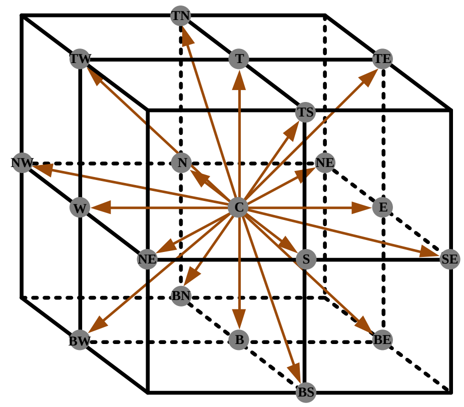

Fig. 2 D3Q19 model for the 3-D LBM.

Bibliography

[1] Mu, H., Yan, Q., Wei, W., and Sullivan, P. E., “Synthetic Jet Performance for Different Axisymmetric Cavities Analyzed with 3-D Lattice-Boltzmann Method,” *AIAA Journal*, vol. 56, 2018, pp. 2499–2505.

[2] Mu, H., Yan, Q.-D., Wei, W., and Sullivan, P. E., “Unsteady simulation of a synthetic jet actuator with cylindrical cavity using a 3-D Lattice-Boltzmann Method,” *International Journal of Aerospace Engineering*, 2018.

[3] Ziadé, P., Feero, M. A., and Sullivan, P. E., “A numerical study on the influence of cavity shape on synthetic jet performance,” *International Journal of Heat and Fluid Flow*, vol. 74, Dec. 2018, pp. 187–197.

[4] Greenblatt, D., Paschal, K. B., Chung-Sheng, Y., and Harris, J., “Experimental Investigation of Separation Control Part 2: Zero Mass-Flux Oscillatory Blowing,” *AIAA Journal*, vol. 44, 2006, pp. 2831–2845.

[5] Feero, M. A., Lavoie, P., and Sullivan, P. E., “Influence of synthetic jet location on active control of an airfoil at low Reynolds number,” *Experiments in Fluids*, vol. 58, Aug. 2017, p. 99.

[6] Pavlova, A., and Amitay, M., “Electronic Cooling Using Synthetic Jet Impingement,” *Journal of Heat Transfer*, vol. 128, 2006, p. 897.

[7] Kercher, D. S., Lee, J. B., Brand, O., Allen, M. G., and Glezer, A., “Microjet cooling devices for thermal management of electronics,” *IEEE Transactions on Components and Packaging Technologies*, vol. 26, 2003, pp. 359–366.

[8] Amitay, M., Smith, D. R., Kibens, V., Parekh, D. E., and Glezer, A., “Aerodynamic Flow Control over an Unconventional Airfoil Using Synthetic Jet Actuators,” *AIAA Journal*, vol. 39, 2001, pp. 361–370.

[9] Glezer, A., and Amitay, M., “Synthetic Jets,” *Annual Review of Fluid Mechanics*, vol. 34, 2002, pp. 503–529.

[10] Lee, C., Hong, G., Ha, Q. P., and Mallinson, S. G., “A piezoelectrically actuated micro synthetic jet for active flow control,” *Sensors and Actuators, A: Physical*, 2003, pp. 168–174.

[11] Ma, X., Guo, H., Fan, Z., and Zhang, L., “Investigating of simulation methods for synthetic jet,” *Procedia Engineering*, 2012, pp. 416–421.

[12] Bhapkar, U. S., Srivastava, A., and Agrawal, A., “Proper cavity shape can mitigate confinement effect in synthetic jet impingement cooling,” *Experimental Thermal and Fluid Science*, vol. 68, 2015, pp. 392–401.

[13] Utturkar, Y., Mittal, R., Rampunggoon, P., and Cattafesta, L., “Sensitivity of synthetic

jets to the design of the jet cavity," *40th AIAA Aerospace Sciences Meeting & Exhibit*, Reno, NV, United States: 2002, pp. 2002–0124.

[14] Jain, M., Puranik, B., and Agrawal, A., "A numerical investigation of effects of cavity and orifice parameters on the characteristics of a synthetic jet flow," *Sensors and Actuators A: Physical*, vol. 165, Feb. 2011, pp. 351–366.

[15] Feero, M. A., Lavoie, P., and Sullivan, P. E., "Influence of Cavity Chape on Synthetic Jet Performance," *Sensors and Actuators A:Physical*, vol. 223, Mar. 2015, pp. 1–10.

[16] Perumal, D. A., and Dass, A. K., "Simulation of Incompressible Flows in Two-Sided Lid-Driven Square Cavities. Part II-LBM," *CFD Letters*, vol. 2, 2010, pp. 25–38.

[17] Perumal, D. A., and Dass, A. K., "Multiplicity of steady solutions in two-dimensional lid-driven cavity flows by Lattice Boltzmann Method," *Computers & Mathematics with Applications*, vol. 61, 2011, pp. 3711–3721.

[18] Wang, C., Tang, H., Duan, F., and Yu, S. C. M., "Control of wakes and vortex-induced vibrations of a single circular cylinder using synthetic jets," *Journal of Fluids and Structures*, vol. 60, 2016, pp. 160–179.

[19] Mautner, T., "Application of the synthetic jet concept to low Reynolds number biosensor microfluidic flows for enhanced mixing: a numerical study using the lattice Boltzmann method.," *Biosensors & Bioelectronics*, vol. 19, Jun. 2004, pp. 1409–19.

[20] Fu, G., Younis, B. A., Sun, L., and Dai, S., "Vortex Shedding Control Using Jets: A Computational Study With Lattice Boltzmann Method," *ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering*, American Society of Mechanical Engineers, 2016, p. V002T08A071-V002T08A071.

[21] Iglberger, K., Thürey, N., and Rüde, U., "Simulation of moving particles in 3D with the Lattice Boltzmann method," *Computers and Mathematics with Applications*, vol. 55, 2008, pp. 1461–1468.