ME615 Project Presentation
Aeroacoustic Simulations using Lattice Boltzmann Method

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Introduction

- Lattice Boltzmann method (LBM) is emerging as a potential tool for simulating fluid flow
- LBM is a mesoscopic approach tailored to simulate incompressible or compressible flow.
- Navier-Stokes equations can derived from LB equations by applying Chapman-Enskog multiscale and small parameter expansion
- Types of lattice Boltzmann methods
  1. Classical LBM (used in the present study)
  2. Finite Difference LBM

Numerical Method

- Lattice Boltzmann equation with BGK-Single Relaxation time is the governing equation
- f_α: particle distribution function
- Ω_α: Collision operator
- τ: Relaxation time
- f_α^{eq}: Equilibrium particle distribution function

Lattice Boltzmann Equation

$$f_\alpha(\mathbf{x} + \mathbf{c}_\alpha \delta t, t + \delta t) - f_\alpha(\mathbf{x}, t) = \Omega_\alpha \tag{1}$$

$$\Omega_\alpha = \frac{1}{\tau}\left[f_\alpha(\mathbf{x}, t) - f_\alpha^{eq}(\mathbf{x}, t)\right] \tag{2}$$

Equilibrium Distribution Function

$$f_\alpha^{eq}(\rho, \mathbf{u}) = w_\alpha \; \rho \; \left[1 + \frac{\mathbf{c}_\alpha . \mathbf{u}}{c_s^2} + \frac{(\mathbf{c}_\alpha . \mathbf{u})^2}{2c_s^4} - \frac{|\mathbf{u}|^2}{2c_s^2}\right] \tag{3}$$

Macroscopic Quantities

$$\rho(\mathbf{x}, t) = \sum_\alpha f_\alpha(\mathbf{x}, t) \tag{4}$$

$$\rho(\mathbf{x}, t)\mathbf{u}(\mathbf{x}, t) = \sum_\alpha \mathbf{c}_\alpha f_\alpha(\mathbf{x}, t) \tag{5}$$

Lattice Details

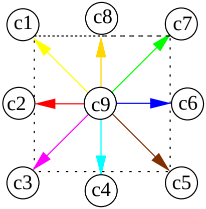


Figure: D2Q9 lattice

- D2Q9 lattice is used in all simulations
- Lattice speed of sound: $c_s = \frac{1}{\sqrt{3}}$; weights are given by:

$$\begin{aligned} w_{k=9} &= 4/9 \\ w_{k=1,2,3,4} &= 1/9 \\ w_{k=5,6,7,8} &= 1/36 \end{aligned}$$

- For $i = 1, 9$, lattice vectors are defined by

$$c_i = \begin{bmatrix} 1 & 0 & -1 & 0 & 1 & -1 & -1 & 1 & 0 \\ 0 & 1 & 0 & -1 & 1 & 1 & -1 & -1 & 0 \end{bmatrix}$$

Streaming Operation

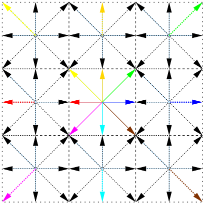


Figure: Schematic showing the streaming operation

Overall Solution Algorithm:

- Collision
- Stream
- Apply Periodic BC
- Compute macroscopic quantities

Streaming operation:

- Solid arrows represent the lattice under consideration
- Respective broken line arrows show the final position after streaming

Results - Initial Sound Pulse

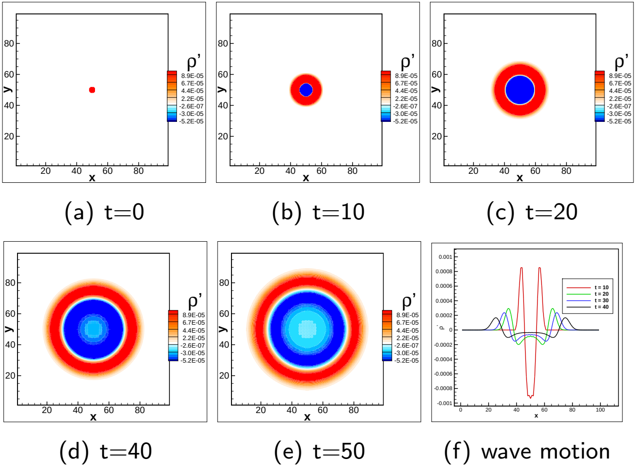
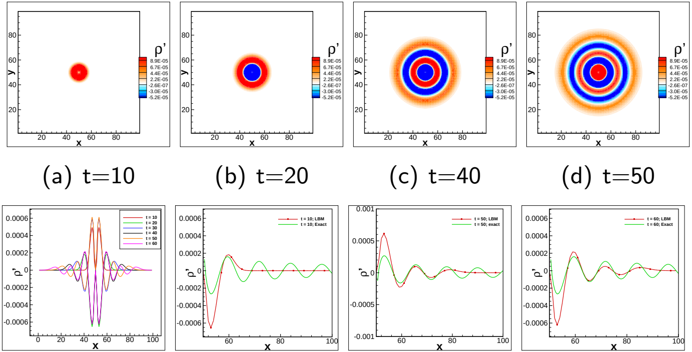


Figure: Propagation of density perturbation waves for the case of pulse

Results - Monopole



(a) t=10 (b) t=20 (c) t=40 (d) t=50

(e) wave motion (f) t=10 (g) t=50 (h) t=60

Figure: Propagation of density perturbation waves for the case of monopole

Results - Monopole, Excitation time period study

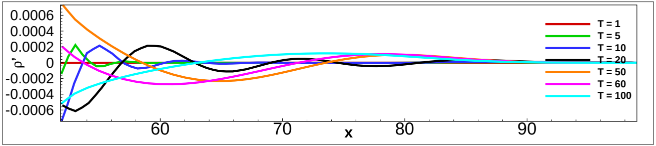
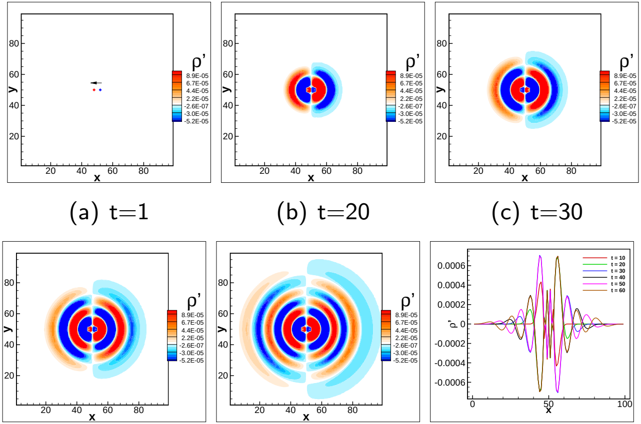


Figure: Propagation of density perturbations for different time periods of excitation

- Time periods of excitation $T = 10$ and $T = 20$ show at least two wave lengths in the density perturbation
- $T = 50$, and $T = 60$ show only one wave length of the density perturbation
- $T = 1$, and $T = 100$ were not captured by the grid solution considered
- Longer domain is needed to capture the waves generated by $T = 100$ excitation

Results - Dipole

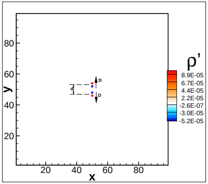


(a) t=1 (b) t=20 (c) t=30

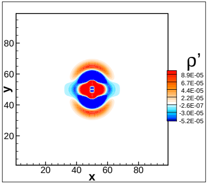
(d) t=40 (e) t=60 (f) wave motion

Figure: Propagation of density perturbation waves for the case of a dipole

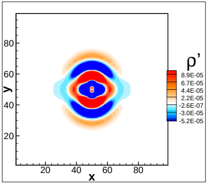
Results - Longitudinal Quadrupole



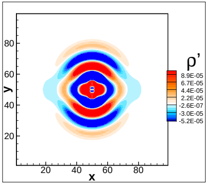
(a) t=1



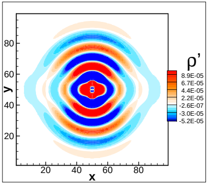
(b) t=20



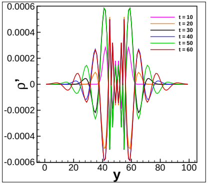
(c) t=30



(d) t=40



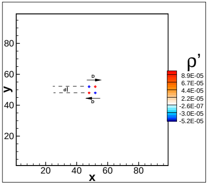
(e) t=60



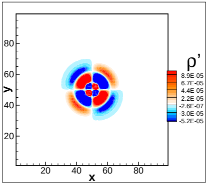
(f) wave motion

Figure: Density perturbation waves for the case of a longitudinal quadrupole

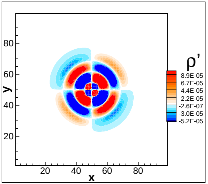
Results - Lateral Quadrupole



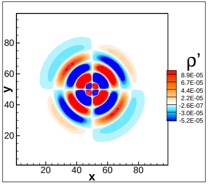
(a) t=2



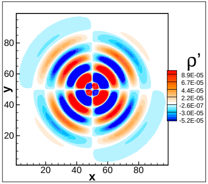
(b) t=20



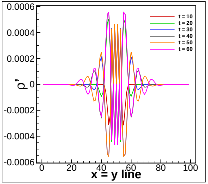
(c) t=30



(d) t=40



(e) t=60



(f) wave motion

Figure: Density perturbation waves for the case of a lateral quadrupole

Conclusions

- Developed a 2D LBM solver in Fortran 90
- Applied the solver to simulating bench-mark problems in aeroacoustics such as, initial sound pulse, monopole, dipole, longitudinal and lateral quadrupole
- The density perturbation field computed is compared to the analytical solution and it is seen that the wave length seems to be accurately represented but there is some discrepancy in the amplitudes which could be because of the grid resolution or the difference in the speed of sound captured.
- Time period of excitation study on the monopole case shows that $T = 10$ and $T = 20$ are ideal cases where as $T = 100$ is not captured by the current domain, and a longer domain is needed to capture this.
- Overall, LBM seems to be a viable approach for simulating aeroacoustics

References

- Dong, Y., and Sagaut, P., *A study of time correlations in lattice Boltzmann-based large-eddy simulation of isotropic turbulence*, Physics of Fluids, **20**, 035105 (2008).
- Luo, L., Krafczyk, M., and Shyy, W., *Lattice Boltzmann method for Computational Fluid Dynamics*, Encyclopedia of Aerospace Engineering, John Wiley & Sons, Ltd.
- Lew, P., T., Mongeau, L., and Lyrintzis, A., *Noise prediction of a subsonic turbulent round jet using the lattice-Boltzmann method*, Journal of the Acoustical Society of America, **128(3)**, 1118-1127 (2010)
- Chikatamarla, S., S., Frouzakis, C., E., Karlin, I., V., Tomboulides, A., G., and Boulouchos, K., B., *Lattice Boltzmann method for direct numerical simulation of turbulent flows*, Journal of Fluid Mechanics, **656**, 298-308, (2010).
- Bhatnagar, P. L., Gross, E., P., and Krook, M., *A Model for Collision Processes in Gases. I. Small Amplitude Processes in Charged and Neutral One-Component Systems*, Physical Review, **94(3)**, 511-525, (1954)
- Pierce, A. D., *Acoustics, An Introduction to Its Physical Principles and Applications*, Acoustical Socienty of America, (1994)
- Chen, S., and Doolen, G., D., *Lattice Boltzmann Method for Fluid Flows*, Annual Review of Fluid Mechanics, **30**, 329-364, (1998)
- Kam, E., W., S., So, R., M., C., Fu, S., C., and Leung, R., C., K., *Finite Difference Lattice Boltzmann Method Applied to Acoustic-Scattering Problems*, AIAA Journal, **48(2)**, (2010)
- Viggen, E., M. *The Lattice Boltzmann Method with Applications in Acoustics*, Masters Dissertation, Department of Physics, NTNU (2009)
- Malaspinas, O., and Sagaut, P., *Advanced large-eddy simulation for lattice Boltzmann methods: The approximate deconvolution model*, Physics of Fluids, **23**, 105103 ,(2011)

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Fini...

Thank You!