Numerical Simulation of a Flue Instrument with Finite-Difference Lattice Boltzmann Method using GPGPU

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***Abstract*—In this work, we discuss the possibility of using GPGPU techniques for Aeroacoustic Simulation (especially for flue instruments) with the finite-difference lattice Boltzmann method (FDLBM). Compressible flow simulation has been used in direct aeroacoustic simulation; however, the computational cost is huge due to the requirement of high computational mesh resolution, with small time steps. The lattice Boltzmann method (LBM) has been used as an efficient method for fluid simulation using GPGPU. However, LBM is not accurate enough when applied to some aeroacoustic problems [1]. On the other hand, FDLBM is able to use high-order finite-difference schemes and it has a high arithmetic intensity compared to LBM. We present a performance evaluation of the LBM and FDLBM with several finite-difference schemes on GPU with the roofline model.**

1. INTRODUCTION

A Flue instrument such as a flute, shakuhachi (Japanese flute), or pipe organ is a musical instrument whose sound source is the aerodynamic sound generated by an air jet impinging on a wedge-shaped object. There is a feedback mechanism between the air jet and the resonance tube, due to the significant influence of the sound pressure in the resonance tube on the air jet. A compressible flow simulation has been used to reproduce the sound vibration of flue instruments [2]; however, the computational cost is huge. The computational mesh size needs to be small enough to reproduce the vortex, and the time step needs to be set as $10^{-7} \sim 10^{-8}$s.

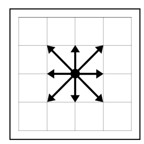
LBM has been used as an alternative method to the Navier-Stokes equations, due to its advantage of simple implementation on many-core accelerators such as GPU. Standard LBM is only second-order accurate in both spatial and temporal dimensions; thus, it is not accurate enough for direct aeroacoustic simulation. In contrast, FDLBM can use finite-difference schemes of an arbitrary order; it is capable of simulating the problem efficiently.

In this work, we present the performance evaluation of LBM and FDLBM, in order to investigate an efficient and practical method for direct aeroacoustic simulation.

2. NUMERICAL METHODS

In this work, we use the FDLBM model (Eq. 1) proposed by Tsutahara [3], and the D2Q9 model (Fig. 1). The third-order upwind (UTOPIA) scheme is used for space discretization, and the second order Runge-Kutta method is used for time discretization. In addition, for the evaluation, we use the Lax-Wendroff Method [4] and the standard LBM.

$$\frac{\partial f_i}{\partial t} + \mathbf{c}_i \frac{\partial f_i}{\partial \mathbf{x}} - \frac{A\mathbf{c}_i}{\tau}\frac{\partial (f_i - f_i^{(0)})}{\partial \mathbf{x}} = -\frac{1}{\tau}[f_i - f_i^{(0)}] \quad (1)$$



i	Discrete velocity vectors	$\lvert\mathbf{c}\rvert$
0	(0,0)	0
$1 \sim 4$	(1,0),(0,1),(-1,0),(0,-1)	1
$5 \sim 8$	(1,1),(-1,1),(-1,-1),(1,-1)	$\sqrt{2}$

Fig. 1. Two-dimensional 9-speed model (D2Q9)

3. PERFORMANCE EVALUATION

In this work, we evaluate the performance of the advection and collision terms (Fig. 2). In FDLBM, the calculation of the advection term takes the most amount of time. The calculation of the equilibrium function is the same in both LBM and FDLBM.

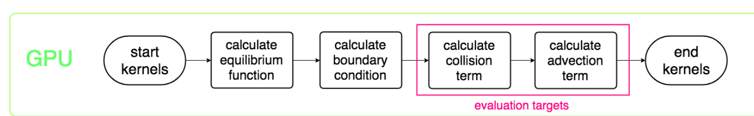


Fig. 2. Flow chart of GPU implementation

The evaluation was carried out using the ITO subsystem B at the Research Institute for Information Technology, Kyushu University. The details of the evaluation environment are listed below. For the evaluation, we took the mesh size as 1024 × 1024.

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Architecture : NVIDIA Tesla P100 (1,328-1,480 MHz)
Compiler : gcc-4.8.5, nvcc (CUDA v.8.0.61)
Optimize Option : -O3
Profiling Tool : Nvidia Profiler (v.8.0.61)
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Fig. 3 shows the average execution time of the kernels with different implementations of FDLBM (UTOPIA). Memory coalescing significantly improves the performance with few code modifications, and the use of local memory improves the performance and arithmetic intensity.

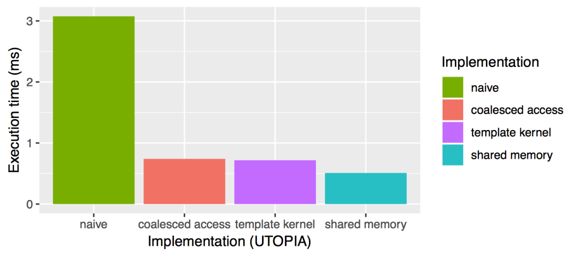

Fig. 3. Average execution time of FDLBM (UTOPIA)

Eq. 2 gives the improved roofline model [5], which predicts the attainable performance. As shown in Fig. 4, we observe that FDLBM achieves high effective performance compared to LBM. The average execution time of the kernels for FDLBM (UTOPIA, shared) is around 0.50 ms, and that for LBM is around 0.45 ms.

$$Flops = \frac{F}{\frac{B}{B_{\text{peak}}} + \frac{F}{F_{\text{peak}}} + etc} \approx \frac{F/B}{\frac{1}{B_{\text{peak}}} + \frac{F/B}{F_{\text{peak}}}} \tag{2}$$

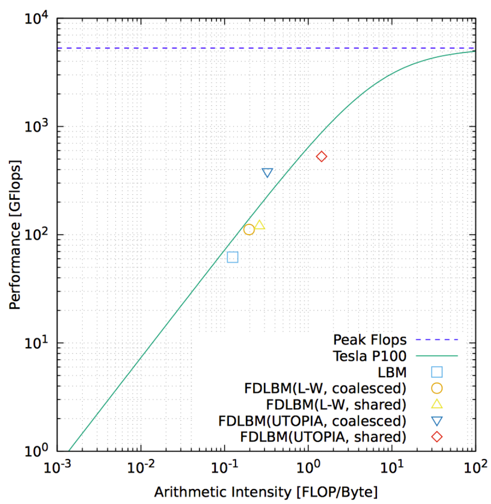

Fig. 4. Relation between performance (Gflops) and arithmetic intensity (FLOP/Byte)

4. NUMERICAL RESULTS

In this section, we discuss the change in characteristic frequencies of the sound waves excited in the pipe with increase in the air jet velocity. We used a simple flue instrument model (Fig. 5) for the simulation, and the parameters were set to $1.5 \times 10^{-5}\text{m}^2/\text{s}$ for kinematic viscosity, $8 \sim 36\text{m/s}$ for inlet flow velocity , 5.3^{-8}s for time steps, and 346.18m/s for sound speed. The sampling point a was set at the right bottom of the pipe to obtain the sound pressure data.

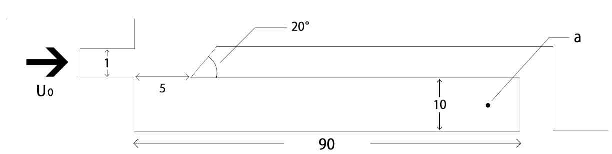

Fig. 5. Flue instrument model (unit: mm)

Brown introduced a semi-empirical equation (Eq. 3) based on the experimental results, which predicts the frequency of the edge tone [6].

$$f = 0.466(100U - 40)(\frac{1}{h}) - 0.07 \tag{3}$$

where U denotes the speed of the air jet, and h is the distance between the flue and the edge. From Fig. 6, it can be observed that our numerical result shows good agreement with the predicted edge tone frequency, and it reproduces the frequency locking to the fundamental and third harmonic resonance of the pipe.

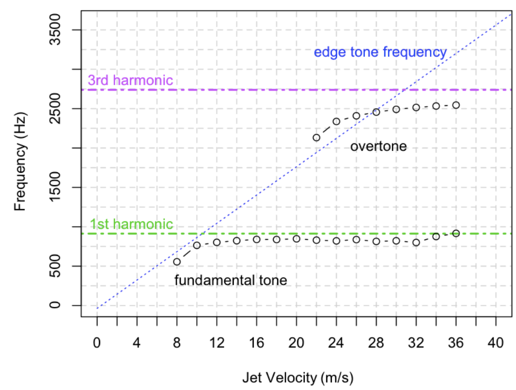

Fig. 6. Changes in oscillation frequencies with air jet velocity

5. CONCLUSION AND FUTURE WORK

- Conclusion
  - FDLBM is capable of achieving high effective performance on low B/F machines.
  - FDLBM is able to reproduce the basic characteristics of the flue instrument.
- Future Work
  - Evaluation with high-order (nonlinear, compact) schemes and DRP schemes.
  - Evaluation using the Cache-Aware Roofline model.

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REFERENCES

[1] E. W. S. Kam, R. M. C. So, S. Fu, and R. Leung, "Finite Difference Lattice Boltzmann Method Applied to Acoustic-Scattering Problems", Aiaa Journal - AIAA J, vol. 48, pp. 354-371, Feb. 2010.

[2] M. Miyamoto et al. "Numerical Study on Acoustic Oscillations of 2D and 3D Flue Organ Pipe Like Instruments with Compressible LES", Acta Acustica united with Acustica, vol. 93, pp. 154-171, Jan. 2013.

[3] M. Tsutahara. "The finite-difference lattice Boltzmann method and its application in computational aero-acoustics", Fluid Dynamics Research, vol. 44, no. 4, Aug. 2012.

[4] A. Fakhari and T. Lee, "Numerics of the lattice boltzmann method on nonuniform grids: Standard LBM and finite-difference LBM", Computers & Fluids, vol. 107, pp. 205-213, Jan. 2015.

[5] T. Shimokawabe, T. Aoki, and N. Onodera. "Scalability model for multi-GPU computation of stencil applications using regular structured meshes with explicit time integration", IPSJ SIG Technical Report, vol. 2013-ARC-207, no. 6, pp. 1-9, Dec. 2013.

[6] G. B. Brown. "The vortex motion causing edge tones", Proceedings of the Physical Society, vol. 49, no. 5, pp. 493-507, Sep. 1937.