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

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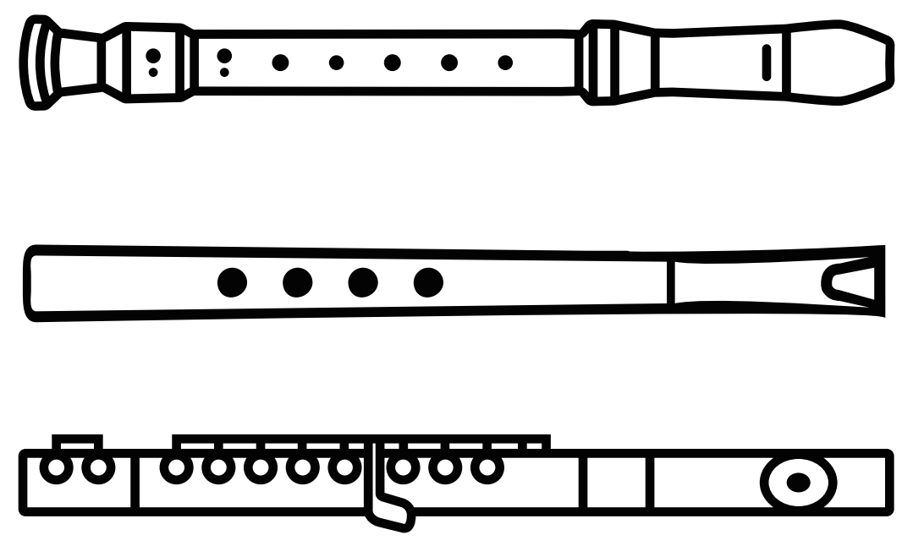
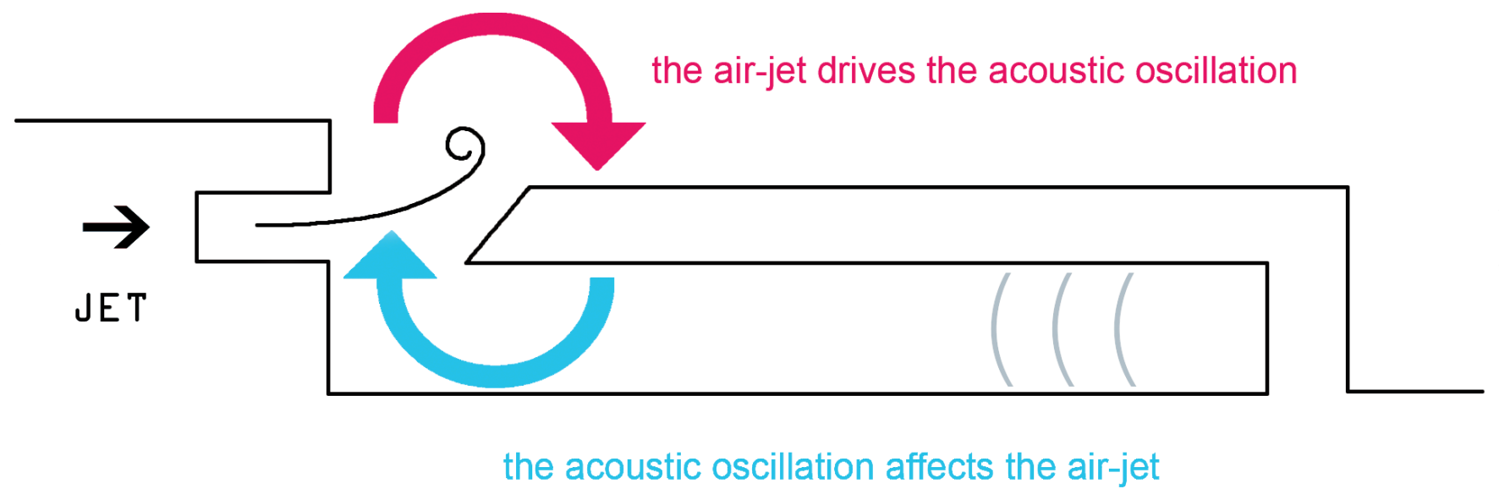
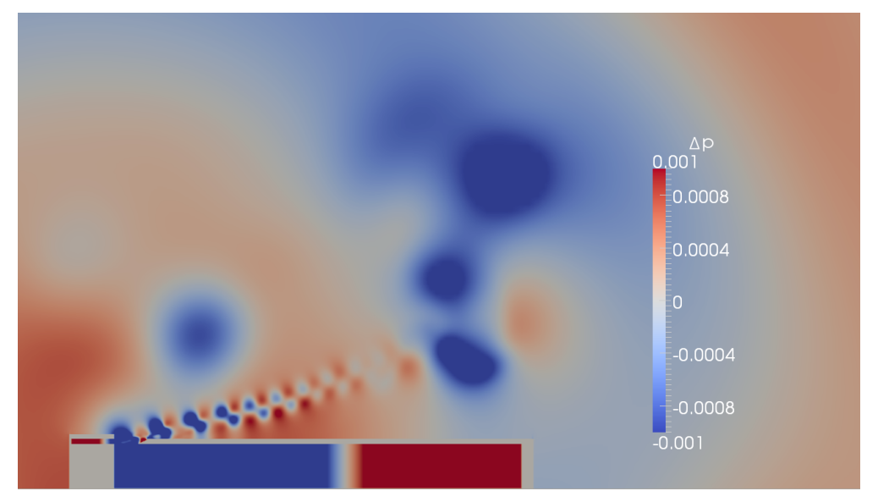
1. Introduction and Motivation



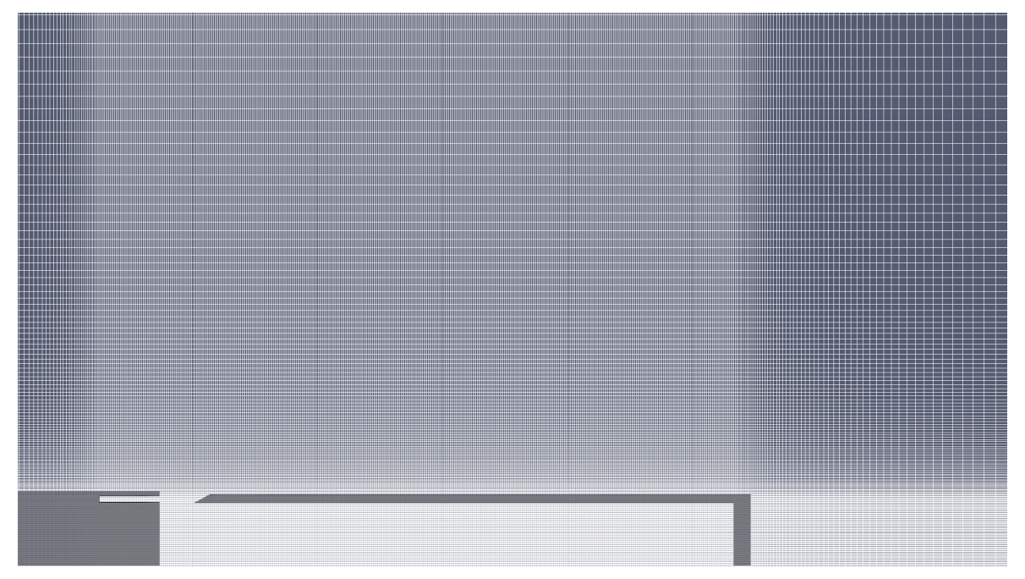
acoustic mechanism of flue instruments is not understood completely



feedback mechanism between the air-jet and a resonance tube



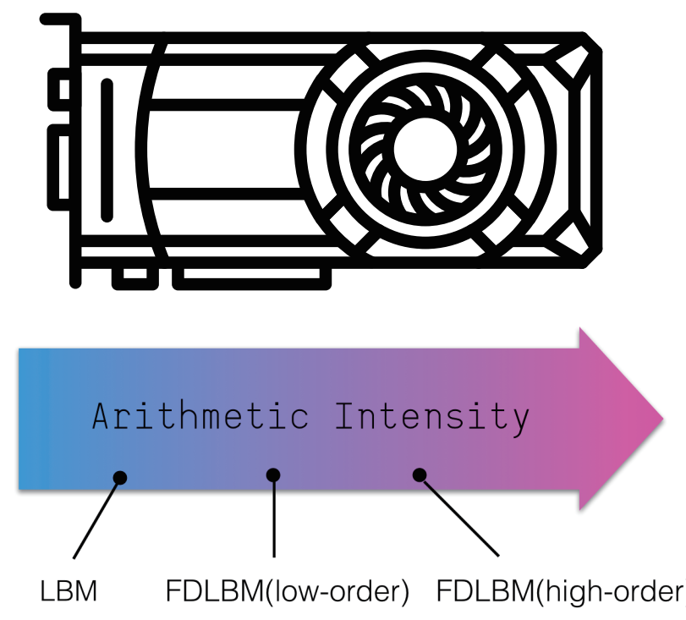
direct aeroacoustic simulation using compressible flow solver [1]



huge computational cost (high-resolution mesh & small time steps)

	Order of Accuracy	Calculation Mesh
LBM	second-order	uniform cartesian mesh
FDLBM	arbitrary-order	generalized coordinate system

(finite-difference) lattice Boltzmann method [2]



high effective performance on low b/f machines [3]

2. Numerical Methods and Implementation

[LBM]

discrete BGK equation

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

first-order upwind
first-order euler

$$\frac{|\mathbf{c}_i|\Delta t}{\Delta x} = 1$$

lattice Boltzmann equation

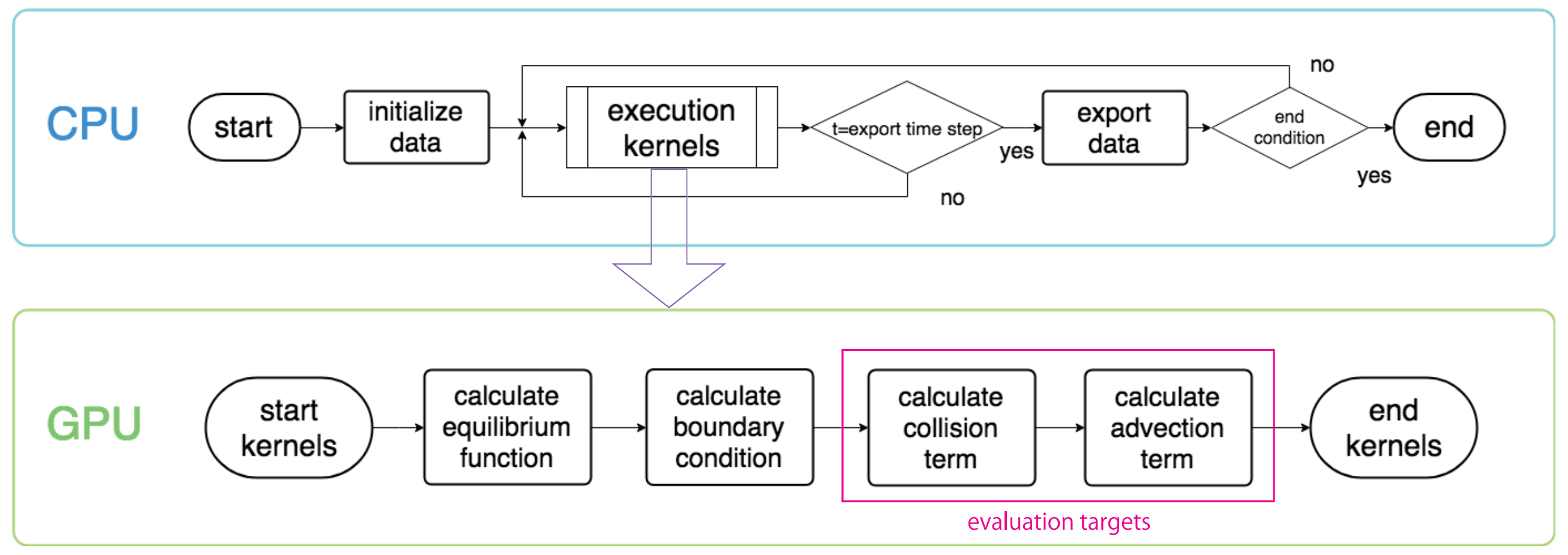
$$f_i(t+\Delta t, \mathbf{x}+\mathbf{c}_i\Delta t) = f_i(t,\mathbf{x}) - \frac{1}{\tau}\left[f_i(t,\mathbf{x}) - f_i^{(0)}(t,\mathbf{x})\right]$$

[FDLBM]

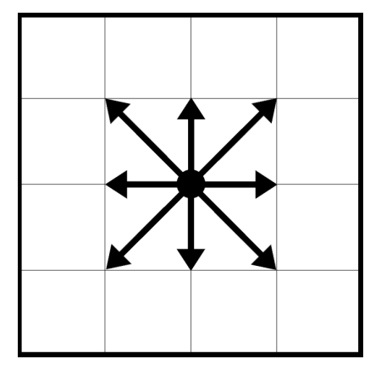
$$\frac{\partial f_i}{\partial t} + \mathbf{c}_i \frac{\partial f_i}{\partial \mathbf{x}} - \frac{A\mathbf{c}_i}{\tau}\frac{\partial (f_i - f_i^{(0)})}{\partial \mathbf{x}} = -\frac{1}{\tau}[f_i - f_i^{(0)}]$$

third-order upwind (UTOPIA)

$$c_x \frac{f}{\partial x} = c_x \frac{f(x-2\Delta x) - 8f(x-\Delta x) + 8f(x+\Delta x) - f(x+2\Delta x)}{12\Delta x} + |c_x| \frac{f(x-2\Delta x) - 4f(x-\Delta x) + 6f(x) - 4f(x+\Delta x)) + f(x+2\Delta x)}{12\Delta x}$$



D2Q9 Model



$$f_i^{(0)} = w_i\rho[1 + 3(\mathbf{c}_i \cdot \mathbf{u}) + \frac{9}{2}(\mathbf{c}_i \cdot \mathbf{u})^2 - \frac{3}{2}\mathbf{u}^2)$$

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)	$\sqrt{2}$

Coalesced Access

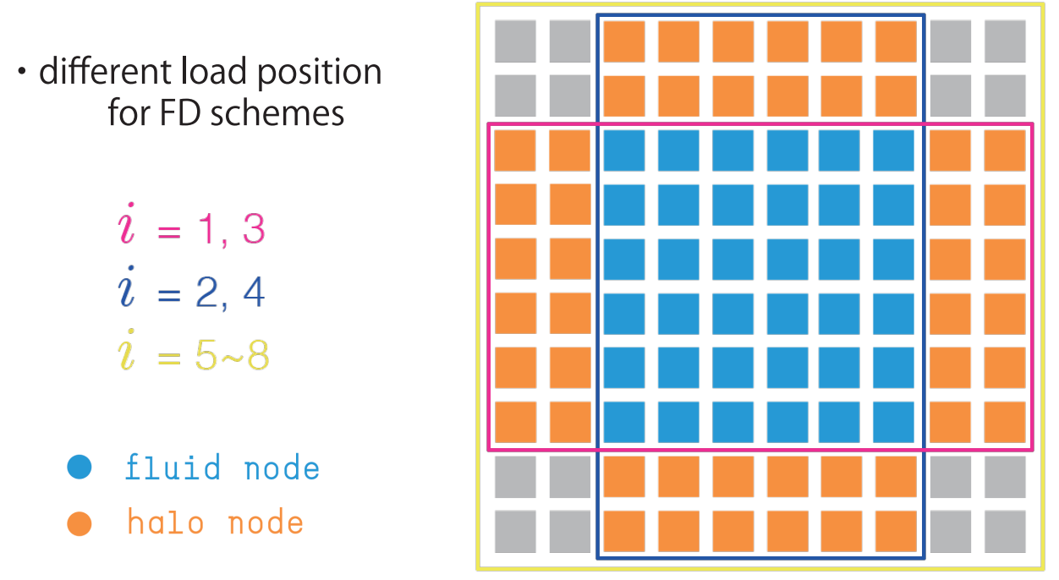
```
for (int k = 0; k < kDirectionNum; k++)
[i + j * x_cell_num_ + k * x_cell_num_ * y_cell_num_]
```

Template Kernel + Concurrent Stream

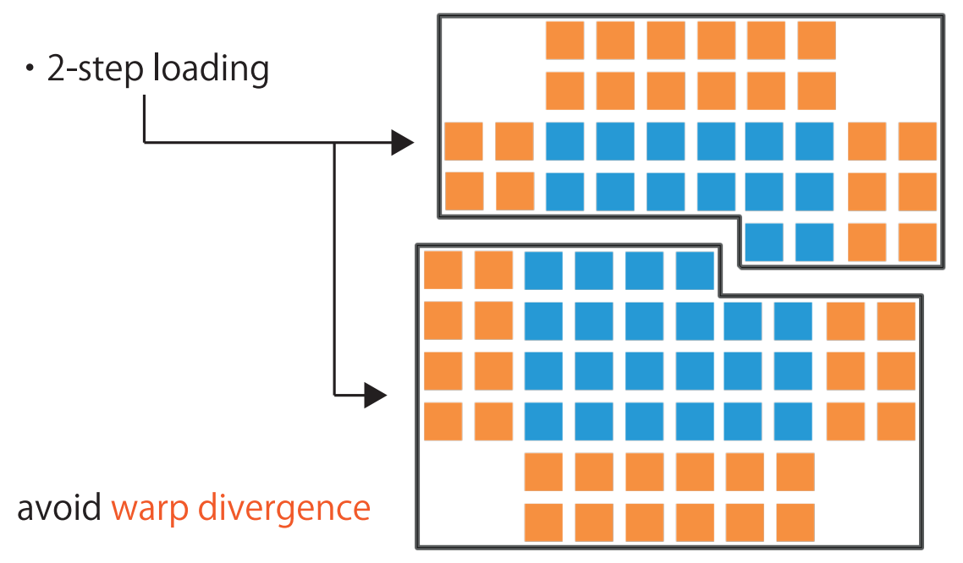
```
template<typename T, int k>
__global__ void update(const T *dfp,const T *ledf,T *df);
update<T,k> <<<grid,block,0,stream[k]>>>(dfp, ledf, df);
```

Shared Memory

- different load position for FD schemes

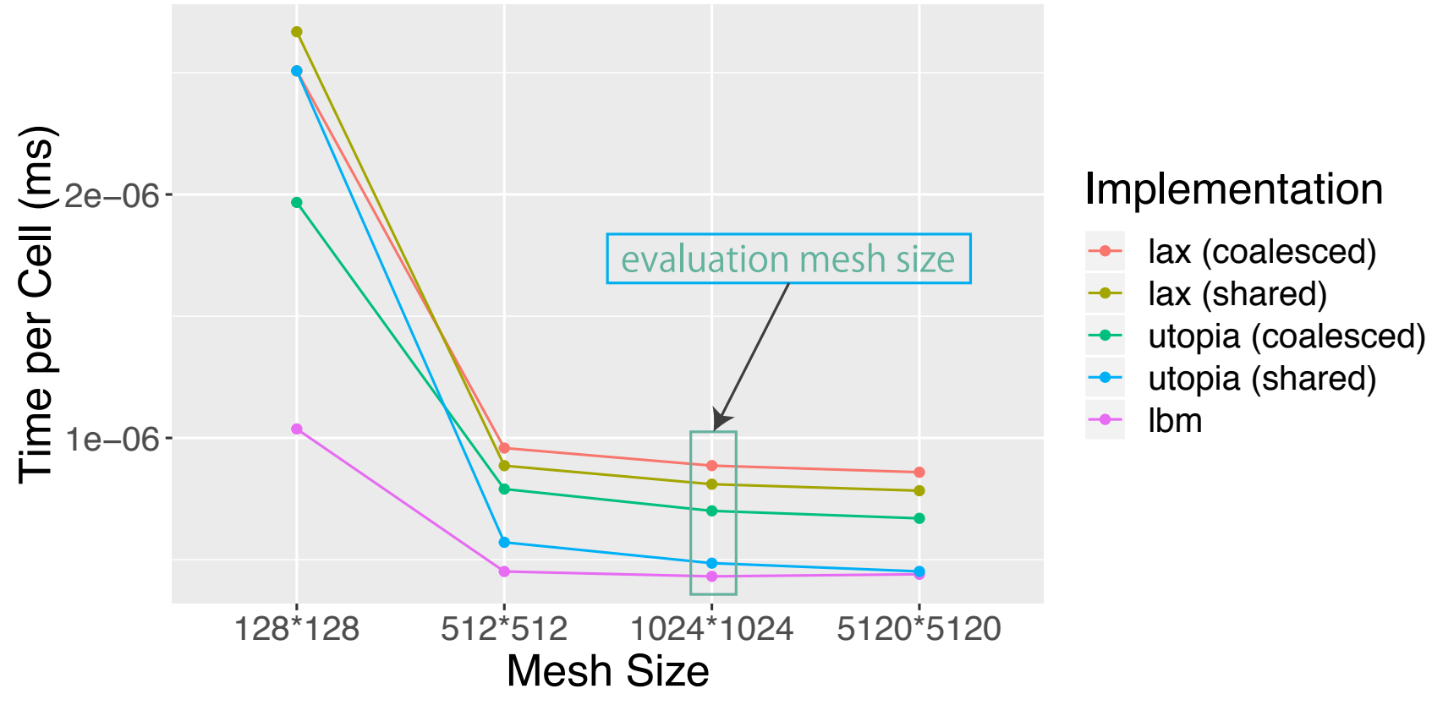


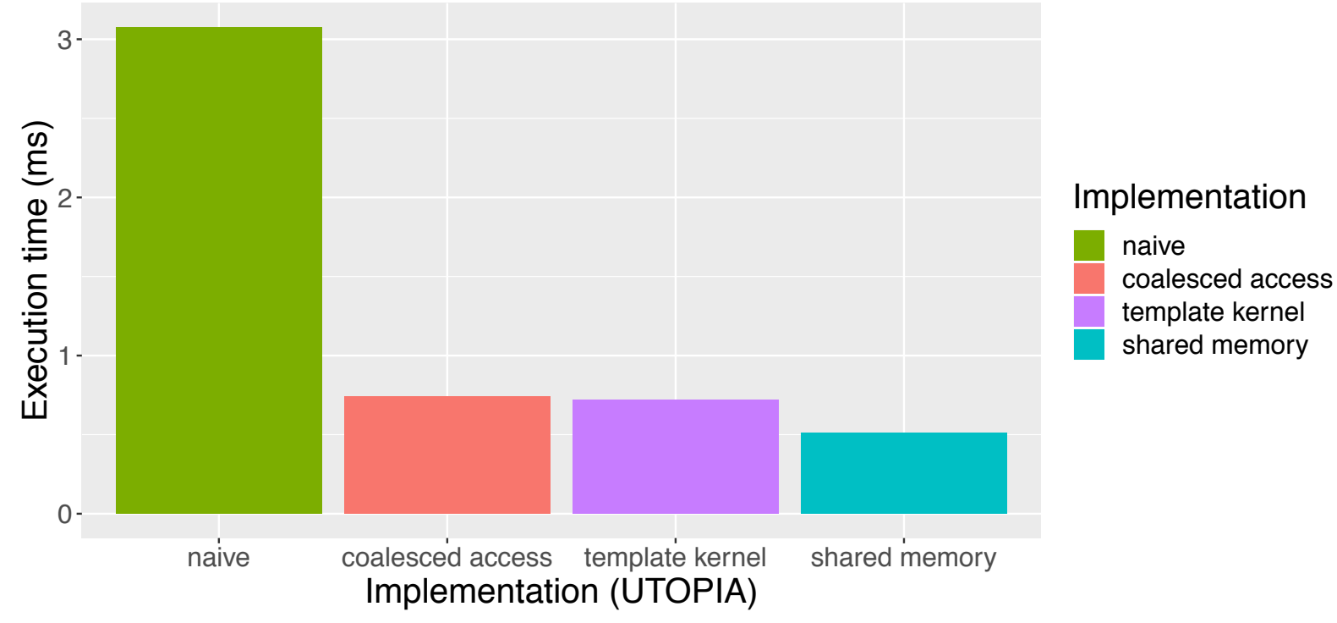
- 2-step loading



avoid warp divergence

3. Performance Evaluation



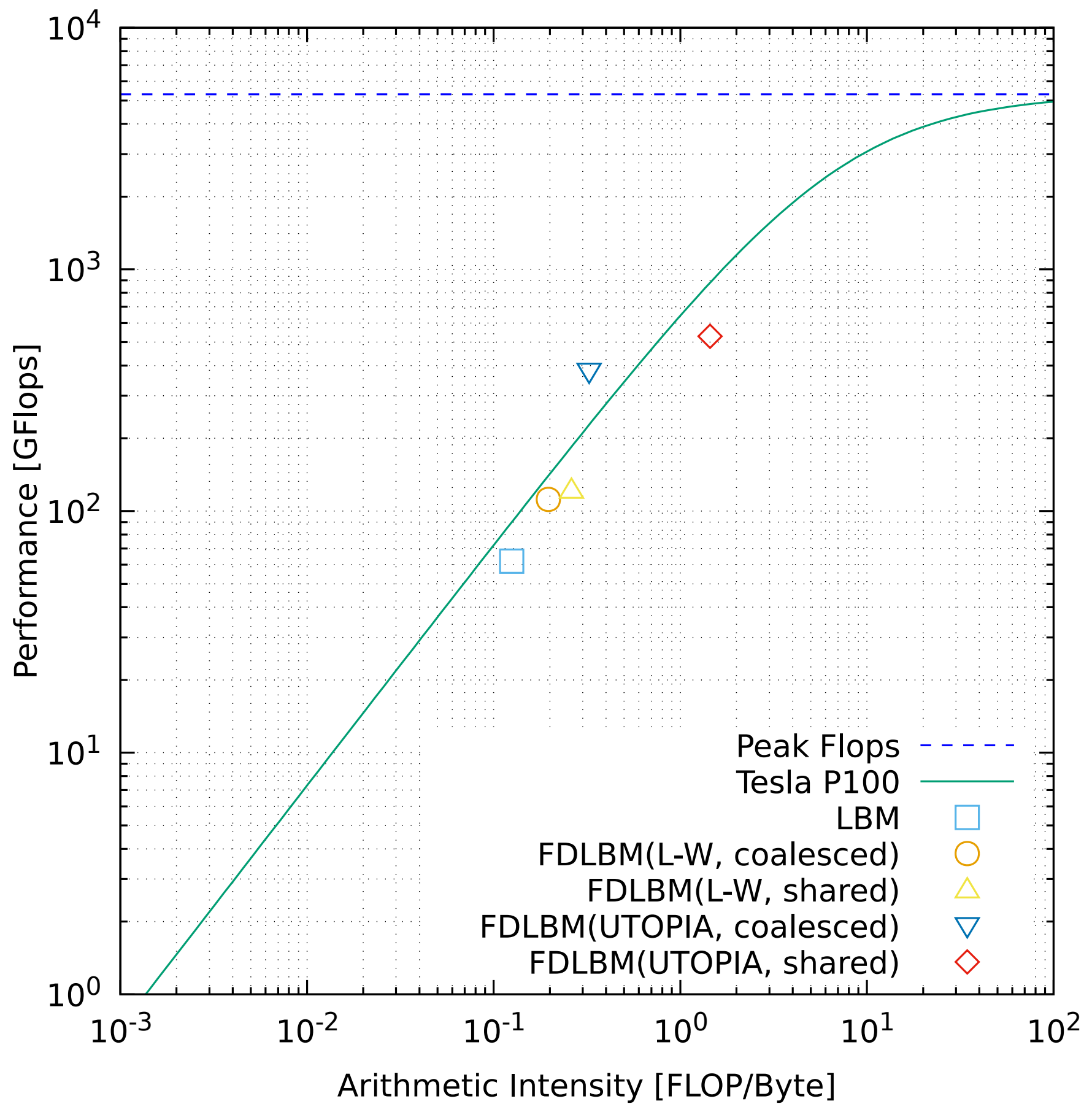


- **Improved Roofline Model** [4]

$$P = \frac{F/B}{\frac{1}{B_{peak}} + \frac{F/B}{F_{peak}}}$$

$$(F_{peak}, B_{peak}) = (5.3TFLOPS, 732GB/sec)$$

Schemes	F/B	GFlops
LBM	0.13	62.06
FDLBM (Lax-Wendroff) [template + coalesced]	0.20	111.68
FDLBM (Lax-Wendroff) [template + shared]	0.26	122.21
FDLBM (UTOPIA) [template + coalesced]	0.32	378.34
FDLBM (UTOPIA) [template + shared]	1.37	528.99

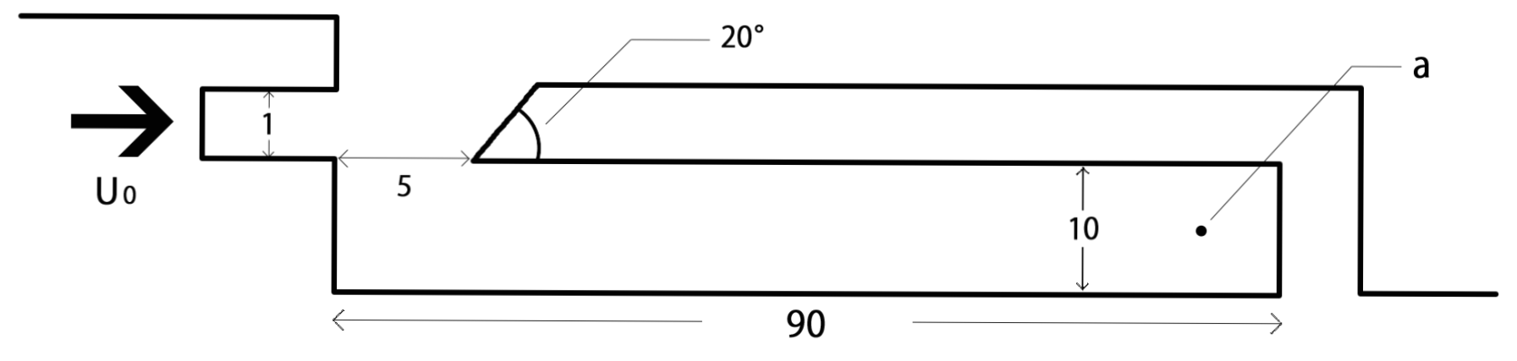


Evaluation Environment

Architecutre : ITO Subsystem B (R.I.I.T of Kyushu University), NVIDIA Tesla P100 (1,328-1,480 MHz), HBM2 : 732 GB/sec

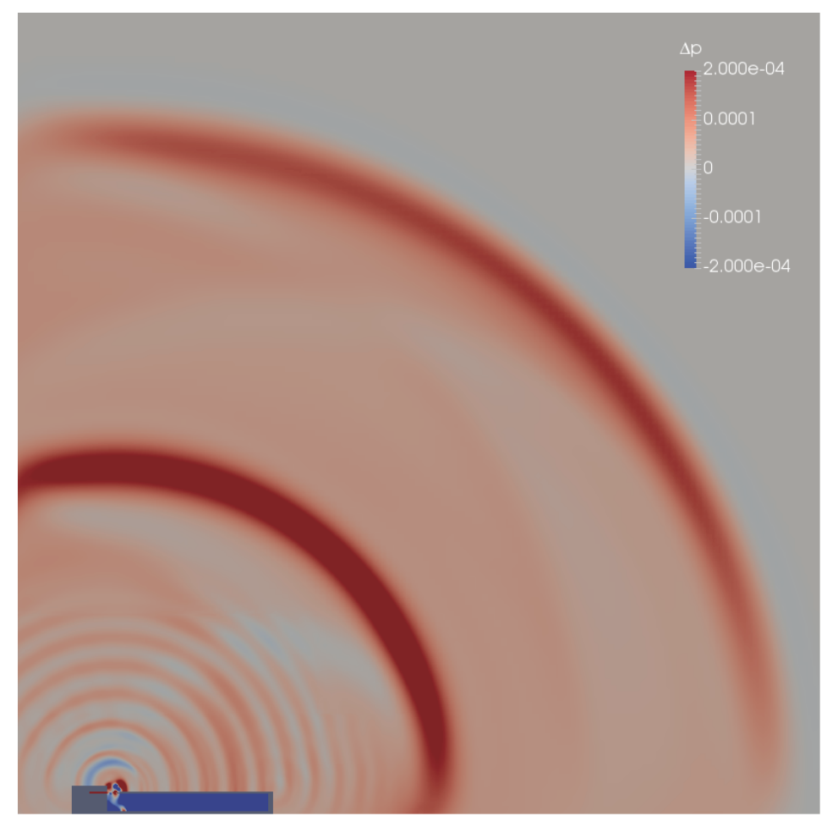
Compiler : nvcc (CUDA v8.0.61), Performance Profiling Tool : Nvidia Profiler (v8.0.61), Optimize Option : -O3

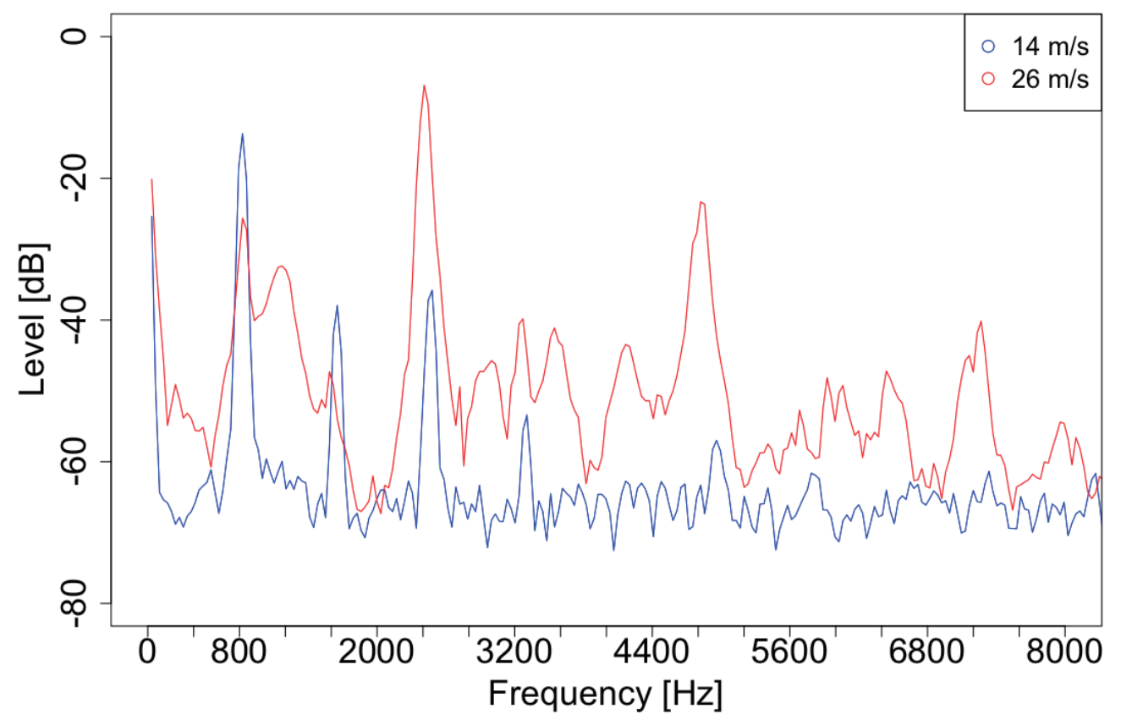
4. Scientific Relevance



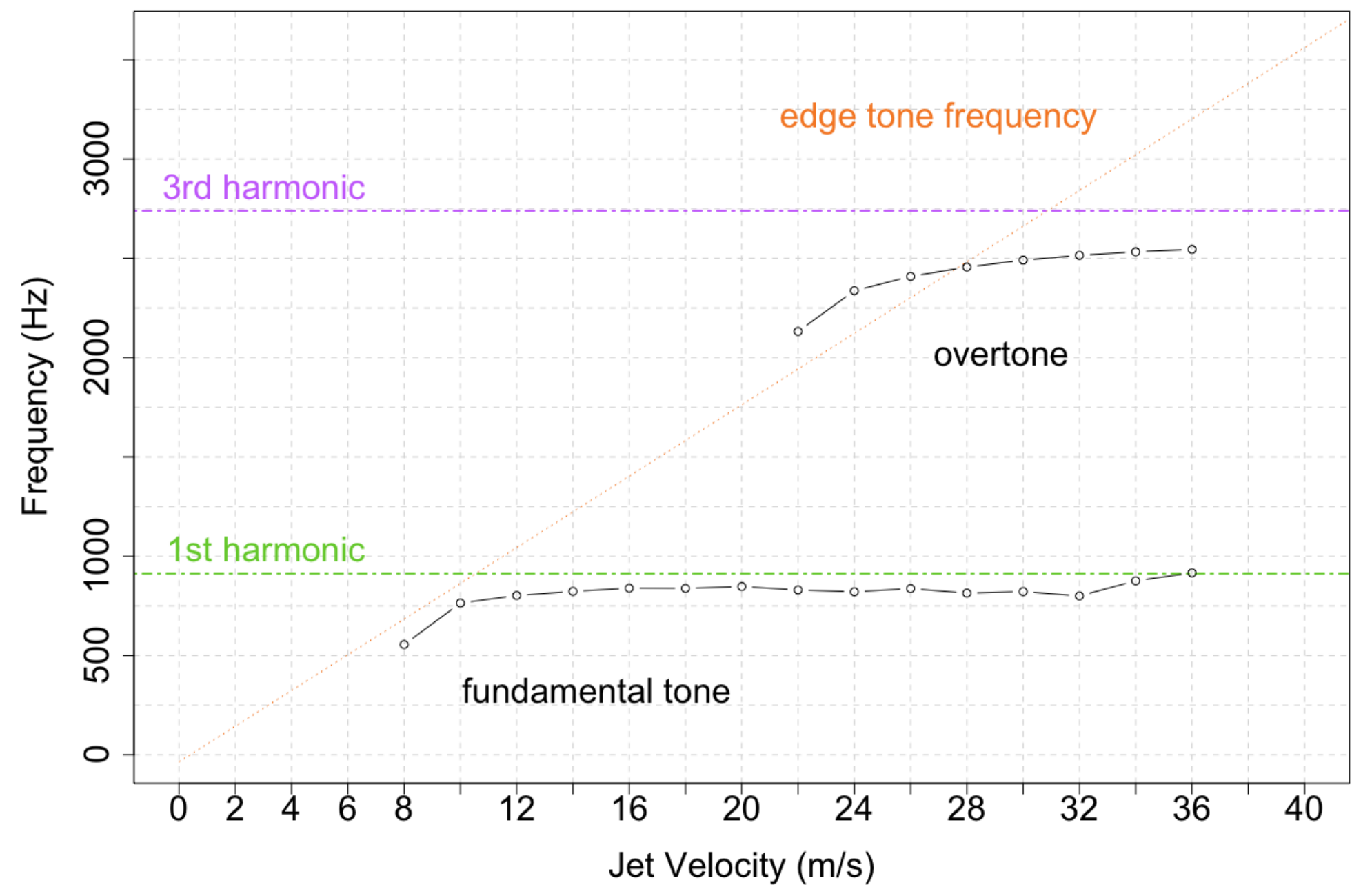
Flue instrument model (unit:mm)

ν = 1.5×10^{-5} m^2/s
U₀ = 8~36m/s
Cs = 346.18m/s
Δt = 5.3^{-8}s
third-order upwind (UTOPIA)
second-order Runge-Kutta





Frequency distribution (14 m/s, 26 m/s)



- Edge tone frequency calculated by Brown's equation [6]

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

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

- Using high-order (nonlinear, compact) schemes and DRP schemes.
- Performance evaluation using the Cache-Aware Roofline model.

6. References

[1] 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.

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

[3] K. Sugihara and T.Aoki, 'Acceleration of large scale high accurate advection calculation for multiple GPUs and its strong scalability'[in Japanese], Transactions of the Japan Society for Computational Engineering and Science, Paper No.20100018, Dec. 2010.

[4] 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.

[5]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.

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

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