PROCEEDINGS of ISMA 2019
International Symposium on Music Acoustics

13 - 17 September 2019 in Detmold, Germany

Numerical study on unsteady fluid flow and acoustic field in the clarinet mouthpiece with the compressible LES

Toshiaki KOIWAYA(1), Sho IWAGAMI(1), Taizo KOBAYASHI(2), Kin'ya TAKAHASHI(1),

(1)Kyushu Institute of Technology, Japan, koiwaya@chaos.mse.kyutech.ac.jp
(2)Kyushu University, Japan, tkoba@cc.kyushu-u.ac.jp

Abstract
The sound generation in the clarinet mouthpiece is still an unsolved problem from the viewpoint of aeroacoustic and has been studied theoretically, experimentally and numerically by many authors. Numerical simulations on the unsteady flow in the clarinet mouthpiece using LBM have been reported by several authors. In this paper, we numerically study unsteady fluid flow and acoustic field in the clarinet mouthpiece with compressible LES. We adopt 2D and 3D models and the 3D model has numerical grids more than one hundred and 50 million to reproduce detail behavior of air-jet motion, vortices and acoustic filed. In our models, the reed is fixed and a uniform flow is injected from the reed slit to study the behavior in the attack transient. The 2D and 3D models behave in different ways. For the 2D model, the injected jet is rolled up making long-lived rotors in the mouthpiece, while for the 3D model it is destabilized in a certain distance is broken into a lamp of turbulence. We also study the station that an alternating current is injected from the slit to reproduce the acoustic resonance.
Keywords: Clarinet, Mouthpiece, Numerical study

1 INTRODUCTION

Elucidation of the sounding mechanism of single reed instruments is one of the important subjects in the field of musical acoustics [1, 2, 3, 4, 5]. Single reed instruments are modelized by differential and difference equations with time delay, which well reproduce the pressure oscillation in the mouthpiece and the volume flow injected through the vibrating reed valve and capture the mechanism of bifurcation, which triggers oscillation with change of a control parameter, e.g., blowing pressure [2, 3, 4, 6, 7].

In delay equation models, it is always assumed that the volume flow U injected through the reed slit changes to the acoustic pressure p, more precisely aerodynamic sound, in the mouthpiece like $p = Z_0 U$, where Z_0 is the characteristic impedance of the mouthpiece[1, 2, 3, 4, 6, 7]. However, no one clearly answers questions of how and where the volume flow changes to the aerodynamic sound and how the assumption $p = Z_0 U$ holds true. In order to answer these questions, one needs an analysis based on the theory of aeroacoustics[8].

The numerical simulation by using compressible fluid solvers is one of the important tools to attack this problem. Actually, compressible fluid schemes simultaneously reproduce the fluid and acoustic fields and can be used for the analysis of the interaction between them[9]. Silva and Scavone succeeded to calculate fluid-structure interactions in single-reed mouthpiece with the Lattice Boltzmann Method (LBM)[10]. However, the mechanism of the transition process from an injected jet to an aerodynamic sound in the clarinet mouthpiece is still an open question.

In this paper, as the first step to attacking this problem, we construct 2D and 3D models of a clarinet mouthpiece and calculate the models by using compressible Large Eddy Simulation (LES) with two manners of driving the mouthpiece: the mouthpiece is driven by a constant flow and by a flow with periodically oscillating velocity. The latter method mimics the flow injected through a vibrating reed valve. The 3D model has a huge mesh with nearly 160 million cells and is calculated with a parallel computation technique by using a supercomputer.

2 SETUP OF NUMERICAL CALCULATIONS

2.1 3D model of clarinet mouthpiece

Figure 1 shows the cross-section of a clarinet mouthpiece (YAMAHA 4C), from which we measure dimensions of the clarinet mouthpiece. First, we construct a 2D model adding reed and square-shaped outer side area ($250 \times 250\text{mm}^2$) to the cross-section of the mouthpiece (see Figure 2). The distance between the mouthpiece tip and the reed, i.e., tip opening, is fixed at 1mm throughout this paper.

For convenience of constructing a 3D model, we add a uniform width of 12mm to the 2D cross-sections of the clarinet mouthpiece and reed and connecting a cube ($250 \times 250 \times 250\text{mm}^3$) as an outside volume to the open end of the mouthpiece (see Figure 3). To make a numerical mesh, the geometry of the 3D model is constructed by using FreeCAD and is converted to a mesh by using Snappy-HexMesh in OpenFOAM utility. As shown in Table 1, the minimum mesh size around the mouth opening is 0.1mm and the number of the cell is nearly 160 million, although the number of the cell is nearly 1.8 million for the 2D model.

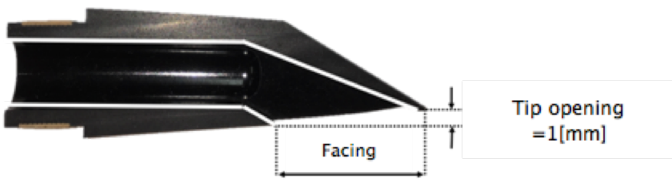

Figure 1. Cross section of clarinet mouthpiece.

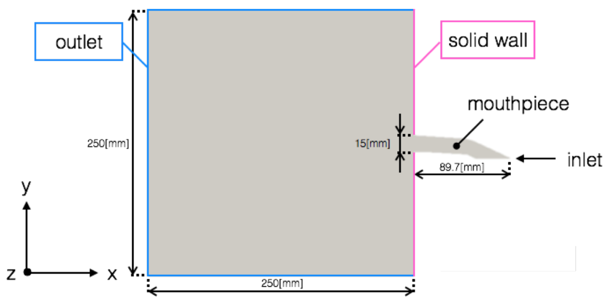

Figure 2. 2D model and boundary conditions.

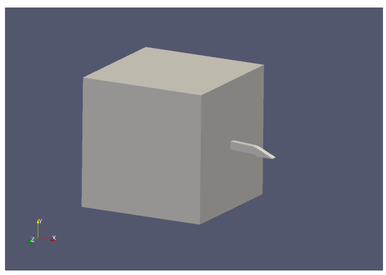

Figure 3. 3D model.

2.2 Numerical Method

To reproduce the transition process from the fluid flow to the aerodynamic sound, one needs a numerical scheme of compressible fluid, which reproduces the fluid and acoustic fields simultaneously. For this purpose, we use the compressible Large Eddy Simulation (LES) with the one-equation sub-grid-scale (SGS) model: RhoPimpleFoam, an unsteady solver of compressible laminar and turbulent flow in OpenFOAM Ver.5.0. Numerical simulations are performed with parallel computing technique by a supercomputer, ITO subsystem A of Kyushu University.

As shown in Table 1, the equilibrium pressure and temperature are set as $p = 100$ kPa and $T = 300$ K, respectively. The time step is set at $\Delta t = 5.0 \times 10^{-8}$ and the simulation is continued up to $t = 0.01$s. To save the amount of the output data for the 3D model, we pick up the data on the central cross-section, which corresponds to the 2D model, by using Function Object of OpenFOAM. We also detect the pressure data at the center of the open end of the mouthpiece.

The 2D and 3D mouthpiece models are driven by two ways. In the first way, the flow velocity at the tip opening takes a constant value of 15 m/s in the steady state (see Table 1). More precisely, the flow velocity is gradually increased and reaches 15 m/s at t = 0.0002s. In the second way, the instrument is driven by the flow, whose velocity periodically changes as

$$v_{in} = 15(1 - \cos \omega t), \tag{1}$$

where ω is the angular frequency of the Helmholtz resonance, which can be estimated from the simulation in the first way as shown later. The flow with periodically changed velocity mimics the flow injected through the vibrating reed, and the simulation in the second way resembles the situation that the mouthpiece is played in the normal way.

Table 1. Numerical parameters

parameter	value
Flow velocity [m/s]	15
Pressure at rest [kPa]	100
Temperature at rest [K]	300
Time step [s]	5×10^{-8}
Calculation time [s]	0.01
Numerical grids (2D)	1801208
Numerical grids (3D)	157417412
Minimum mesh size [mm]	0.1

3 NUMERICAL RESULTS

3.1 Results for the case that the 2D and 3D mouthpiece are driven by a constant flow.

In this subsection, we consider results for the case that the 2D and 3D mouthpiece are driven by a constant flow. Figure. 4 (a) and (b) show the spatial distributions of velocity and pressure at $t = 0.01$s for the 2D model, respectively. Figure 5 (a) and (b) show the spatial distributions of velocity and pressure at $t = 0.01$s for the 3D model, respectively.

As shown in Figure 4 (a), for the 2D model, the jet injected from the tip opening first goes along the bottom reed, but suddenly bends up, touches the aslope ceiling of the mouthpiece and forms an anti-clockwise rotor, which induces a clockwise rotor in the left side. As shown in Figure 5 (a), for the 3D model, the jet behaves in a similar way to that for the 2D model. However, the anti-clockwise rotor becomes weak breaking up into a lump of turbulence and the clockwise rotor disappears. This comes from the fact that vortex tubes are more robust for 2D systems than 3D systems owing to the two-dimensional inverse energy cascade[9].

The pressure distribution in Figure 4 (b) indicates that there is no clear resonance oscillation in the mouthpiece, although the pressure takes negative values in the areas of vortices. On the other hand, the pressure distribution in Figure 5 (b) forms a resonance field in the mouthpiece.

Fig.6 (a) and (b) show the time evolution of the pressure fluctuations for the 2D and 3D models, respectively. For both cases, damped oscillations are observed, but the pressure oscillation for the 2D model attenuates more rapidly. This is owing to the fact that the reflectance at an open end for a 2D pipe becomes smaller than that for a 3D pipe, especially in high frequency range (see Appendix of Ref.[9]). This fact also indicates that the resonance field for a 3D pipe is more stronger than that for a 2D pipe. Anyway, for the 2D model, the oscillation amplitude becomes very small at $t = 0.01$s and the resonance oscillation almost disappears. From the periods of the damped oscillations, we can estimate the resonance frequencies of the 2D and 3D mouthpiece: 949.4 Hz for the 2D model and 1041.7 Hz for the 3D model.

(a) (b)

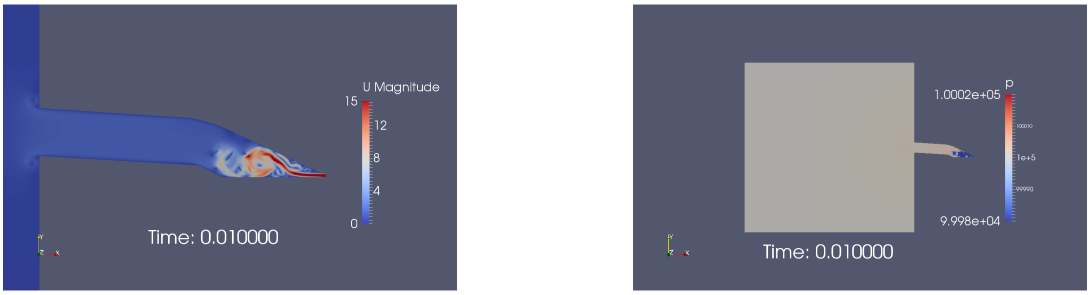

Figure 4. Spatial distributions of velocity and pressure at $t = 0.01$s for the 2D model driven by a constant flow. (a) Velocity. (b) Pressure.

(a) (b)

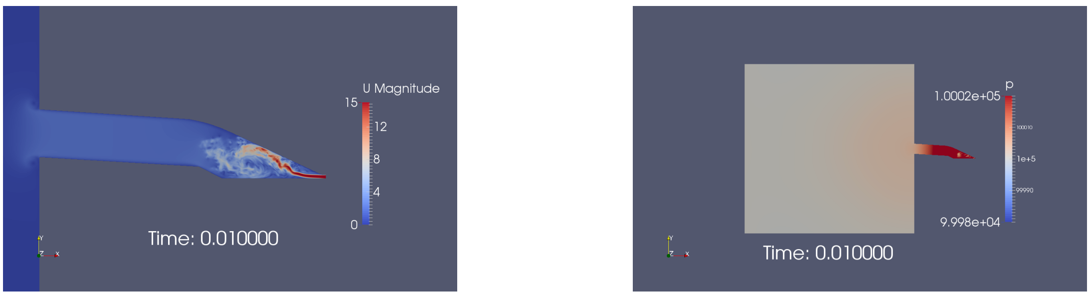

Figure 5. Spatial distributions of velocity and pressure at $t = 0.01$s on the center cross section of the 3D model driven by a constant flow. (a) Velocity. (b) Pressure.

(a) (b)

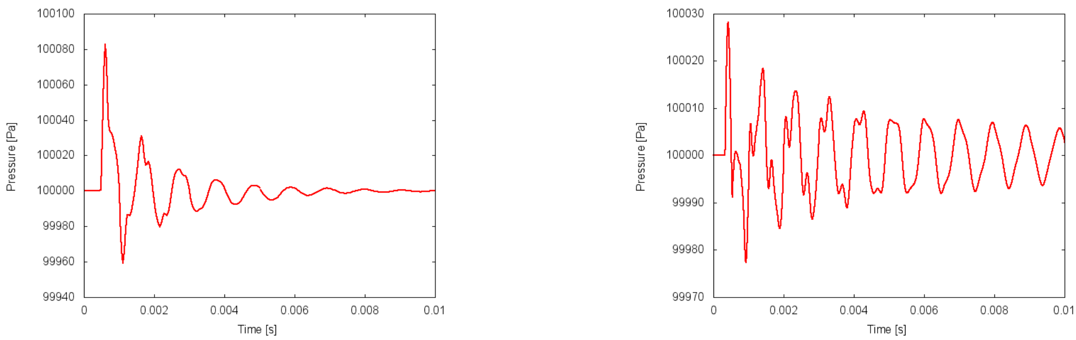

Figure 6. Time evolution of the pressure when a constant flow is injected. (a) 2D model. (b) 3D model.

3.2 Results for the case that the 2D and 3D mouthpiece are driven by an oscillating flow.

Let us consider results for the case that the 2D and 3D mouthpiece are driven by an oscillating flow. The driving angular frequencies are 949.4 Hz and 1041.7 Hz for the 2D and 3D models, respectively.

Figure. 7 (a) and (b) show the spatial distributions of velocity and pressure at $t = 0.01$s for the 2D model, respectively. Figure 8 (a) and (b) show show the spatial distributions of velocity and pressure at $t = 0.01$s for the 3D model, respectively.

As shown in Figure 7 (a) and Figure 8 (a), the jet generated by the oscillating flow at the tip opening behaves in a different manner from the jet with a constant velocity. For the 2D model, the jet, from the beginning, goes along the sloped ceiling of the mouthpiece, but after going a short way it changes to a rolled up eddy. For the 3D model, the jet also goes a rather long way along the sloped ceiling and breaks up into a lump of turbulence. Comparing with the case of the constant flow injection, fluid velocity, i.e, jet, eddies and turbulence, exists in a rather small area. This fact indicates that a strong acoustic resonance filed affects the fluid motion.

As shown in Figure 7 (b) and Figure 8 (b), strong pressure oscillations in resonance are observed for both 2D and 3D models. Fig.9 (a) and (b) show the time evolution of the pressure fluctuations for the 2D and 3D models, respectively. Resonance oscillations are observed for both cases. For the 2D model, the oscillation rapidly grows and reaches the steady oscillation with the amplitude of nearly 500Pa at $t = 0.01$s. For the 3D model, the oscillation grows rather slowly and does not reach the steady state at $t = 0.01$s, yet. The amplitude of the 3D model at $t = 0.01$s is nearly 650Pa, which is larger than that of the steady state for the 2D model. This means that the resonance for the 3D model is stronger than that for the 2D model.

(a) (b)

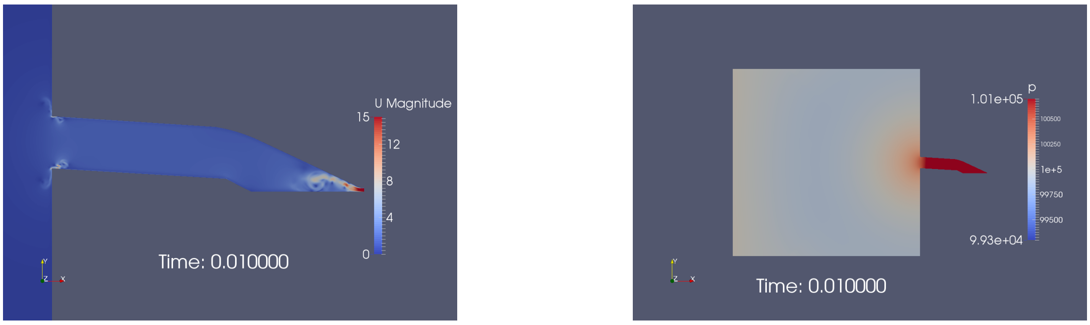

Figure 7. Spatial distributions of velocity and pressure at $t = 0.01$s for the 2D model driven by a periodically oscillating flow. (a) Velocity. (b) Pressure.

(a) (b)

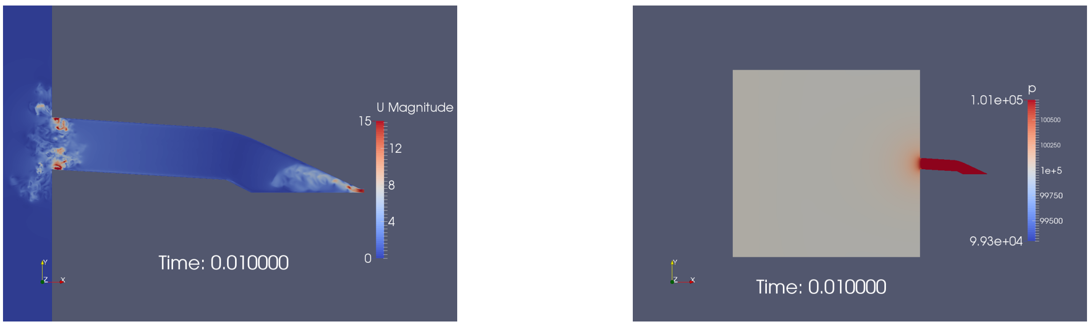

Figure 8. Spatial distributions of velocity and pressure at $t = 0.01$s on the center cross section of the 3D model driven by a periodically oscillating flow. (a) Velocity. (b) Pressure.

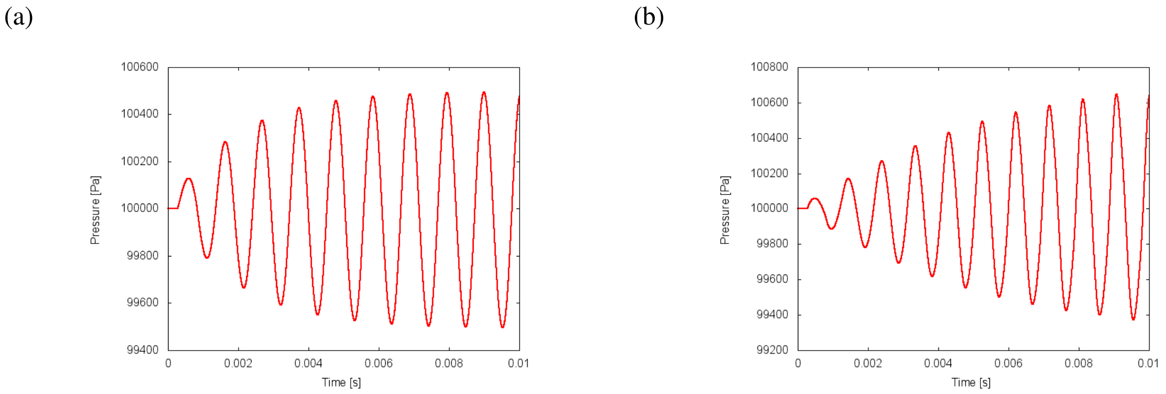

Figure 9. Time evolution of the pressure when a periodically oscillating flow is injected. (a) 2D model. (b) 3D model.

4 CONCLUSIONS

In this paper, as the first step to exploring the mechanism of the transition from an injected jet to an aerodynamic sound in the clarinet mouthpiece, we calculated the 2D and 3D models of the clarinet mouthpiece. As a result, we found the differences in the fluid motions and acoustic oscillations between the 2D and 3D models and the changes of the fluid motions and acoustic oscillations depending on the input boundary conditions, the constant flow driving and the oscillating flow driving.

Due to the weakness of the acoustic reflectance at the open end and the robustness of vortex tube for 2D systems, the weak acoustic resonance is observed and clear rolled up eddies are created compared with the 3D model. Thus, the calculation of the 3D model is necessary for our purpose.

When the mouthpiece is driven by the constant flow, the damped oscillations are observed. On the other hand, when the mouthpiece is driven by the flow with oscillating velocity, the acoustic resonance oscillations are excited in the mouthpiece. In this sense, the flow with oscillating velocity well mimics the flow injected through the vibrating reed and our model may become a minimal model for the study of the mechanism of the transition from an injected jet to an aerodynamic sound in the clarinet mouthpiece. For future work, we are planning to develop a moving reed model as a more realistic model.

ACKNOWLEDGEMENTS

The present work was supported by Grant-in-Aid for Scientific Research (C) Nos. 16K05477 and 19K03655 from the Japan Society for the Promotion of Science (JSPS), “Joint Usage/Research Center for Interdisciplinary Large-Scale Information Infrastructures” and “High Performance Computing Infrastructure” in Japan (Project IDs: jh180007-MDH and jh190010-MDH), and Kawai foundation for sound technology & music.

REFERENCES

[1] N. H. Fletcher and T. D. Rossing, The Physics of Musical Instruments, 2nd ed. (Springer-Verlag, New York, 1998).

[2] A. Hirschberg, J. Kergomard, G. Weinreich (eds.), Mechanics of Musical Instruments (Springer-Verlag, Vienna and New York, 1995).

[3] R. T. Schumacher: “Abinitio cal culations of the oscillations of a clarinet”, Acustica 48, 71–85 (1981).

[4] M. E. McIntyre, R. T. Schumacher, J. Woodhouse: "On the oscillations of musical instruments", J. Acoust. Soc. Am. 74, 1325–1345 (1983).

[5] T. Idogawa, T. Kobata, K. Komuro, M. Iwaki: "Nonlinear vibrations in the air column of a clarinet artificially blown", J. Acoust. Soc. Am. 98, 540–551 (1993).

[6] T. Tachibana, K. Takahashi: "Sounding mechanism of a cylindrical pipe fitted with a clarinet mouthpiece", Prog. Theor. Phys. 104, 265–288 (2000).

[7] K. Takahashi, H. Kodama, A. Nakajima, T. Tachibana: "Numerical study on multi-stable oscillations of woodwind single-reed instruments", Acta Acustica united with Acustica, 95, 1123-1139 (2009).

[8] M. J. Lighthill, "On sound generated aerodynamically", Proc. R. Soc. London Ser. A 211, 564-587 (1952).

[9] M. Miyamoto, Y. Ito, T. Iwasaki, T. Akamura, K. Takahashi, T. Takami, T. Kobayashi, A. Nishida, and M. Aoyagi, "Numerical study on acoustic oscillations of 2D and 3D flue organ pipe like instruments with compressible LES", Acta Acustica united with Acustica, 99, 154-171 (2013).

[10] A. Ricardo da Silva and G. P. Scavone, "Numerical simulations of fluid-structure interactions in single-reed mouthpiece" J. Acoust. Soc. Am. 122, 1798-1809 (2007).