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Numerical Simulation of Aerodynamics Sound in an Ocarina Model

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Abstract

The body of an ocarina is regarded as a Helmholtz resonator. Thus, we can expect differences in sounding mechanism between ocarinas and other air-jet instruments with a resonance pipe. Furthermore, ocarinas are driven by cross blowing like transverse flutes so that the driving mechanism with an air-jet should be different from that for vertical flues like a recorder. In this paper, we numerically explore the sounding mechanism of an ocarina from the viewpoint of aeroacoustics with compressible fluid simulation. We adopt compressible LES as a numerical scheme of compressible fluid, which simultaneously reproduces fluid and acoustic fields and with which we can investigate the interaction between the fluid and acoustic fields near the mouth opening. Our 3D model has numerical grids more than one hundred and 50 million to reproduce detail behavior of air-jet motion, vortices and acoustic filed near the mouth opening. We numerically observed an acoustic oscillation with the Helmholtz resonance frequency in the body together with the detail structure of fluid field.

Keywords: Sound, Music, Acoustics

1 INTRODUCTION

The sounding mechanism of air-jet instruments has been studied in the field of musical acoustics for many years [1, 2, 3]. The numerical simulation based on the theory of aeroacoustics is one of the important tools to attack this problem [4, 5, 6, 7, 8]. The main difficulty in the numerical study of air-jet instruments comes from the mutual interaction between the fluid field and the acoustic field, which is hardly reproduced by the hybrid method of the fluid solver and acoustic solver, although it is commonly used for the analysis of aerodynamic noise in the case that the feedback from the acoustic field to the fluid field is negligible [1, 5]. For the analysis of air-jet instruments, the feedback from the acoustic oscillation in the resonator to the jet motion is key to understanding the sounding mechanism.

There are two types of air-jet instruments, which are different in the function of the resonator. The group of the flute, recorder, flue organ pipe and so on has a pipe as a resonator and the pitch is determined by the resonance of the air column. On the other hand, the body of the ocarina is regarded as the Helmholtz resonator and the pitch is determined by the Helmholtz resonance. Furthermore, the ocarina is driven by cross blowing like transverse flutes so that the driving mechanism with an air-jet should be different from that for those vertical flues like a recorder, which have been numericaly studied by several authors[4, 5, 6, 7, 8].

Nearly ten years ago, the author's group numerically studied the 2D and 3D models of an ocarina with compressible LES[9]. Then, the 3D model with a mesh of nearly 1.3 million cells was calculated up to 0.005s; thus, an oscillation in an attack transient was roughly reproduced and the behavior of the jet motion and that of the acoustic oscillation were not analyzed in detail. In this study, to explore the sounding mechanism of ocarinas from the viewpoint of aeroacoustics, we construct a 3D model of an ocarina with a finer mesh of nearly 160 million cells and calculate the 3D model with parallel computation technique by using a supercomputer.

The structure of this paper is as follows. In section 2, we roughly explain the sounding mechanisms of the edge tone and air-jet instruments and introduce the 3D model of the ocarina. In Section 3 we explain the numerical method and shows the numerical results: spatial distributions of velocity and pressure, and pressure oscillation at an observation point with its power spectrum. Then, we discuss the characteristic properties of the ocarina with a Helmholtz resonator. Section 4 is a conclusion.

2 THREE DIMENSIONAL OCARINA

2.1 Frequency of Edge tone

The sound source of air-jet instruments is an aerodynamic sound called the edge tone, which is generated by an air jet impinging on a sharp edge [1, 10]. The edge tone has been a long standing problem in the fields of aeroacoustics and musical acoustics, but its detail mechanism is not fully understood yet. In 1937, Brown introduced the semi-empirical equation, which gives the relation between the jet velocity V[m/s] and the oscillation frequency f[Hz] [11],

$$f = 0.466j(100V - 40)(1/(100l) - 0.07), \tag{1}$$

where l[m] is the distance between the nozzle and the edge, j is a parameter taken as $j = 1.0$, 2.3, 3.8 and 5.4, where $j = 1$ corresponds to the fundamental mode of hydrodynamic oscillation, and others corresponds to the overtones, which appear through hysteretic transitions with increasing the jet velocity. The frequency f of the fundamental mode is proportional to the jet velocity V. However, when the jet velocity V exceeds a certain threshold value, a transition to the next mode occurs. The transitions with increasing and decreasing the jet velocity are hysteretic, namely the threshold value of the downward transition is smaller than that of the upward transition. The fundamental mode is normally used for the air-jet instruments.

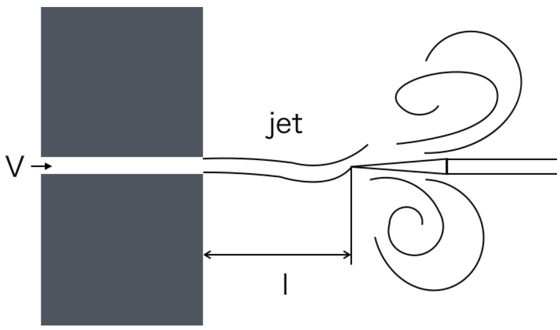

Figure 1. Edge tone.

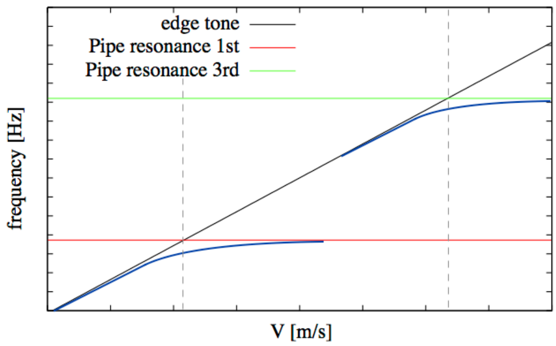

Figure 2. Relationship between jet velocity and oscillation frequency.

2.2 Sounding mechanism of air-jet instruments

Due to the interaction between the acoustic oscillation in the resonator and the jet motion, the characteristic frequencies of air-jet instruments do not obey Brown's equation (1)[1, 12]. As shown in Fig.2, with increasing the jet velocity, the frequency of sound oscillation first follows that of the edge tone. However, just before it reaches the first resonance frequency of the pipe, the frequency locking starts so that the frequency of sound converges to the first resonance frequency. Furthermore, a little before the edge tone frequency reaches the second resonance frequency, the frequency of an overtone appears and converges to the second resonance frequency. Finally, the second mode dominates the first mode in magnitude. For the ocarina with a Helmholtz resonator, there is no overtone or the resonance frequencies of the cavity, i.e., overtones are much higher than the Helmholtz resonance frequency. Then, the transition to an overtone substantially disappears.

2.3 Dimensions of the 3D model and the frequency of Helmholtz resonance

Figure 3 (a) shows the inner volume of the 3D model of Night Pla Ocarina soprano C (Otsuka Musical Instrument), whose lowest note is A5, and Figure 3 (b) shows its cross section, called Central cross section. The length of the Helmholtz resonator is 86mm and the area of the mouth opening is $6 \times 5\text{mm}^2$. The resonance

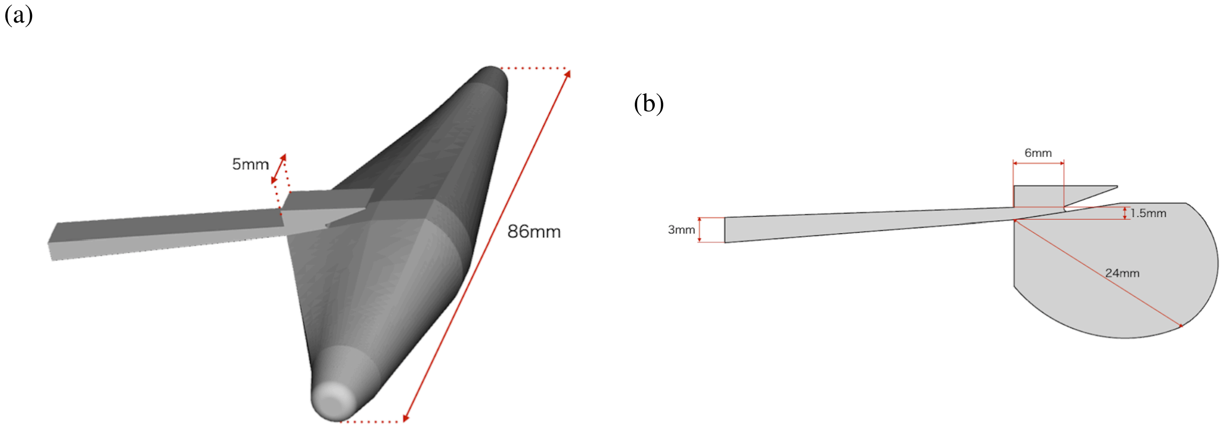

Figure 3. Inner volume of the 3D ocarina model. (a) Dimensions of the inner volume. (b) Cross section of the inner volume (Central cross section).

frequency is estimated by the theory of the Helmholtz resonance, which is caused by the elastic properties of air volume. The resonator frequency depends on the volume of the body and the geometry of the neck[1],

$$f_0 = \frac{c}{2\pi}\sqrt{\frac{S}{VL}}, \tag{2}$$

where L, S and V are the effective length of the neck, its cross-section and the volume of the cavity. Taking the end correction into account, the neck length is estimated as $L \simeq d + 2 \times 8\alpha/3\pi$, where α is the effective radius of the opening obtained from $S = \pi\alpha^2$. For our model, the parameters are given by $V = 9.425 \times 10^{-6}\text{m}^3$, $S = 3.0 \times 10^{-5}\text{m}^2$, $\alpha = 3.09 \times 10^{-3}\text{m}$, $d = 1.5^{-3}\text{m}$ and $c = 340\text{m/s}$. Then, the resonance frequency of the model is estimated as

$$f_0 = 1175\text{Hz}, \tag{3}$$

although this value is quite higher than the lowest note $A5$ (880Hz). We need to check the frequency of the model with numerical calculation.

3 OSCILLATION IN THE 3D OCARINA MODEL

3.1 Numerical method

In this paper, to reproduce fluid motion and acoustic oscillation, the compressible Large Eddy Simulation (LES) with the one-equation sub-grid-scale (SGS) model was used[5, 13, 14, 15]. Actually, we adopted RhoPimpleFoam, an unsteady solver of compressible laminar and turbulent flow in OpenFOAM Ver.5.0.

The numerical mesh of the ocarina model is shown in Figure 4 and the mesh parameters are shown in Table 1. A rectangular parallelepiped $500 \times 500 \times 400\text{mm}^3$, which works as an outside area, is put on the mouth opening. The geometry of the 3D model is constructed by using FreeCAD and is converted to a mesh by using SnappyHexMesh in OpenFOAM utility. The minimum mesh size around the mouth opening is 0.1mm and the number of the cell is nearly 160 million.

To calculate fluid motion for such a huge mesh model, parallel computing by using a supercomputer is necessary. Actually, we used ITO subsystem A of Kyushu University. To make the videos of spatial distributions of pressure and velocity, we pick up the data on the Central cross section (see Figure 3 (b)) by using Function Object of OpenFOAM. We also observe the fluid velocity and vorticity near the edge and detect the sound pressure at the right end tip of the resonator, where the acoustic field dominates and fluid field is negligibly small. Thus, the resonance frequency and amplitude of the sound oscillation are calculated from the data at the end tip.

The equilibrium pressure and temperature are set as $p = 100$ kPa and $T = 300$ K, respectively. To reproduce the oscillations of the ocarina, the sound wave and the fluid motion must be calculated simultaneously. The speed of sound $c \approx 340$ m/s is greater by a degree of magnitude than the fluid velocity, which is estimated as several tens m/s at the highest. To capture sound waves accurately, the time step is set at $\Delta t = 1.0 \times 10^{-7}$ s and the simulation is carried out up to $t = 0.02$s.

In Figure 4 (a) and (b), the arrow shows the inlet, whose the area of the cross-section is 3×5mm. The flow velocity at the inlet is gradually increased and reaches 10 m/s at $t = 0.0002$s. Since the ratio of the height of the inlet to that of the flue exit is 2, the average jet velocity at the flue exit becomes 20 m/s in the steady state. For the top wall and side walls of the rectangular volume over the instrument, i.e., the outside, the transparent boundary condition is adopted and other walls are solid walls.

Table 1. Numerical parameters of 3D ocarina model.

Caluculation time	Δt	p at rest	T at rest	Number of cells	Minimum mesh size
0.02 sec	1×10^{-7} sec	100 kPa	300 K	159680000	0.1[mm]

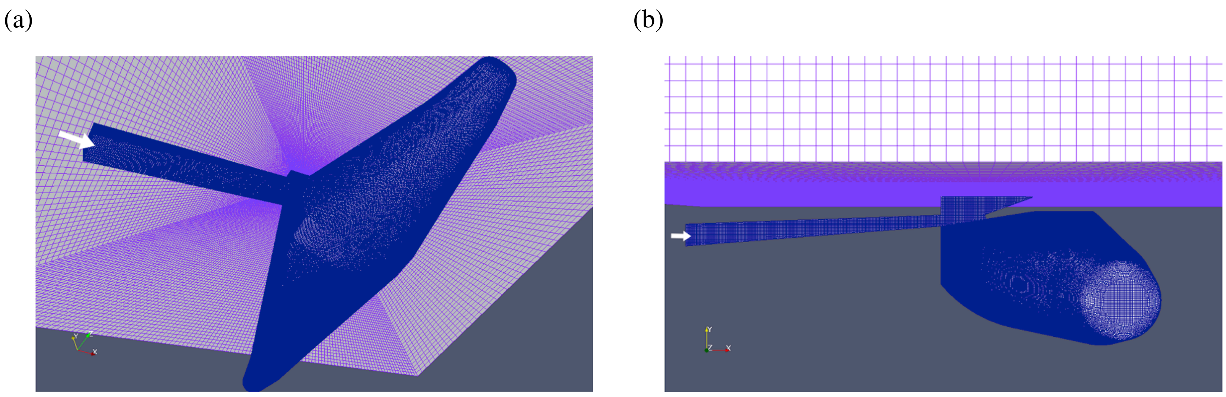

Figure 4. Numerical mesh of the ocarina model. The arrow indicates the inlet. (a) Bottom view. (b) Side view.

3.2 Spatial distributions of velocity and pressure

Figure 5 (a) and (b) show the spatial distributions of fluid velocity and the pressure on the Central cross-sectional at $t = 0.02$. As shown in Figure 5 (a), the jet oscillation is well sustained in the steady state. A part of the jet flow is injected into the resonator body and is spread over some area being broken into smaller scale vortices. Another part of the jet flow goes outside and is also broken into smaller scale vortices. As shown in Figure 5 (b), a nearly spherical pressure wave is emitted from the mouth opening. Therefore, our numerical simulation seems to well reproduce the jet motion and acoustic oscillation for the ocarina.

3.3 Frequency of pressure oscillation

Figure 6 (a) and (b) show the oscillation of pressure in the resonator, which is detected at the end tip of the resonator and the Fourier spectrum of the pressure oscillation, respectively. The amplitude of the pressure oscillation is nearly 300Pa and the waveform approaches a sinusoidal wave in time evolution. From the Fourier spectrum, the resonance peak exists at $f = 850 \pm 50$ Hz. Thus, the lowest note A5 (880Hz) is in its error range ($800 < f < 900$), although the theoretical estimation given by Eq.(3), 1175Hz, is much higher than it.

(a) (b)

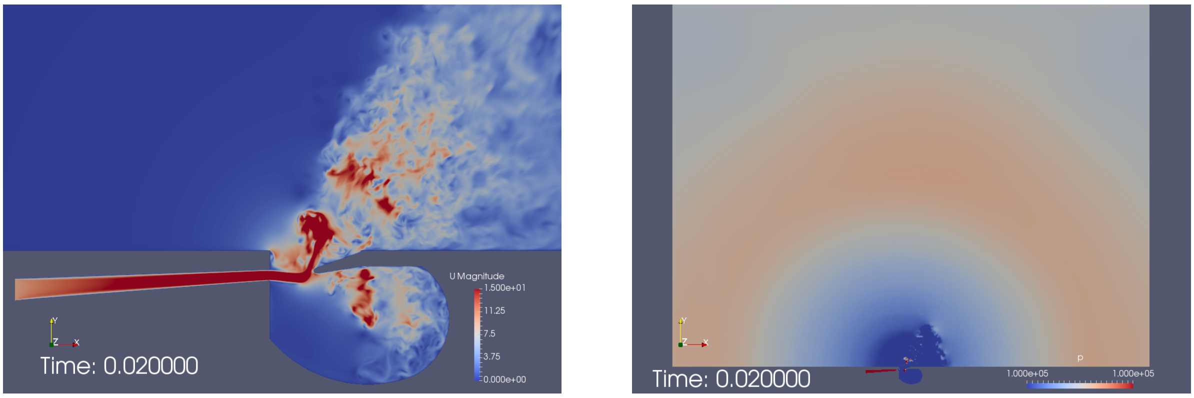

Figure 5. Spatial distributions of velocity and pressure at $t = 0.02$s on the Central cross section. (a) Velocity. (b) Pressure.

The overtone peaks are quite smaller than the main resonance peak, which is the characterisic of the Helmholtz resonator.

(a) (b)

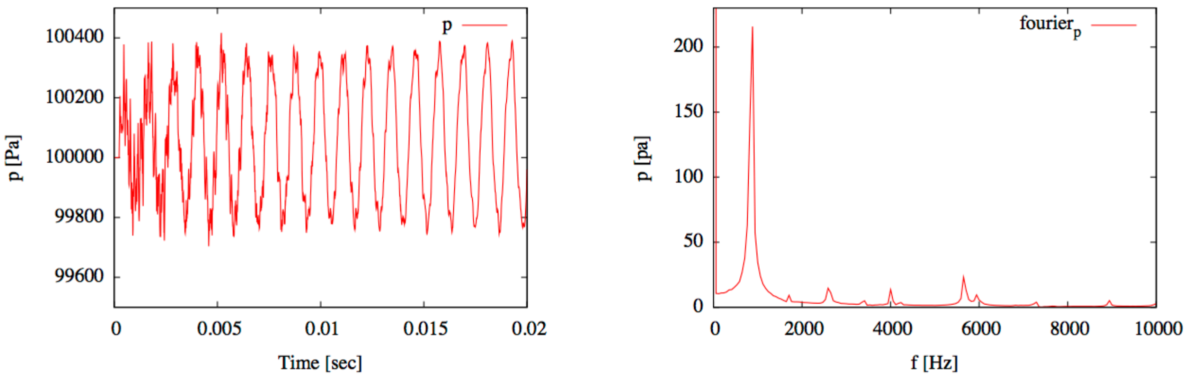

Figure 6. Pressure at the observation point. (a) Pressure oscillation. (b) Fourier decomposition.

4 CONCLUTION

We numerically studied the 3D model of the ocarina with compressible LES. The acoustic oscillation of the ocarina is well reproduced by the numerical simulation. The acoustic oscillation numerically reproduced well captures the properties of the Helmholtz resonance which are regarded as the characteristics of ocarinas. Namely, the peaks of the overtones are much smaller than the peak of the Helmholtz resonance. In this paper, we treated the 3D model with a large number of cells, nearly 160 million, and demonstrated that such a huge 3D model is well handled with parallel computing technique. In future work, we will check the change of the resonance frequency with the jet velocity. Furthermore, we are planning to create a 3D model with tone holes and to reproduce the change of the pitch depending on the change of fingering.

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