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NUMERICAL STUDY ON A THREE-DIMENSIONAL MODEL OF A FLUE ORGAN PIPE: RELATIVE PHASE BETWEEN PIPE AND FOOT, AND STABILITY

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ABSTRACT

To clarify the role of the foot of flue organ pipes, we numerically studied a three-dimensional model with changing foot geometry by compressible LES. The foot acts as a Helmholtz resonator and influences the acoustic oscillation in the pipe. We found that the relative phase of oscillations between the pipe and foot changes depending on the geometry of the foot, and the change of the relative phase can be explained by the theory of forced harmonic oscillators: the pipe works as a force driving the foot. When the resonance frequency of the foot, f_f, is smaller than the frequency of acoustic oscillation, f_a, anti-phase synchronization between the pressure oscillation in the pipe and that in the foot is observed, while synchronization is observed when the f_f is larger than f_a. If f_f is nearly equal to f_a, the pressure oscillation in the foot is delayed by $\pi/2$ to that in the pipe, and the amplitude of the acoustic oscillation is smaller than in other cases. The weak instability observed in this case seems to be caused by nonlinear interaction between the pipe and foot via the jet oscillation.

Keywords: *flue organ pipe, foot, helmholtz resonator, aeroacoustic simulation.*

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1. INTRODUCTION

The study of the sounding mechanism of flue organ pipes is one of the long-standing problems in the field of musical acoustics. There are several crucial points for understanding the acoustic and hydrodynamic properties of flue organ pipes [1]. As one choice, the influence of the window way, e.g., flue length and chamfers, has been studied by several authors [1]. Ségoufin *et al.* experimentally studied the influence of the geometry of the flue with or without chamfers on the jet motion and acoustic oscillation for a recorder-like flue organ pipe [2]. Their result indicated that shortening the flue allows better control of the instrument and makes the sound spectrum richer in high harmonics, while adding chamfers to the flue is effective in stabilizing oscillation only for a long flue but not for a short flue.

On the other hand, the influence of the foot geometry on the jet motion and acoustic oscillation has seemed to attract less attention, although as a related issue the effect of the vocal tract on the sound production of recorders was reported by several authors [3, 4]. In the previous works [5, 6], we found with two-dimensional (2D) numerical simulations that the foot acts as a Helmholtz resonator and the change of its resonance frequency affects the stability of the acoustic oscillation and the relative phase between the pressure oscillation in the pipe and that in the foot. Note that the 2D models well captured the basic properties experimentally observed for the recorder-like flue organ pipe [2, 5].

In this paper, we explored the role of the foot of flue organ pipes with 3D numerical simulation because 3D simulation provides more realistic results. That is, acoustic oscillations and fluid motions are more stable in 3D systems than in 2D systems due to the intrinsic nature of 2D fluid, e.g., inverse energy cascade, and the end correction is larger at low frequencies for 2D systems than for 3D systems (see Ref. [7] and references therein). For aeroacoustic simulation, we adopted a compressible Large Eddy Simulation (LES) because the reliability of the compressible LES has been confirmed in several situations [7]. Indeed, the compressible LES reproduces the basic properties of air-jet instruments, e.g., the relation between jet speed and acoustic oscillation frequency.

2. MODEL

We studied a model system similar to the flue organ pipe experimentally studied by Ségoufin *et al.* [2]. To reduce the mesh size, we adopted a closed pipe with a length of 141.5mm, which has almost the same fundamental pitch as the open pipe with a length of 283mm used by Ségoufin *et al.* [2, 5]. Figure 1 (a) and (b) show the schematic of the 'Reference model' and dimensions in an area of the mouth opening. The foot consists of a rectangular parallelepiped with a length of 60mm and a channel connecting with a flue, whose underside is formed by a quarter-cylinder block. This quarter-cylinder block is almost the same as that in the experiment, while the length of the flue, $l_f = 3$mm, is shorter than that in the experiment, i.e., 15mm, [2], because the 2D model with these foot and flue resulted in a short attack transient and a stable oscillation in the stationary state [5]. Note that in the attack transient and stationary state, the properties of the 2D model were very similar to those observed in the experiment [2, 5].

To explore the role of the foot, we adopted two more models which are different in length of the rectangular parallelepiped: the 'Short model' with a length of 30mm and the 'Mid model' with a length of 45mm. Since the foot acts as the Helmholtz resonator, the three models are different in the foot resonance frequency as shown later.

For aeroacoustic simulation, we utilized a compressible LES solver: the rhoPimpleFoam with a one-equation eddy viscosity subgrid scale model in the OpenFOAM Ver.5.0 and v2006. The minimum grid size was $\Delta x = 0.1$mm in an area of the mouth opening, and the number of cells was 165312887 for the Reference model. The time step was set as $\Delta t = 5.0 \times 10^{-8}$s. The temperature and pressure in equilibrium were set as $T_0 = 300$ K and $p_0 = 1.0 \times 10^5$ Pa, respectively. The average velocity in the flue was set at 6m/s in the steady state. The flow injected from the left end of the inlet (see Fig.1 (a)) was gradually increased until $t = 2$ms to reach a uniform flow with a velocity of 4m/s since its cross section is 1.5 times larger than that of the flue. The top and side walls of the outside were set as the outlet boundary condition and the others were non-slip solid walls.

(a)

(b)

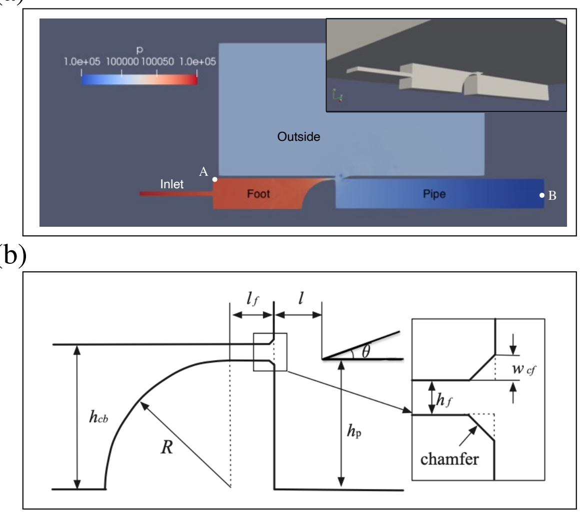

Figure 1. Reference model. (a) Geometry of the model and pressure distribution: the inset shows the 3D view; 'A' and 'B' denote the observation points in the foot and pipe, respectively. (b) Dimensions of the edge, flue with chamfers and foot channel: $h_p = 20$ mm, $l = 4$ mm, $\theta = 20°$, $w_{cf} = 0.71$ mm, $h_f = 1$ mm, $l_f = 3$ mm, $h_{cb} = 20.8$ mm, $R = 19.8$ mm; the width of the pipe is 20 mm.

3. NUMERICAL RESULT

3.1 Resonance frequencies of the three foot models

Since the foot is intricately shaped, it is difficult to clearly determine the boundary between its body and neck, which is necessary to obtain the Helmholtz resonance frequency with the theoretical formula. Thus, we numerically estimated the resonance frequencies of the foot without the pipe for the three models (for details, see [5]). Table 1 shows the resonance frequencies of the foot f_f compared with the frequencies of acoustic oscillations f_a in the pipe. Then, f_f decreases as the volume of the foot increases.

Table 1. Helmholtz frequencies of the foots f_f and frequencies of the acoustic oscillations f_a.

	Reference	Mid	Short
f_f[Hz]	400 ± 10	470 ± 10	550 ± 10
f_a[Hz]	481	469	461

3.2 oscillations in the pipe and foot for the three models

Figure 2 shows pressure oscillations observed at the points A and B in Figure 1 (a) for the three models. For all the models, stable pressure oscillations at the frequency f_a (see Table 1) are observed in the stationary state.

For the Reference model, the pressure in the foot oscillates nearly in anti-phase with that in the pipe after a short attack transient. Note that the large pressure peak in the foot observed in the attacking period $0 < t < 2$ms is attributed to the increasing volume flow from the inlet. The amplitude of oscillation in the foot is nearly half of that in the pipe in the stationary state. On the other hand, the Short model has a relatively long attack transient, and the pressure in the foot oscillates nearly in phase with that in the pipe. The amplitude of oscillation in the foot is also nearly half of that in the pipe.

For the Mid model, the pressure oscillations however behave in a bit more complicated manner. They have a relatively longer attack-transient and behave in a slightly unstable manner. Indeed, the pressure oscillation in the pipe first grows and that in the foot follows. Then, they slightly reduce. In this sense, the Mid model is weakly unstable. In the stationary state, the pressure oscillation in the pipe leads that in the foot by nearly $\pi/2$, and they are almost the same in amplitude. Thus, pressure oscillation is much smaller than those for the other models.

The phase difference between the pressure oscillation in the pipe and that in the foot can be explained by relying on the theory of forced harmonic oscillators (TFHO) [5]. Namely, the acoustic oscillation at $f = f_a$ in the pipe drives the foot with the resonance frequency f_f. Therefore, the Short, Mid and Reference models are considered to be in the stiffness-controlled ($f_a < f_f$), damping-controlled ($f_a \approx f_f$), and mass-controlled ($f_a > f_f$) regions, respectively.

According to TFHO, the oscillation in the foot should become the maximum in amplitude owing to resonance for the Mid model. However, this is not the case, and the oscillation in the pipe, i.e., the driving force, becomes

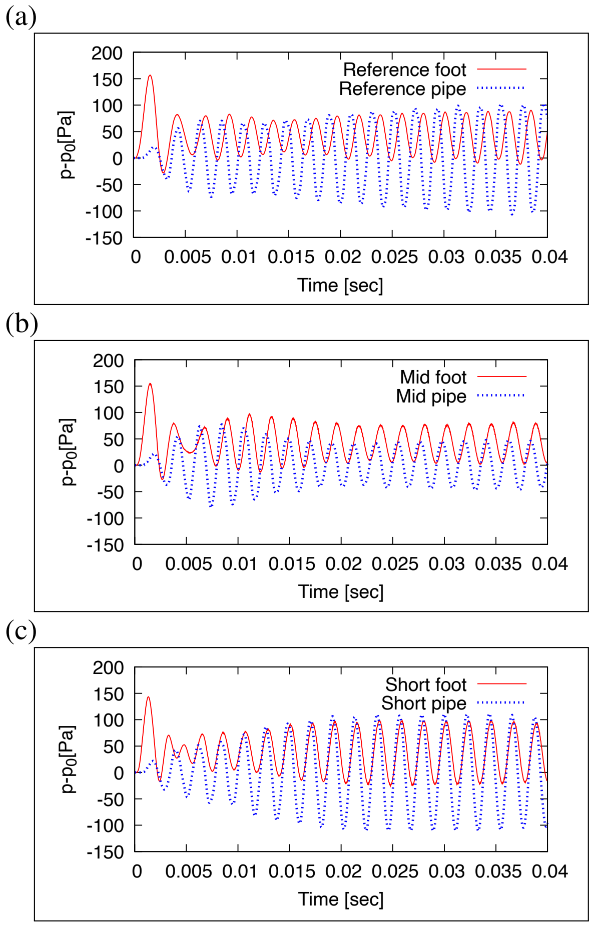

Figure 2. Pressure fluctuation $p - p_0$ in the foot and that in the pipe, where p_0 is the equilibrium pressure. (a) Reference model. (b) Mid model. (c) Short model.

relatively smaller than those for the Reference and Short models. The enhancement of energy transfer from the pipe to the foot owing to resonance seems to consume the acoustic energy, reducing the amplitude of the oscillation in the pipe. We expect that the hydrodynamic interaction between the pipe and foot through the osculating jet is the key to understanding this process in detail.

Finally, we compare the results with those for 2D systems studied in the previous works [5, 6], where the Reference and Short models were studied. Since the end correction for 2D systems is larger than that for 3D systems at low frequencies [7], the resonance frequencies of the foots become lower for the 2D systems: $f_f = 380 \pm 5$Hz and

$f_a = 482$Hz for the Reference model; $f_f = 495 \pm 5$Hz and $f_a = 481$Hz for the Short model. For the Reference model with $f_a > f_f$, similar anti-phase synchronization between the foot and the pipe occurs. For the Short model with a nearly resonant condition $f_a \approx f_f$, the oscillation in the foot is delayed by $\pi/2$ to that of the pipe, and the oscillation in the pipe is smaller in amplitude than that for the Reference model. Furthermore, the pressure oscillations in the foot and pipe are a little unstable and gradually fluctuated as a beat sound wave. Such instability for the 2D system should be attributed to the instability of hydrodynamic motions owing to the inartistic nature of the 2D fluid [7].

4. DISCUSSION

In this paper, we numerically studied the 3D flue organ pipe model, focusing on the role of the foot, which acts as a Helmholtz resonator, and showed how the detuning of the pipe acoustic oscillation frequency from the resonance frequency of the foot affects the phase difference between the acoustic oscillation in the pipe and the pressure oscillation in the foot. We successfully explained the change in the relative phase of the oscillations between the pipe and foot by using TFHO. Furthermore, for the resonance condition, $f_f \approx f_a$, the acoustic oscillation in the pipe and that in the foot become smaller, even though a resonance is expected from TFHO. To understand this phenomenon and to develop the theory based on TFHO, we should investigate the nonlinear interactions among the oscillation in the foot, the jet motion and the oscillation in the pipe, in particular focusing on relative phases among them [6]. We consider that the study of the relative phases is the key to understanding the whole story. This task is left for future work.

In relation to recorders, the oral cavity and vocal track seem to play the same role as the foot and affect the stability and phase change of acoustic oscillations [3, 4]. Indeed, similar synchronization and anti-phase synchronization were observed experimentally and discussed theoretically [4]. Our numerical result and prediction should be checked by experiments on flue organ pipes and recorders. Then, if they are true, those points will be taken into account for the design of the flue organ pipe.

5. ACKNOWLEDGMENTS

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