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Anti-phase synchronization between the oscillation in the pipe and that in the foot of a flue organ pipe

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Abstract

In the recent work (Acoust. Sci. & Tech. vol.40, No.1 pp.29-39 (2019)), we found with the numerical study of a 2D flue organ pipe model that the foot works as a Helmholtz resonator. When the frequency of acoustic oscillation in the pipe is higher than the resonance frequency of the Helmholtz resonator by almost the full-width at half-maximum, the most stable oscillation is observed, and the oscillation in the foot is anti-synchronized with that in the pipe. However, if the Helmholtz resonance frequency is nearly equal to the acoustic oscillation frequency, the oscillations in the pipe and foot become rather unstable and the oscillation in the foot lags behind that in the pipe by nearly $\pi/2$. In this paper, we study the phase relations among the pressure oscillation in the foot, that in the pipe, and the hydrodynamic oscillation of the jet, which are the key to understanding the mechanism of stabilizing and destabilizing oscillations of the flue organ pipe.

Keywords: Flue Organ Pipe, Foot, Anti-phase synchronization

1 INTRODUCTION

The sounding mechanism of flue organ pipes has been studied by many authors in the field of musical acoustics[1, 2, 3, 4, 5, 6, 7, 8]. The major difficulty in studying flue organ pipes from the view of Physics comes from the fact that the sound source of flue organ pipes, the edge tone, is aerodynamic sound that is caused by the unsteady motion of a fluid flow with non-zero vorticities[1, 9, 10]. For studying flue organ pipes experimentally and numerically, one has to pay special attention to the interaction between the acoustic oscillation in the pipe and hydrodynamic oscillation of the jet. The numerical method with compressible fluid solvers, which allows us to simultaneously calculate the jet motion and acoustic oscillation in the pipe, has been recently developed by several authors[11, 12, 13, 14].

In a recent study[15], we found with the numerical study of a 2D flue organ pipe that the foot works as a Helmholtz resonator and plays an important role in stabilizing the acoustic oscillation in the pipe. Namely, when the frequency of acoustic oscillation in the pipe is higher than the resonance frequency of the Helmholtz resonator by almost its full-width at half-maximum, the most stable oscillation is observed, and the oscillation in the foot is anti-synchronized with that in the pipe. However, if the Helmholtz resonance frequency is nearly equal to the acoustic oscillation frequency, the oscillations in the pipe and foot become rather unstable and the oscillation in the foot lags behind that in the pipe by nearly $\pi/2$.

In this paper, we give a short review of this study. Furthermore, to clarify the mechanism of stabilizing and destabilizing oscillations, we consider the interactions among the acoustic and hydrodynamic oscillations. Actually, we study the phase relations among the pressure oscillation in the foot, that in the pipe, and the hydrodynamic oscillation of the jet. The volume flow supplied through the flue to the pipe periodically changes owing to the pressure oscillation in the foot. In order to sustain and stabilize the oscillation in the pipe, the volume flow supplied to the pipe becomes the maximum at a certain time in the period of oscillation, otherwise the oscillation is destabilized, and the foot with an appropriate volume of the body, namely an adjusted Helmholtz resonator, assists this process.

2 MODEL AND NUMERICAL METHOD

We use the same model studied by the recent work[15] (see Fig.1 (a)), which is a 2D analog of the flue organ pipe studied by Ségoufin *et al.*[8]. The model consists of an inlet with a length of 50mm and a height of 3mm, a foot, a flue with a length of 3mm and a height of 1mm and a pipe with a length of 141.5mm and a height of 20mm. The volume labeled 'Out side' indicates the outside space with the external atmosphere. Our model has a closed pipe while the instrument studied by Ségoufin *et al.*[8] has an open pipe with a length of 283mm. Thus, they have almost the same fundamental pitch around 500Hz, when they are driven by a jet. The foot consists of the left rectangular part and the right channel part connecting with the flue, where the lower channel block below the channel is a quarter circle. The length of the rectangular part is 60mm for the model in Fig.1. Figure 2 shows the dimensions of the mouth opening, flue and channel block. The flue has chamfers at the right end, which stabilize the jet motion and acoustic oscillation[8, 15].

Let us call the 2D model shown in Fig.1 the Reference model. To investigate the role of the foot, considering how the geometry and volume of the foot influence the jet motion and acoustic oscillation, we treat three other models. Models called the Short and Long models have the rectangular parts of the foot with a length of 30mm and 120mm, respectively. We also investigate a model without the foot and inlet called the Non-foot model.

For the numerical calculation, we adopt a compressible LES (Large Eddy Simulation) with the one-equation sub-grid-scale (SGS) model [11, 16]. In practice, we use a compressible LES solver 'rhoPisoFoam' in the open source software, OpenFOAM ver.2.2.2[15]. The pressure and temperature at the rest are taken as $p_0 = 10^5$Pa and $T_0 = 300$K, respectively. The smallest mesh size around the mouth opening is $\Delta x = 0.1$mm and the time step of the numerical integration is $\Delta t = 5.0 \times 10^{-8}$s. For the Reference model, the number of mesh cells is 120165. The mean jet velocity at the flue exit is taken as $V = 6$m/s in the steady state, at which a stable oscillation is observed for the Reference model. Since the height of the inlet is 3 mm, which is three times as large as that of the flue, the flow velocity at the left end of the inlet should be set as one-third of the desired jet velocity, namely 2m/s. In practice, the flow velocity at the inlet is gradually increased to reach the desired value at $t = 2$ms. Note that for the Non-foot model, the air flow is directly injected from the left end of the flue. The inlet boundary condition is taken for the left end of the inlet except for the Non-foot model, for which the left end of the flue is an inlet. The outlet boundary condition is taken for the right, left and top walls of the volume labeled 'Out side' in Fig.1 (a). The pressure oscillations are observed at the center of the right end of the pipe and at the upper-left point of the rectangular part of the foot. The jet velocity is observed at the center of the flue exit.

(a) (b)

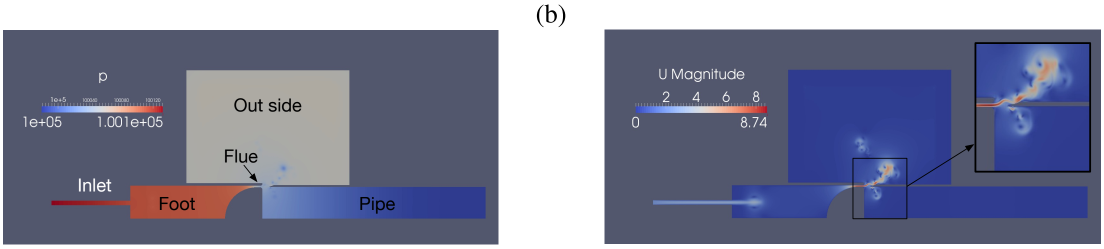

Figure 1. Snapshots of spatial distributions of pressure and velocity for the Reference Model. (a) Pressure distribution. (b) Velocity distribution.

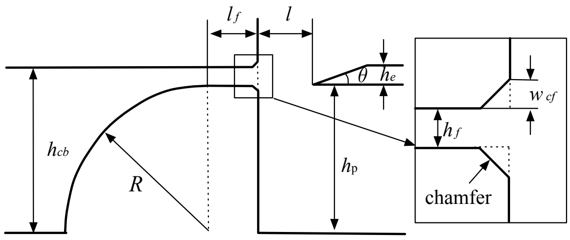

Figure 2. Dimensions of the edge, flue with chamfers and foot channel: $h_p = 20$mm, $l = 4$mm, $h_e = 1.2$mm, $\theta = 20°$, $w_{cf} = 0.71$mm, $h_f = 1$mm, $l_f = 3$mm, $h_{cb} = 20.8$mm, $R = 19.8$mm.

3 NUMERICAL RESULT

3.1 Pressure oscillations in the pipe and foot

Figure 1 (a) and (b) show pressure and velocity distributions in the steady state for the Reference model. In the steady state, pressure oscillations are well sustained in both pipe and foot, but they seem to be in anti-phase synchronization. Indeed, at the moment shown in Fig. 1 (a), the pressure takes the minimum and maximum values in the pipe and foot, respectively, while in another half period, the opposite distributions are observed in the pipe and foot. As shown in Fig. 1 (b), the oscillating jet collides with the edge emitting the edge tone, which drives the resonance pipe.

Figure 3 (a) shows the time evolution of the pressure oscillation in the pipe for the Reference model compared with that for the Non-foot model. The pressure oscillation for the Reference model is more stable and larger in amplitude than that for the Non-foot model. This means that the interaction between the pipe and foot assists the acoustic oscillation in the pipe to be stabilized with large amplitude. Figure 3 (b) shows the time evolution of the pressure oscillation in the pipe compared with that in the foot for the Reference model. In the steady state, the pressure oscillations in the pipe and foot have the same frequency at $f_a = 482$Hz, but they are in anti-phase synchronization.

As shown in Fig.4 (a), for the Short model, the pressure oscillation in the pipe at $f_a = 481$Hz is more unstable and smaller in amplitude than that for the Reference model. On the other hand, the pressure oscillation in the foot is in the same order as that for the Reference model but is more unstable. The pressure oscillations in the pipe and foot seem to strongly correlate to each other and, most of the time, the pressure oscillation in the foot lags behind that in the pipe by nearly $\pi/2$.

As shown in Fig.4 (b), for the Long model, the pressure oscillation in the pipe at $f_a = 479$Hz is slightly unstable and is slightly smaller in amplitude than that for the Reference model. However, the pressure oscillation in the foot is much smaller in amplitude than that for the Reference model and irregularly fluctuates in first stage of the time evolution, though the oscillations in the pipe and foot seem to fall into anti-phase synchronization in the steady state.

Figure 5 shows the horizontal velocity at the center of the flue exit v_x for the Reference, Short and Long models. The behavior of v_x shows the same tendency as the pressure oscillation in the pipe for all the models. That is, for the Reference model, v_x is the most stable and the largest in amplitude among the three models. On the other hand, for the Short model, v_x is the most unstable and the smallest in amplitude among the three models. For the Long model, v_x is slightly unstable and slightly smaller in amplitude than that for the Reference model. The phase relation between v_x and the pressure oscillation in the pipe will be discussed in the next subsection.

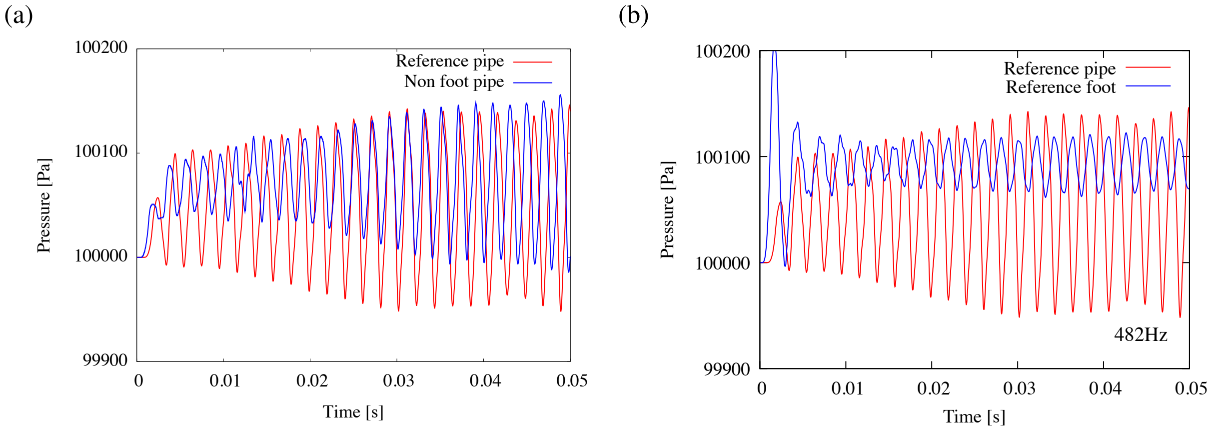

Figure 3. Pressure oscillations for the Reference model. (a) Pressure oscillation in the pipe compared with that for the Non-foot model. (b) Pressure oscillations in the pipe and foot.

3.2 The role of the foot and relative phases among the acoustic and hydrodynamic oscillations

In the recent study[15], we found that the function of the foot depends on its volume and it acts as a Helmholtz resonator. To consider the properties of the foot as a Helmholtz resonator, we use the foot model without the pipe, which is formed by the flue and foot connected to the inlet (see Fig.6 (a)). The frequency of the Helmholtz resonator f_H is normally given by

$$f_H = \frac{c}{2\pi}\sqrt{\frac{S}{V_H L}}, \tag{1}$$

where c is the speed of sound in air, S is the cross section of the neck, L is the length of the neck and V_H is the volume of air in the resonator's body. For the 2D model, S and V_H are the height of the neck and the 2D area of the foot, respectively[15]. However, to obtain the resonance frequency of the foot, we hardly use Eq.(1), because there is no method to determine the boundary between the resonator's body and neck for a complex-shaped resonator like the foot. Here, we use the compressible LES to obtain the resonance frequency of the foot separated from the pipe. To obtain the frequency response of the foot, the flow velocity at the inlet is periodically changed as $U_{in} = U_0 \sin\omega t$, where $U_0 = 1$m/s.

Figure 6 (a) shows a snapshot of the pressure for the Reference model without the pipe at $f = 380$Hz, at which the amplitude of the pressure oscillation takes the maximum value. Figure 6 (b) shows the frequency response of the amplitude of the pressure oscillation in the foot. A resonance peak is observed at $f = 380$Hz. However, the frequency of the acoustic oscillation at $f_a = 482$Hz is higher than the Helmholtz resonance frequency at $f_H = 380$Hz by nearly the value of the full-width at half maximum (FWHM).

Table 1 shows the Helmholtz frequency f_H compared with the acoustic frequency f_a for the Reference, Short and Long models. When $f_a - f_H \geq$ FWHM, anti-phase synchronization occurs. If $f_a \approx f_H$, the pressure oscillation in the foot lags behind that in the pipe by nearly $\pi/2$. From this fact, we can presume that the acoustic oscillation in the pipe drives the pressure oscillation in the foot[15]. Actually, the theory of forced harmonic oscillators (TFHO) well explains the change of phase difference between the pressure oscillations in the pipe and foot with change of f_H.

Table 2 shows relative phases among the oscillations of pipe, foot and horizontal jet velocity at the flue exit v_x, where, for example, values in the column labeled 'pipe - foot' indicate how much the oscillation in the pipe lead that in the foot in phase. Roughly speaking, the relative phase of the oscillation in the pipe from that in the foot take values at $\theta_r \approx \pi$ for the Reference and Long models and at $\theta_r \approx \pi/2$ for the Short model. But,

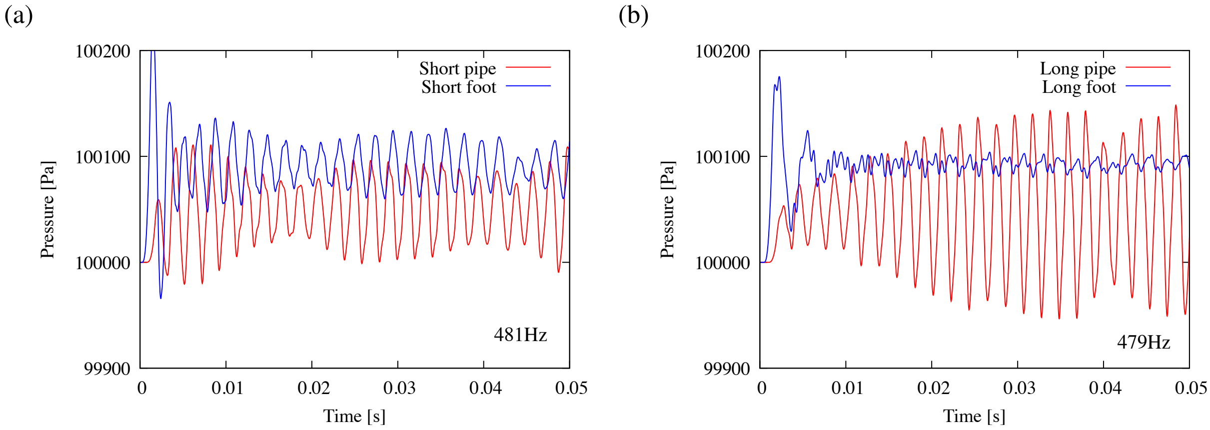

Figure 4. Pressure oscillations in the pipe and foot. (a) Short model. (b) Long model.

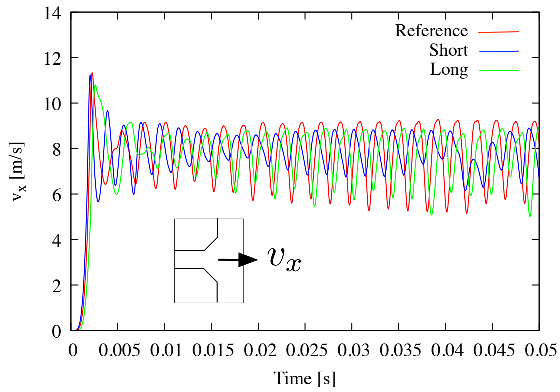

Figure 5. Horizontal velocity at the center of the flue exit v_x.

more precisely, it increases with $f_a - f_H$ and is close to π for the Long model. For the Short mode, it is less than $\pi/2$, since f_a is slightly less than f_H by 14Hz. Such a change of the relative phase can be explained with TFHO. TFHO also explains the decrease in amplitude of the oscillation in the foot with increasing $f_a - f_H$, when $f_a - f_H \geq$ FWHM. However, TFHO cannot explain the destabilization of oscillations in the pipe and foot, when $f_a \approx f_H$. The strong interactions among the oscillation in the foot, the jet motion and the oscillation in the pipe should destabilize themselves.

To consider the interactions among the acoustic and hydrodynamic oscillations, we check relative phases among them as shown in Table 2. As shown in the columns labeled 'foot - jet velocity v_y' and 'jet velocity v_x - pipe', the oscillation of v_x lags behind the oscillation in the foot and leads that in the pipe for all models. The relative phase of the pressure oscillation in the foot from the oscillation of the jet velocity v_x decreases with increasing $f_a - f_H$. On the other hand, the relative phase of the oscillation of the jet velocity v_x from the pressure oscillation in the pipe is almost fixed in a small range $(1.4 < \theta_r < 1.5)$ for the Reference and Long models, for which stable oscillations are observed, while it takes a much different value as $\theta_r = 2.301 \approx 3\pi/4$ for the Short model, for which the oscillation is destabilized.

The change of v_x indicates the change of the supply of the volume flow to the pipe. Therefore, to sustain and stabilize the oscillation in the pipe, the volume flow supplied through the flue to the pipe becomes the maximum at a certain time in the period of oscillation, otherwise the oscillation is destabilized, and the foot with an appropriate volume of the body, namely an adjusted Helmholtz resonator, assists this process.

(a) (b)

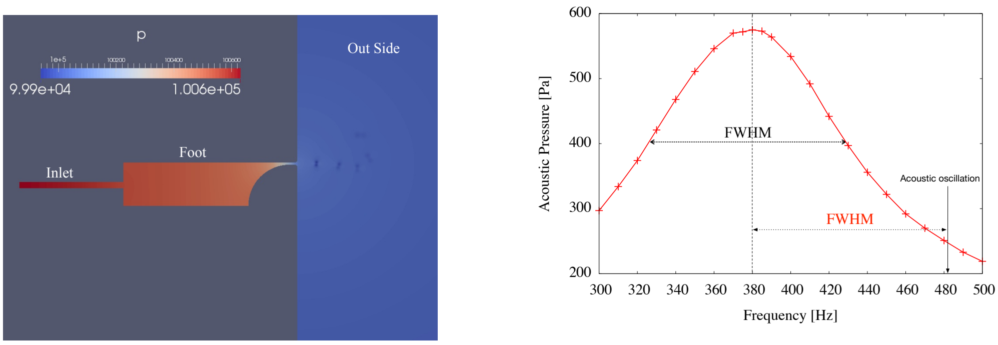

Figure 6. Helmholtz resonator (foot) of the Reference model. (a) Snapshot of the pressure distribution at $f = 380$Hz. (b) Frequency response of the Helmholtz resonator of the Reference model.

Table 1. Helmholtz frequency f_H compared with the frequency of the acoustic oscillation f_a for the representative models.

	Reference	Short	Long
f_H[Hz]	380±5	495±5	265±5
f_a[Hz]	482	481	479
$f_a - f_H$	FWHM	-14 [Hz]	2FWHM

Table 2. Relative phases among the pressure oscillation in the pipe, that in the foot and the oscillation of horizontal jet velocity at the flue exit v_x.

Model	pipe - foot	foot - pipe	foot - jet velocity v_x	jet velocity v_x - pipe
Reference	$2.857 \lesssim \pi$	$3.426 \gtrsim \pi$	$1.955 \gtrsim \pi/2$	$1.471 \approx \pi/2$
Short	$1.215 \lesssim \pi/2$	$5.068 \gtrsim 3\pi/2$	$2.767 \gtrsim 3\pi/4$	$2.301 \approx 3\pi/4$
Long	$3.229 \approx \pi$	$3.054 \approx \pi$	$1.629 \approx \pi/2$	$1.425 \approx \pi/2$

4 CONCLUSIONS

In this paper, we studied the problem of how the geometry of the foot influences the acoustic oscillation in the pipe by using numerical simulations of the 2D flue organ pipe model with three different shaped foots. As a result, it was found that the function of the foot depends on its volume and it acts as a Helmholtz resonator. We gave a conjecture that the acoustic oscillation in the pipe drives the oscillation in the Helmholtz resonator. The theory of forced harmonic oscillators (TFHO) well explains the change of phase difference between the pressure oscillations in the pipe and foot with change of the Helmholtz frequency f_H.

For the Reference model, where the frequency of the oscillation in the pipe f_a is higher than that of the Helmholtz resonator f_H by almost the resonator's FWHM, the most stable oscillation is observed among the three models and anti-phase synchronization between the oscillations in the pipe and foot occurs. For the Long model with $f_a - f_H \approx$ 2FWHM, anti-phase synchronization still occurs and the oscillation in the pipe is stable, but the oscillation in the foot is very small in amplitude accompanied with small irregular fluctuations. The results for the Reference and Long models are almost explained with TFHO. For the Short model with $f_a \approx f_H$, the oscillation in the pipe leads that in the foot in phase by nearly $\pi/2$, which can be explained with TFHO. However, both oscillations in the pipe and foot are destabilized by interactions among the acoustic and hydrodynamic oscillations, which can not be explained with TFHO.

To consider the interactions among the acoustic and hydrodynamic oscillations, we checked relative phases among them. As a result, the relative phase of the jet velocity v_x from the pressure oscillation in the pipe is almost fixed in a small range $(1.4 < \theta_r < 1.5)$ for the Reference and Long models, for which stable oscillations are observed, while it takes a much different value as $\theta_r = 2.301 \approx 3\pi/4$ for the Short model, for which the oscillation is destabilized. This fact means that to sustain and stabilize the oscillation in the pipe, the volume flow supplied through the flue to the pipe should take the maximum at a certain time in the period of oscillation, otherwise the oscillation is destabilized, and the foot with an appropriate volume of the body, namely an adjusted Helmholtz resonator, assists this process. To unravel the detailed mechanism of stabilizing and destabilizing oscillations, we need more precise knowledge of the jet motion disturbed by the oscillations in the foot and the pipe[1, 17]. This task is left for future work. It should also be checked by simulations of 3D models and experiments.

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