EFFECTS OF JET OFFSET IN FLUTE BLOWING ON JET FLUCTUATIONS AND SOUND

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ABSTRACT

To investigate the effects of jet offset in flute blowing on jet fluctuations and sound, direct aeroacoustic simulations were performed under conditions of two jet offsets (the relative height of the jet from the edge) within a practical range for human players. For a large jet offset, the jet was observed to split into two jets around the center of the mouth opening. One of the jets traveled straight to the edge without fluctuating. This behavior of jet was not observed for a small jet offset, where the jet was fluctuating up and down around the edge. The sound pressure levels of the fundamental tone and harmonics were smaller for the large jet offset. The relevancy between the jet fluctuations and the sound is to be discussed.

Keywords: *Jet, Jet offset, Sound, Flute*

1. INTRODUCTION

In flute-like (flue) instruments, including the flute, the sound production is maintained by the interaction between the jet and the acoustic field in the resonator [1-3]. Therefore, the radiated sound changes depending on the blowing conditions such as the jet velocity and the geometrical conditions between the jet and the instrument. The changes in the sound pressure levels of fundamental tone and harmonics with the jet offset (the relative height of the jet from the edge) have been calculated from the changes of the flow rate into the resonator [4,5], assuming that the jet fluctuates symmetrically with respect to the edge. However, in blowing states, the jet was observed to fluctuate asymmetrically depending on the blowing conditions [6]. To investigate the effects of blowing conditions on the jet fluctuations and the sound under blowing states, this study investigates the flow and acoustic fields by direct aeroacoustic simulations for a flute head joint under two jet offset conditions.

2. PARAMETERS

The blowing conditions of the flute depend on the jet velocity and geometrical condition between the flute and the oral cavity. This study defined the geometrical condition as shown in Fig. 1, as in the previous study [6]. The blue line shows the reference jet direction measured without the flute. The origin, $\mathrm{o_j}$, is the center of the cavity exit. The directions x_{j}, y_{j}, and z_{j} are defined as the reference jet direction, its vertical direction, and the longitudinal direction of the flute, respectively. The geometrical conditions are defined on the spanwise center of the cavity and the mouth opening ($z_{\mathrm{j}} = 0$) as follows: the jet offset, $y_{\mathrm{j,e}}$, is the relative height to the edge of the jet traveling in the reference jet direction, the jet angle, θ_{j}, is the angle between the reference jet direction and the mouth opening, the exit-edge distance, l, is the distance from $\mathrm{o_j}$ to the edge. The values related to distance are nondimensionalized with the height of the cavity throat, h. The values for the blowing parameters are shown in Table 1. This study performed computations by varying the jet offset conditions to $y_{\mathrm{j,e}} / h = 0$ and 0.37. The values for parameters other than the jet offset are fixed to the values measured for a human player [6].

The flow rate into the resonator at the edge distance ($x_{\mathrm{j}} / l = 1$) is calculated in Sec. 4 by integrating the jet velocity in

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the x_j-direction, u_j. The integration range in the y_j-direction is from the height that u_j is 50% of the maximum of the time-averaged velocity profile inside the edge ($y_j < -y_{j,e}$), $y_{j,low}$, to the edge height, $-y_{j,e}$. The integration range in the z_j-direction, $z_{j,w}$ and $-z_{j,w}$, is that the y_j-direction integral value of u_j is within 80% of the value at $z_j = 0$. The values are shown in Table 2.

Table 1. Blowing conditions for computations

Parameter	Value
Jet angle θ_j [°]	39
Exit-edge distance l / h	5.6
Jet offset $y_{j,e}$ / h	0, 0.37
Flow rate Q [L / min]	16.0
Cross-sectional mean jet velocity at minimum cross-section of oral cavity U_0 [m / s]	21.5

Table 2. Integration range for flow rate into resonator

Parameter		Value
Lower limit $y_{j,low}$ / h	$y_{j,e}$ / $h = 0$	−2.6
	$y_{j,e}$ / $h = 0.37$	−2.4
Width $z_{j,w}$ / h		1.7

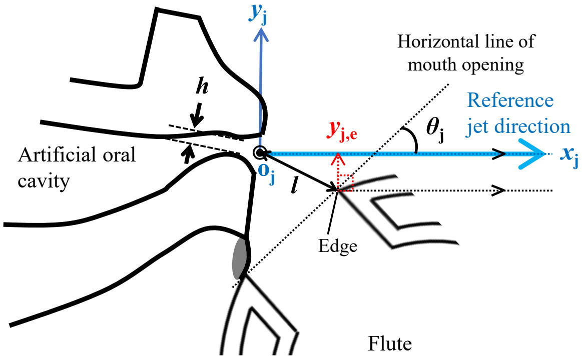

Figure 1. Definitions of blowing parameters

3. COMPUTATIONAL METHODOLOGIES

3.1 Governing Equations and Finite-Difference Formulation

The computational method is the same as the previous study for recorders [7]. The governing equations are based on the 3D compressible Navier-Stokes equations. The shapes of a flute head joint and an oral cavity are reproduced by a volume-penalization (VP) method. Spatial derivatives were evaluated by the sixth-order compact finite-difference scheme (fourth-order accuracy at boundaries) [8]. Time integration was performed by the third-order Runge-Kutta method [9].

3.2 Computational Model

Figure 2 shows the computational models of the flute head joint and the artificial oral cavity. The shapes of the models were reproduced from CAD images of the artificial blowing device used for the experiments in the previous study [6]. The radiated sound was measured 100 mm from the end of head joint. The shape of cavity was reproduced from the cavity exit to about 30 mm inside. Velocity was given uniformly in a duct connected to the 30 mm inside position. The acoustic and flow fields under the jet offset condition of $y_{j,e}$ / $h = 0$ were compared with the experiments [6], where the predominancy of the second and the third harmonic and the spatial distributions of jet fluctuation center were almost reproduced by the computation [10].

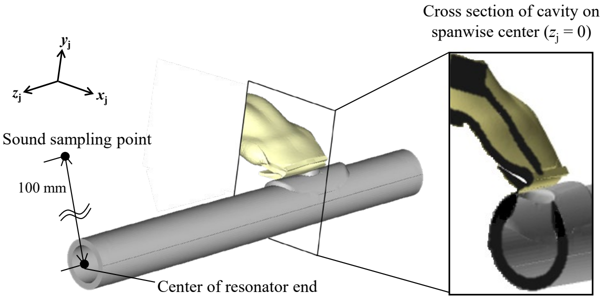

Figure 2. Computational model of flute head joint and artificial oral cavity

4. RESULTS AND DISCUSSION

Figure 3 shows the sound pressure spectra of the radiated sound under the jet offset conditions $y_{j,e}$ / $h = 0, 0.37$. The frequency resolution is 87 Hz, and the data length is 0.017 seconds. The fundamental frequencies of both conditions are about 870 Hz. The sound pressure levels of the fundamental and the second and third harmonics are higher for $y_{j,e}$ / $h = 0$ than for $y_{j,e}$ / $h = 0.37$.

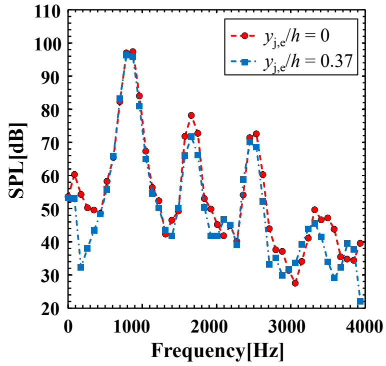

Figure 3. Sound pressure spectra

This difference in the radiated sounds is discussed from the flow field. Figure 4 shows the temporal variation of flow field at $z_j = 0$ during one period. The vorticity is shown by grayscale to visualize the shear layers of jet. The pressure is shown by colored contours. Time $t = 0$ is the instant when the pressure in the resonator becomes the minimum, and T_1 is one period of the fundamental frequency f_1. At $t / T_1 = 0$, for both the jet offset conditions, the pressure in the resonator is low, and the jet deflects outside the edge. Half a period later, at $t / T_1 = 2 / 4$, the pressure is high, and the jet deflects inside. The phase conditions between the jet and the pressure under both conditions are favorable [11] for the radiation of fundamental tone.

When comparing the jet fluctuations, under the condition of $y_{j,e} / h = 0$, the jet fluctuates inside and outside the edge, apart from the edge. Under the condition of $y_{j,e} / h = 0.37$, the jet fluctuates near the edge with a smaller amplitude. At $t / T_1 = 0$ of $y_{j,e} / h = 0.37$, near the center of mouth opening , the jet splits into two jets with strong positive and negative vorticity distributions. The lower jet travels straight toward the edge without fluctuating. This reduces the amplitude of jet as a whole, consisting of both sides of the split jet.

To study the relationship between the jet fluctuations and the radiated sound, the flow rate into the resonator at the edge distance ($x_j / l = 1$) was investigated. The flow rate into the resonator, V_{in} , was defined by the following equation:

$$V_{in}(t) \equiv \int_{-z_{j,w}}^{z_{j,w}} \int_{y_{j,low}}^{-y_{j,e}} u_j(t) \mathrm{d}y_j \mathrm{d}z_j. \qquad (4)$$

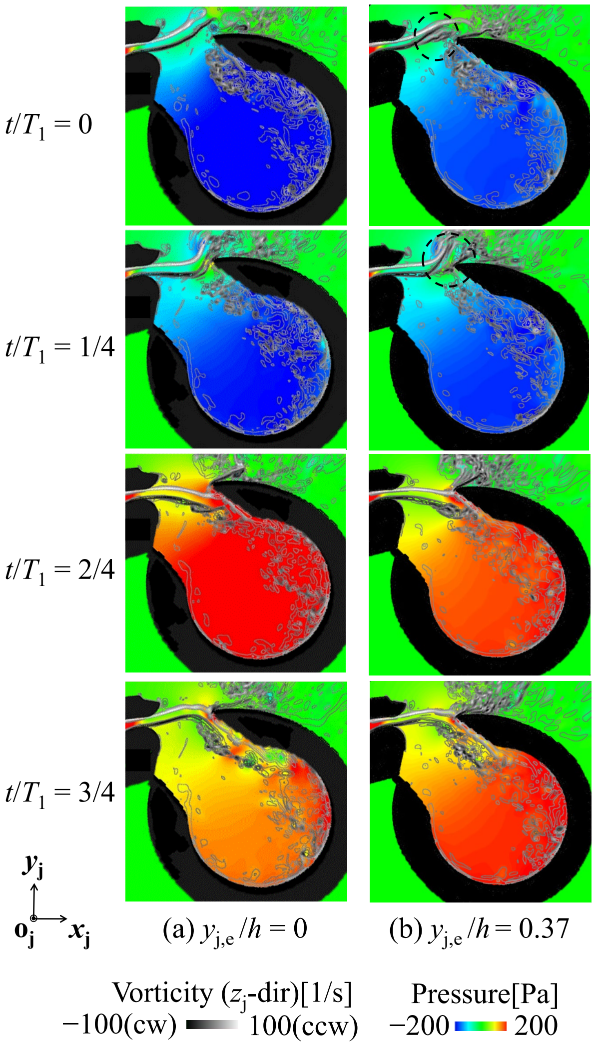

Figure 4. Temporal variation of flow field at the cross section of spanwise edge center ($z_j = 0$), where vorticity and pressure are respectively shown by grayscale and colored contours. The areas surrounded by a broken line show the areas where the jet splits into two jets.

Figure 5 shows the temporal variations of nondimensional flow rate into the resonator, where $V_{in,ave}$ and $V_{in,amp}$ are the time-averaged value and the amplitude of V_{in} respectively.

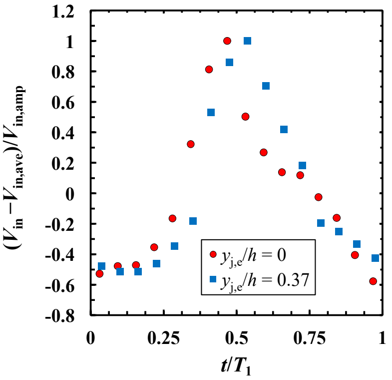

Figure 5. Temporal variations of nondimensional flow rate into the resonator, where $V_{in,ave}$ and $V_{in,amp}$ are the time-averaged value and the amplitude of V_{in} respectively.

The amplitude of flow rate ($V_{in,amp}$) at $y_{j,e} / h = 0$ was about 1.7 times larger than that at $y_{j,e} / h = 0.37$ because the amplitude of jet is larger at $y_{j,e} / h = 0$. As a result, the sound pressure level is larger at $y_{j,e} / h = 0$. The time around $t / T_1 = 0.5 - 1.0$ is the time when the jet is deflecting outside the edge, as shown in Fig. 4. Nevertheless, under the condition of $y_{j,e} / h = 0$, the change of V_{in} becomes temporarily constant around $t / T_1 = 0.7$. Under the condition of $y_{j,e} / h = 0.37$, V_{in} decreases without becoming constant. For $y_{j,e} / h = 0$, since the flow rate into the resonator is non-sinusoidal, the generation of harmonic seems to be promoted. The cause of non-sinusoidal variation of V_{in} is under investigation, considering the effects of the circulation flow of the jet, which flows again into the resonator with the jet.

5. CONCLUSION

The changes of flow and acoustic fields with the jet offset condition were investigated by performing direct aeroacoustic simulations. The acoustic fields showed that the sound pressure levels of the fundamental tone, the second and third harmonic were lower for the larger jet offset condition (the jet is ejected from a higher position). The flow fields showed that the jet split into two jets around the center of the mouth opening under the larger jet offset condition. One of the jets traveled straight to the edge without fluctuating. This reduces the jet amplitude as well as the acoustic radiation. This split of jet was not observed for the smaller jet offset condition. Although theoretical calculations assume symmetric fluctuation of jet, in blowing states, the behavior of jet was shown to change depending on the geometrical condition between the jet and the edge, affecting the acoustic radiation for both the fundamental tone and harmonics.

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