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Measurement of the Flow and Its Vibration in Japanese Traditional Bamboo Flute Using the Dynamic PIV

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Abstract : All wind instruments produce sound due to the vibration of air inside of the instrument. In the case of a trumpet or a clarinet, the mouth or a reed helps to generate variable tones. In the case of a flute, there is no mechanical vibration. Additional detail about the flow and the sound vibration inside and outside of the flute are investigated in order to understand the mechanism of the wind instrument and to aid in the manufacture of quality instruments. In this report, a traditional Japanese bamboo flute was investigated experimentally. The dynamic PIV technique was applied to measure the vibration. Two kinds of experiments were performed. Argon-gas flow containing an oil mist as tracer particles both inside and outside the bamboo flute was measured using a high frequency pulse laser. The periodical flow near a hole of the bamboo flute was successfully measured. The flow was found to go into and out from the flute and the balance of a mass flow rate and the averaged velocity were almost zero at the hole. Then, the flow in the bamboo flute was visualized when a human played the instrument, using a CW-laser and water-mist as the tracer. It was discovered that the two instructors had unique methods for playing the flue instrument.

Keywords : Visualization, dynamic PIV, vibration, sound.

1. Introduction

All wind instruments produce sound due to the vibration of air inside the instrument. The sound output of wind instruments is resulted from the acoustic oscillation of the resonant air column within the instrument.

This report experimentally investigates a traditional Japanese bamboo flute. The mouthpiece or reed of a trumpet or clarinet helps to generate variable tones. A clarinet consists of a closed cylindrical air column with a bell-shaped opening at the end whose mouthpiece contains a single reed. A flute, however, has no mechanical vibration generated by lips or a reed. Flue instruments, such as the recorder flute and the transverse flute, have different mouth geometries and acoustical responses. A simple recorder has a fixed flue-structure, but the transverse flute has only an embouchure. The Japanese bamboo flute has only five openings in the tube wall and is shaped in the form of an open cylindrical air column about 470 mm long.

In the flue instrument, sound is produced by the interaction of a jet with a sharp edge (called the labium) placed in the opening (mouth) of a resonator (body of the instrument). The jet is formed by flow separation at the end of a slit (the flue channel or lips), which then travels along the mouth of the resonator towards the labium. Coupling between jet oscillations in the mouth and acoustical resonances in the body provides self-sustained oscillations of the jet and maintains sound production.

Self-sustained oscillations of flue instruments involve a combination of very complicated hydrodynamic phenomena that occur in the embouchure of the instrument. In this tiny region, one can simultaneously observe a hydrodynamically unstable jet, vortex shedding, and turbulence, all of which interact with the acoustic field from the resonator. Modeling the operation of flue instruments is further complicated by their great variety of geometry and blowing conditions, which results in a wide diversity of timbres and tone qualities. The behavior of flue instruments appears, however, to be governed by common mechanisms.

Sound from a flute is produced by blowing onto a sharp edge, which causes air enclosed in a tube to vibrate. The embouchure at which the edgetone (Powell, 1961) is produced is near one end and constitutes a second open end, making the flute an open cylinder in harmonic content. As with other edgetone-instruments, the tone production is made more efficient by the coupling of the slit formed by the player's lips, the edge, and the air column.

One advantage of a flute over a recorder is that the player has direct control over the angle at which air from the lips strikes the embouchure hole. Rolling in or out with the lips relative to the edge gives the player a greater range of volume and expression, and aids in the process of "overblowing" needed to achieve the higher register. This direct access to the edge also permits the player to make small fine tuning adjustments.

An open hole produces a pressure node at a point where the fundamental mode produces a significant pressure variation, so that the lowest vibrational mode cannot be sustained. The higher notes of the flute are obtained by opening holes on the side of the instrument to shorten the air column, raising the fundamental frequency of the open air column. To achieve much higher notes, one forces the air column to sound its second harmonic, up an octave from the fundamental. This is achieved by "overblowing" the flute. The flute generates sound by the edgetone principle: directing air on an edge causes it to oscillate. Increasing the airstream velocity tends to make the pitch go up, and "rolling in" the player's lips toward the edge aids that tendency. By rolling in and simultaneously increasing the airstream velocity, the air column can be made to pop cleanly from its fundamental to its second harmonic, raising the pitch by an octave. The flute is overblown to its second or third harmonic by a combination of increasing the airstream velocity and "rolling in" to decrease the gap between the player's lips and the edge.

Blowing technique is a vital part of playing any wind instrument. For this reason, the study of physical parameters, such as blowing conditions, has not attracted as much attention even though studies were conducted as far back as 1970. Measurement techniques, however, have rapidly advanced in this decade, e.g., Leptuch, P. A. and Agrawal, A. K. (2006). The goal of this study is to obtain more detail about the flow and vibrations both inside and outside a bamboo flute, in order to fully understand the mechanism of the wind instrument and to aid in the manufacture of high quality instruments. It is the purpose of the present paper to report more extensive measurements of the flow vibrations and the blowing techniques for different flute players and to interpret these findings visually. The tests consisted of a series of steady notes played by two instructors while using stable gas flow from an argon gas bomb. Previous detailed measurements on flutes or other wind instruments studied the sounds from various points of view, but did not measure the velocity field as time-series data. In the present paper, the dynamic PIV technique was applied to measure the flow vibration with high time-resolution. These data are helpful in understanding the phenomena involved in sound production and in determining the critical parameters that should be considered when modeling this type of instrument. It also provides quantitative criteria to evaluate numerical simulation results.

2. Experiments and Discussion

2.1 Sounding Mechanisms of the Flue Instrument

Flue instruments produce sound as a result of the coupling between a hydrodynamically unstable flow and the resonant acoustic field in a pipe. The geometry of a typical flue instrument is shown in Fig. 1. The flow is generated by blowing through a narrow way called the flue (lips in case of the flute). At the flue exit, a free jet is formed by flow separation. This jet flows across the mouth or window of the instrument and is directed toward a sharp edge called the labium. At the flue exit, the jet is subjected to the transverse acoustic flow due to the oscillation in the pipe of the instrument. Because of its intrinsic instability, the jet is very sensitive to these perturbations. They propagate on the jet and are amplified as they travel toward the labium. This results in the flipping of the jet on each side of the labium at the same frequency as the acoustic field. This jet motion around the labium provides energy and helps maintain the acoustic field. This energy can accumulate in standing waves that correspond to the resonances of the pipe of the instrument, which favors oscillations at specific frequencies.

The functioning of flue instruments, therefore, is typically represented by a feedback loop where the jet-edge system, the nonlinear exciter, is coupled to the pipe of the instrument, which is represented as a linear acoustic resonator. In this representation, steady-state amplitude is reached by the saturation of the jet flow on each side of the labium when the amplitude of the jet oscillations at the labium becomes greater than the half-width of the jet. Early models of the functioning of flue instruments are based on variants of this representation. These models have contributed significantly to the understanding of the sound-producing mechanisms of flue instruments.

Verge et al. (1997a and 1997b) pointed out that early feedback models could not correctly predict the basic tone features of flue instruments, such as the steady-state amplitude and spectrum, because the details of the flow at the labium, which appear to be fundamental in the functioning of the instrument, were neglected. Verge et al. also pointed out that taking into account the effect of vortex shedding at the edge of the labium was very important when trying to determine the amplitude of flue instruments. Vortex shedding, therefore, also contributes to the tone of the instrument.

For sufficiently high jet velocities, the jet flow becomes turbulent and provides another sound source. Turbulence generates a broadband noise that corresponds to the whistling and windy sounds that are very typical of the timbre of flue instruments. The production of sound by turbulence is further enhanced in this type of instrument by the presence of the labium in the jet flow.

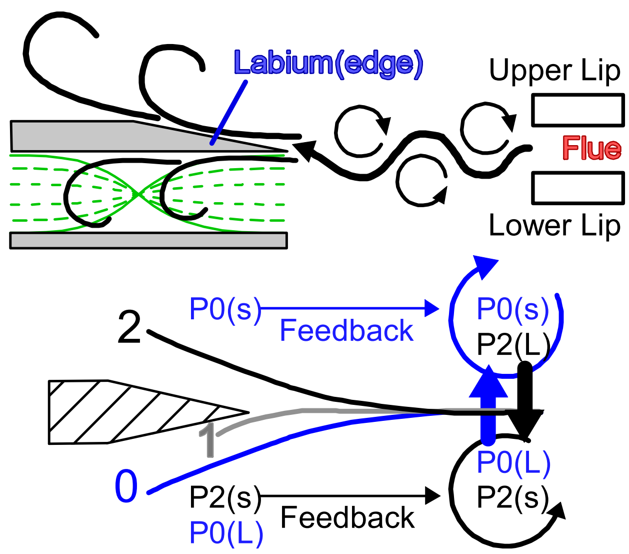

Fig. 1. The schematics of the mechanism of the edge-tone with a resonator.

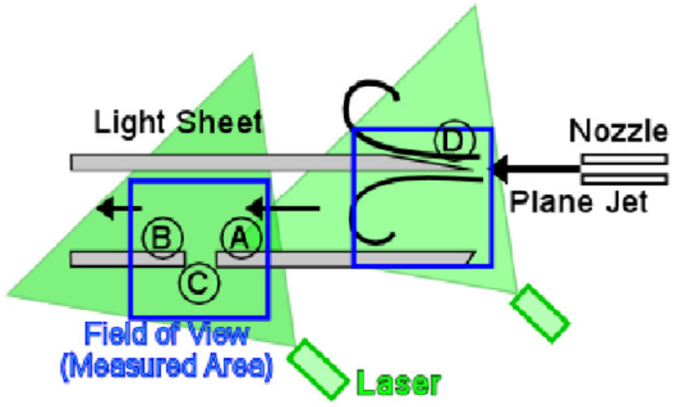

Fig. 2. The diagram of the experimental apparatus.

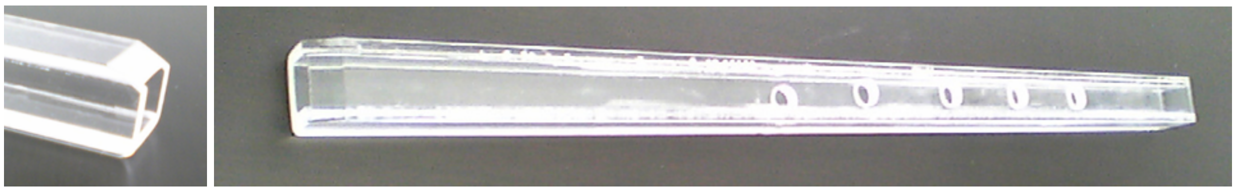

Fig. 3. Pictures of the rectangular model of a bamboo flute.

2.2 Experiments

Experiments were carried out using a laser light sheet and a high-speed camera (Fastcam APX-RS manufactured by Photron). The oscillating gas flow was measured near the first hole and near the labium, as shown in Fig. 2. The experimental apparatus consisted of a plane jet and a tube of acrylic resins having a square cross-sectional area of 15 mm x 15 mm and a 5 mm wall thickness, as shown in Figs. 2 and 3. The tube model of the bamboo flute has a sharp edge, labium, in the embouchure of the instrument. The Japanese bamboo flute has a series of only five openings. The first hole, nearest to the labium, is positioned approximately 195 mm from the labium. The distance from the first hole to the second hole is 30 mm. The other four openings are located along the opposite side at intervals of 55 mm. The flue channel was modeled by a rubber hose with a slit in the aperture measuring 1 mm high and 10 mm wide.

The gas flow and its vibration were measured two-dimensionally by the PIV method. The frequency of the sound vibration was ~600 Hz. Therefore, the dynamic PIV technique was employed. During the experiments, 5000 images, each having a 512 x 512 spatial resolution and 8 bits per pixel of gray scale resolution, were captured. The field of view was around 35 mm x 35 mm. The Argon-gas flow with sound inside and outside of the bamboo flute was measured at 5000 Hz using a high frequency pulse laser (~6 mJ/pulse). An oil mist emitted by a Ruskin-nozzle was mixed into the gas-flow as tracer particles. The average diameter of the tracer particles was estimated to be 5 μm or less. The velocity field was calculated using recursive-type PIV analysis. The initial interrogation window size was 64 x 64 pixels, and the correct vectors were searched recursively with a smaller interrogation window.

In addition, attempts were made to measure the flow while an individual was playing the bamboo flute using a CW-laser and water-mist as the tracers. The output energy of the CW-laser was relatively small. The visualized images, measuring 1024 x 1024 pixels, were captured at a slower frame rate of 3000 fps. Two different instructors played the bamboo flute while wearing safety goggles for 532 nm of green light. A water mist formed by a supersonic-type humidifier was blown into the player's face while a laser light sheet illuminated the mist flow near the lips. This allowed the separated flow outside of the bamboo flute, just downstream of labium, to be visualized.

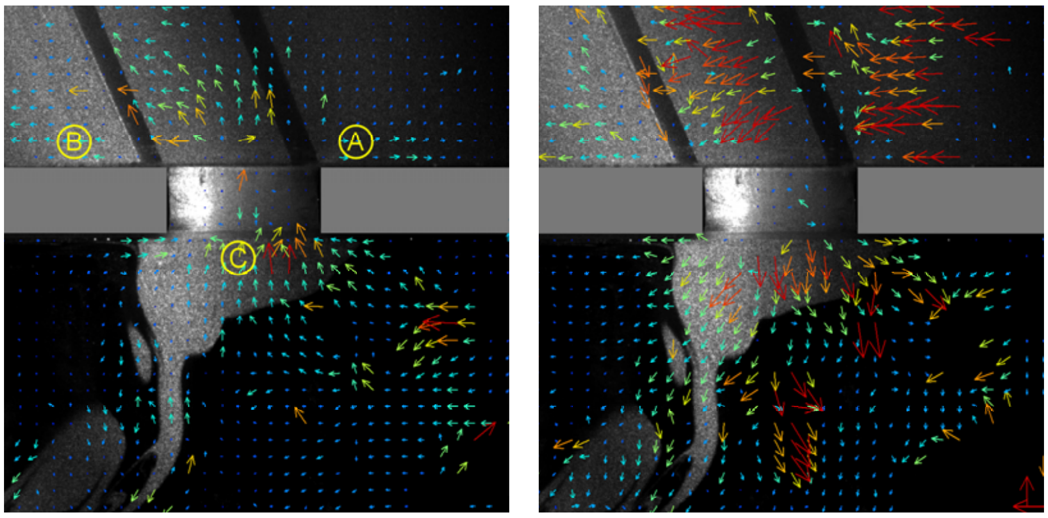

Fig. 4. Visualized pictures overlaid with measured velocity map at t[msec] = 5(left) and at t = 5.8(right).

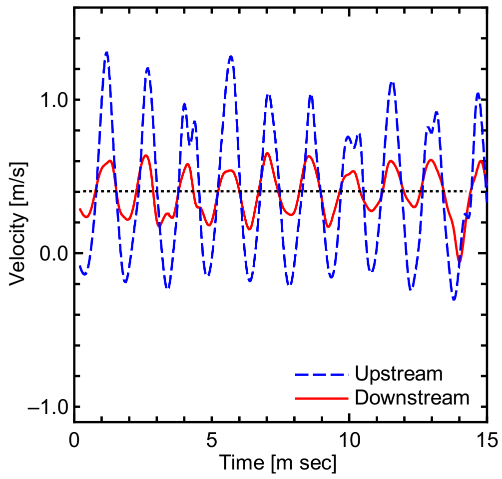

Fig. 5. The time series data of the horizontal velocity at A (upstream) and at B (downstream).

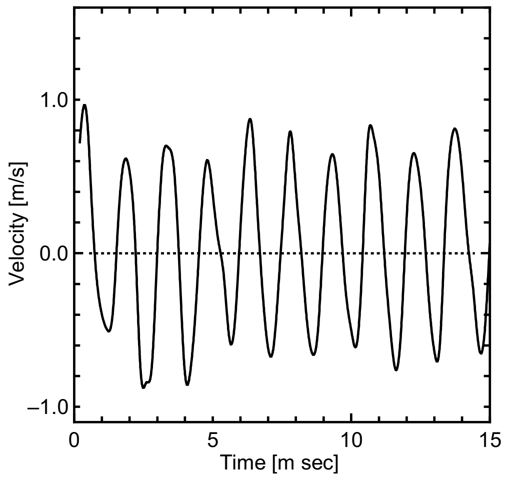

Fig. 6. The time series data of the vertical velocity at C.

2.3 Results and Discussion

Figure 4 shows the visualized images and the calculated velocity fields near the first opening hole. The diameter of the hole was 10 mm and the thickness of the wall was 5 mm. The top of the figures shows the inside of the instrument, as depicted in Fig. 2. Point A was upstream and the black lines on the upper side of the figures were shadows generated by the curved opaque wall of the opening hole. The figure on the right side was captured just 0.8 msec after the left image was recorded, and the images were captured at intervals of 0.2 msec. The vertical component of the velocity at point C was highest at the moment when the left figure was captured, and it was the lowest for the right image. The leftward velocity at point A was also the highest in the right image. The horizontal velocity at point A in the left figure became a negative value.

The time series data of these velocities at points A, B and C are shown in Figs. 5 and 6. The blue broken line in Fig. 5 depicts the velocity at A and the red solid line depicts the velocity at B. The dotted black line represents the average value, about 0.4 m/s. The average value was almost same at points A and B. The amplitude of the velocity fluctuation was about 0.6 m/s at point A and about 0.2 m/s at point B, and there was no phase difference in the oscillations at points A and B. This result indicates that only the amplitude of oscillation was damped at the opening hole. Figure 6 shows the vertical velocity at point C, with an amplitude of about 0.6 ~ 0.8 m/s. The black dotted line represents the average value of 0.0 m/s, resulting from the fact that only the amplitude of oscillation was damped at the hole. The balance of a mass flow rate and the averaged velocity were almost zero in a period at point C.

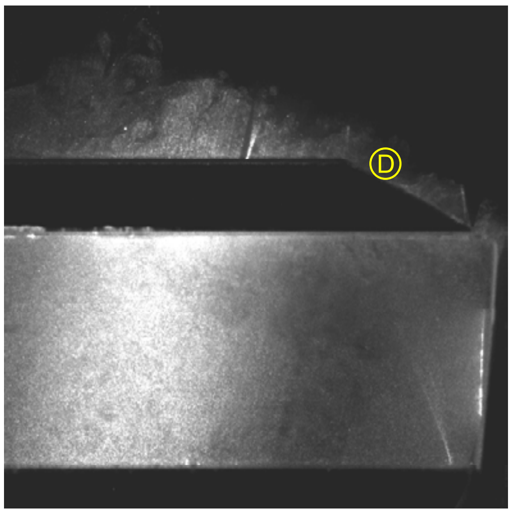

Fig. 7. A visualized image near the edge of the bamboo flute.

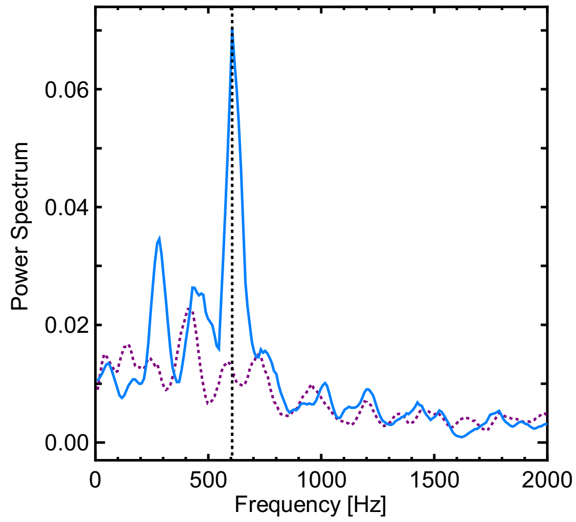

Fig. 8. Results of the FFT-analysis of the measured velocity at D. Blue colored spectrum was calculated from the vertical component of velocity. Another dotted line was from the horizontal one.

Figure 7 displays a visualized image of the argon gas flow around the labium. Figure 8 shows the results of the FFT-analysis on the measured velocity at D. In this figure, the blue spectrum was calculated from the vertical component of the velocity and the dotted curve was calculated from the horizontal component. In these experiments, the model instrument and the labium were rectangular. The gas flow oscillated perpendicularly around the two-dimensional structure, so only the vertical velocity had a dominated frequency, about 600 Hz, which corresponded with those implied in Figs. 5 and 6. The sound frequency of 600 Hz is the musical scale of overblowed high "re" (in Do-Re-Mi).

As mentioned above, attempts were made to measure the flow while an individual was playing the bamboo flute. Figures 9 and 10 show the visualized images captured for the flow of breath experiment. From these images, it was discovered that the two instructors had unique methods for playing the flue instrument.

The breath flow itself did not include any mist from the supersonic-type humidifier, so the breath flow was identified as dark path from the lips. The breath flow entered the flue instrument in Fig. 9, only sometime the breath flowed outside of the flute. The breath flowed outside of the instrument in case of Fig. 10, while the breath flow flickered inside only in a moment. It was found that the oscillations produced by the human players were not exactly sinusoidal. For example, in case of the instructor A in Fig. 9, the breath periodically flowed outside for an instant. Figure 11 shows a visualized image overlaid with the measured velocity distribution, which corresponds to the Fig. 9, the instructor A. At this time, the player produced a low note "so(G, 396 Hz)" by closing a hole. Figure 11 shows the result of the FFT-analysis of the measured velocity at E. The peak value was found to be at a frequency of about 400 Hz, but it was not more strongly dominant when compared with that in Fig. 8. The non-sinusoidal oscillation and turbulent flow near the labium could also affect the result, which is the small peak in Fig. 12. Further investigations using the acrylic model are needed, however, because many interesting results were obtained by this rudimentary study.

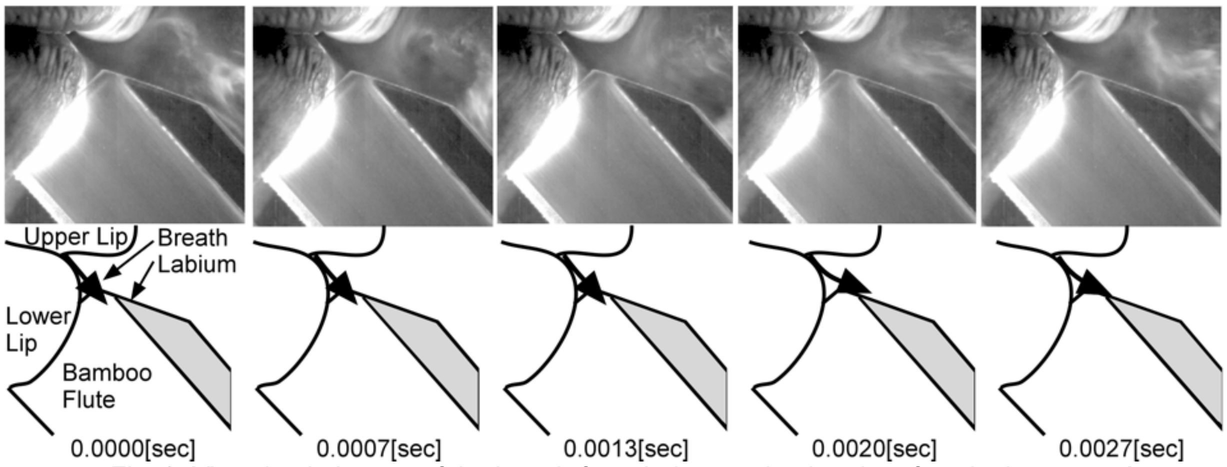

Fig. 9. Visualized pictures of the breath-flow during playing bamboo flute by instructor A.

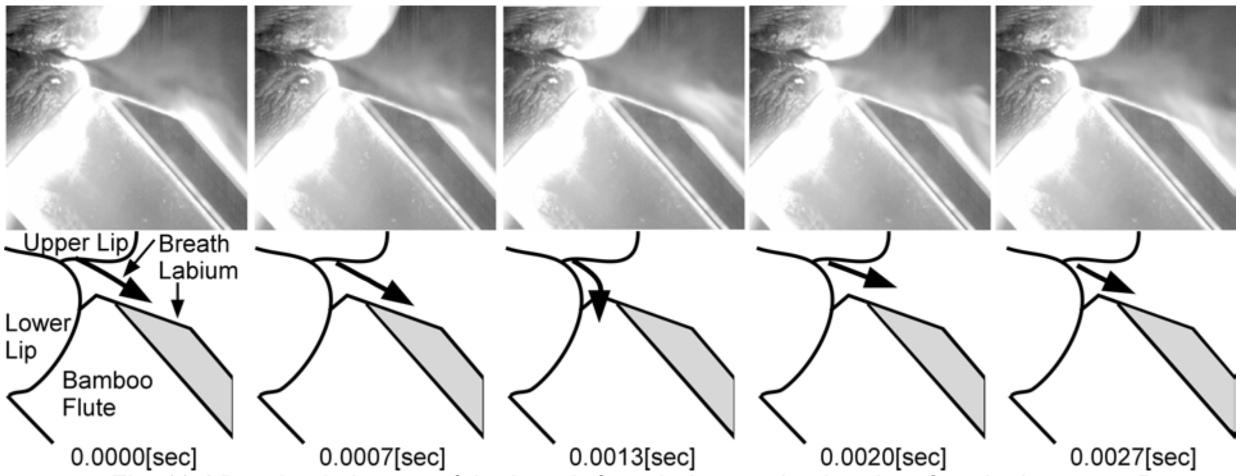

Fig. 10. Visualized pictures of the breath-flow during playing bamboo flute by instructor B.

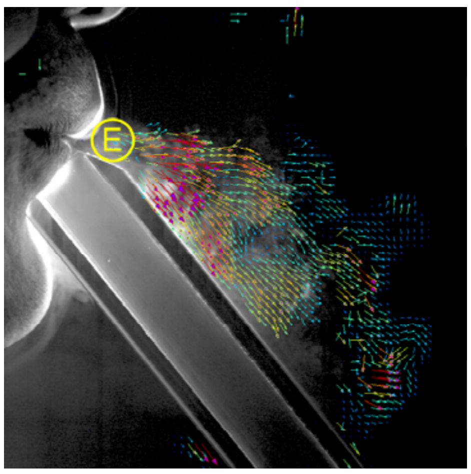

Fig. 11. The visualized picture overlaid with measured velocity map.

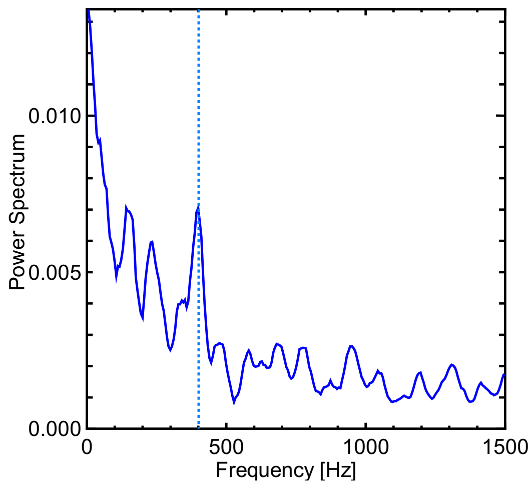

Fig. 12. The result of FFT-analysis of the vertical component of the velocity.

3. Conclusion

In this paper, the oscillating flows inside and outside a Japanese bamboo flute were successfully visualized. The jet of argon gas was introduced into a transparent acrylic model and was measured near the labium and near the first hole. It was clarified that the average velocity of the gas flow inside of the flue instrument was constant, but the amplitude of the oscillating flow was remarkably damped at the opening hole that produced an antinode. The flow around the first hole periodically went out and came into the bamboo flute, making the average velocity at the hole almost zero, i.e., no gas was dispersed at the hole.

The air flow during flute playing was also visualized. This allowed for the visualization of the unique methods used by each instructor to play the bamboo flute.

This study successfully visualized the air oscillation, i.e., the sound of the bamboo flute. These data can help to clarify the mechanisms of the wind instrument and to aid in the manufacture of high quality instruments. In other words, they are helpful the understanding of important phenomena involved in sound production and in determining the critical parameters that should be considered when modeling this type of instrument. This study also provides quantitative criteria to evaluate numerical simulation results.

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