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Interferometric measurement of aerodynamic sound generated by parallel plates inside flow field

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ABSTRACT

Optical measurement of sound play an important role to understand the physical natures and spatial distributions of sound. The optical measurement of sound is especially useful under the conditions where microphones cannot be installed such as inside high-temperature fields, narrow spaces, and flow fields. Flow-induced sound generated by parallel plates is one of such situations. The measurement of the sound by microphones is difficult because the spaces between plates are narrow and the objective sound is inside flow fields. While previous research investigates the pressure field including sound fields between flat plates by computer simulations, experimental measurement have not been well investigated. In this paper, we performed the measurement of the aerodynamic sound generated by flat plates inside a flow field by parallel phase-shifting interferometry in order to experimentally capture the sound field including spaces between flat plates. The result shows that the phases of sound between plates were opposite, which is consistent with the simulation in prior research.

Keywords: Measurement of aerodynamic sound, Flat plates, Optical measurement
I-INCE Classification of Subject Number: 72

1. INTRODUCTION

Aerodynamic sound generated from flat plates is an important phenomenon for noise engineering, because the sound is a cause of noises generated from front grilles of automobiles and building louvers. Pressure fluctuations caused by vortices generated from flat plates in a flow field resonate with flat plates and emit a large sound pressure. Therefore, understanding the mechanisms of generation of the sound is required in order to reduce the resonated sound.

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Research have been conducted by computer simulations and experiments of fluid flow around circular and square cylinders [1, 2]. The research indicated that vortex sheddings from both circular and square cylinders were affected by the distance between cylinders. Other researchers have considered resonance effects for generation of sound and vortex shedding [3, 4]. The research indicates that the sound pressure generated from flat plates became loud at a specific velocity of flow [3]. The cause of this was suggested in [4] by a computer simulation that the synchronization of vortex sheddings from adjacent plates affects the generation of large sound pressure. Although many researchers have focused on the flow field around the flat plates, research focusing on the sound field has not well-discussed especially in experiments. We think that investigating the sound field around flat plates experimentally is also important for reducing the noise.

In order to investigate the sound filed, microphones and microphone arrays are usually used. However, the method using microphones has difficulty in measuring near sound sources and inside narrow spaces such as between flat plates. On the other hand, optical measurement of sound [5–9], which we are concentrating on, can capture sound fields near the sound sources and inside narrow spaces because it measures sound fields without installing any devices inside measurement sections. Some optical measurement methods have been investigated, such as Schlieren method [5], laser Doppler Vibrometer (LDV) method [6–8], and parallel phase-shifting interferometry (PPSI) [9]. Especially, the PPSI has good aspects of both the Schlieren method and the LDV method, which are two-dimensional and quantitative measurement, respectively. In our studies, we conducted capturing near the source of the aerodynamic sound [10–12] and inside narrow transparent cavity [13] using PPSI. Therefore, the PPSI would be effective for capturing the aerodynamic sound generated from flat plates.

In this paper, we performed measurement of aerodynamic sound generated from parallel flat plates using PPSI. Three flat plates, whose size was 50 mm in a flow direction and 2 mm in a vertical direction to the flow, were used for the experiment. The acoustic resonance and radiated sound fields including spaces between flat plates were captured.

2. METHODS

2.1 Optical measurement of sound

The principle of the optical measurement of sound utilizes the nature of phase of light modulated by a refractive index of a medium. The relation between them can be described as

$$\phi(\boldsymbol{r}, t) = k \int_L n(\boldsymbol{l}, t)\, \mathrm{d}\boldsymbol{l}, \tag{1}$$

where ϕ is the phase of light, $\boldsymbol{r}$ is the position vector, t is the time, k is the wave number of light, L is the optical path, and n is the refractive index of the medium. As the refractive index of air is related to the sound pressure:

$$n(\boldsymbol{r}, t) = n_0 + \frac{n_0 - 1}{\gamma p_0} p(\boldsymbol{r}, t), \tag{2}$$

where p_0 is the atmospheric pressure, n_0 is its refractive index, γ is the specific heat ratio of the air, and p is the sound pressure. Equations (1) and (2) indicate that the sound pressure can be captured by measuring the phase of light.

2.2 Parallel phase-shifting interferometry (PPSI)

PPSI can capture the phase of light instantaneously and quantitatively. The schematic diagram of the PPSI system used in our study is shown in Figure 1. The light emitted from the laser is divided into reference and object light. While the reference light is reflected by the optical flat in front of the test section, the object light passes through the test section with the phase modulated by the sound pressure. The object light including the information of sound is combined with the reference light, which produces interference fringes. The interference fringes are captured by the high-speed polarization camera [14] as the intensity of light.

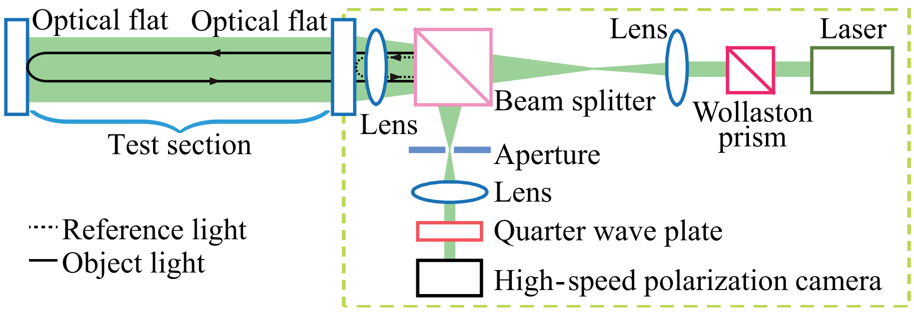

Figure 1: Schematic diagram of the PPSI system used in our experiment.

3. EXPERIMENT

3.1 Experimental setup

We conducted an experiment to visualize both the radiation and resonance sound from flat plates inside a flow field. The experimental setup is shown in Figure 2. Three aluminum plates, whose size was 50 mm length in a flow direction and 2 mm height in a vertical direction to flow, were used. These flat plates were installed at intervals of 10 mm. In order to visualize the sound field between plates, acrylic boards were used for fixing the flat plates. The size of the nozzle outlet was 30 mm height in a vertical direction to flow and 100 mm width in a spanwise direction. The mean velocity of flow emitted from this nozzle was 26 m/s in a center position of the outlet. A microphone was set 100 mm above from the top of the plate as a reference measurement. The distance from the nozzle and the flat plates was 10 mm, where the sound pressure was large enough to be captured by PPSI. The frame rate of the high-speed camera was set to 20000 frames per second and the measuring size was in a circle with a diameter of 50 mm.

3.2 Result and discussion

The frequency spectrum of measured sound captured by a microphone is shown in Figure 3. The peak frequency was 2910 Hz and the sound pressure level was 90.8 dB.

The visualized images captured by PPSI were shown in Figure 4. These images were obtained using an accurate phase retrieval method [15] and time-directional band-pass filtering for wrapped phase [16] from raw data. The time interval of these images was 0.05 ms from upper-left to lower-right. The color of these images indicates the phase of light which corresponds to the sound pressure. Both radiated sound and the sound field inside flat plates can be visualized by PPSI. The timing of the radiation from the upstream

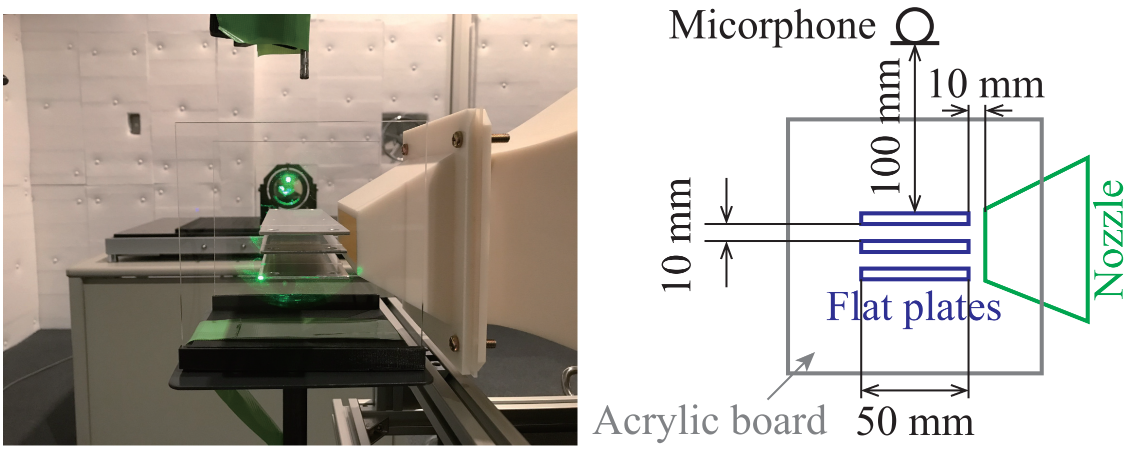

Figure 2: Experimental setup of flat plates.

side and the downstream side was different. Modes that are not in-phase within the same flat plates were observed such as $t = 0.1$ ms, $t = 0.25$ ms, and $t = 0.45$ ms. This feature has also been observed by a computer simulation in previous research [4].

The amplitude and phase image at 2910 Hz were shown in Figure 5. The left image was the amplitude and the right image was the phase. According to the amplitude image, the amplitude of the center of the flat plates was large and damped to the same extent on the upstream and downstream. This result indicates that the sound field inside flat plates would not be influenced by the flow. According to the phase image, the phase between the top and middle plates was 0 radian, whereas the phase between the middle and bottom plates was π radian. This result suggests that the sound between the top and middle plates was in opposite phase to the sound between middle and bottom plates.

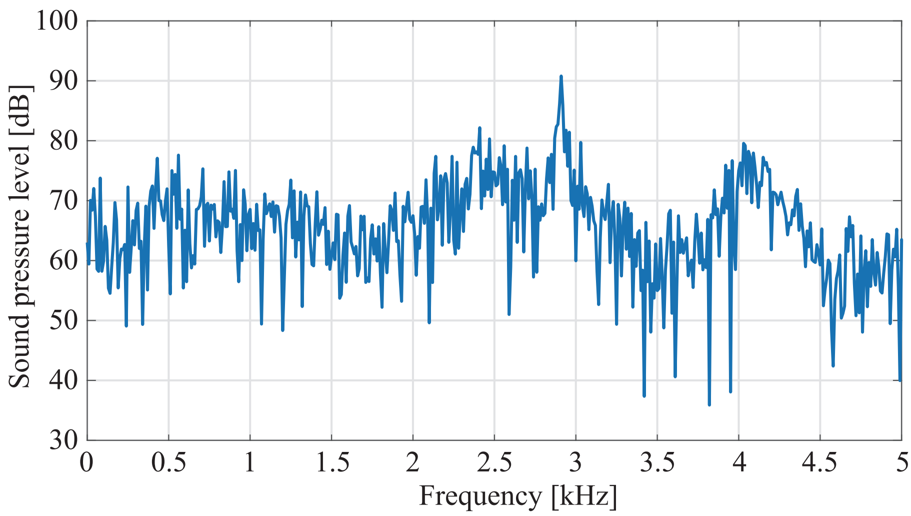

Figure 3: Frequency spectrum captured by a microphone.

4. CONCLUSIONS

In order to visualize sound fields around flat plates installed in flow fields, we performed the visualizing measurement using PPSI. The result shows that PPSI can experimentally capture both radiated sound and the sound field inside flat plates. In addition, the

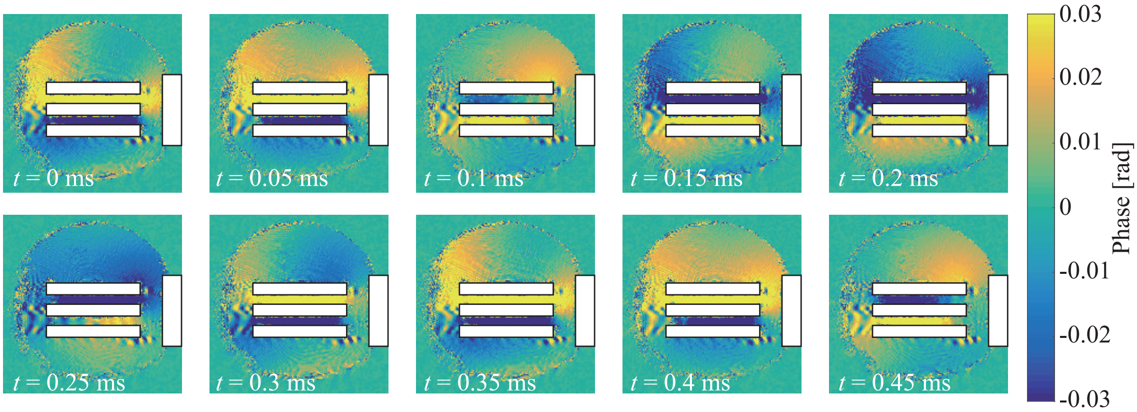

Figure 4: Visualized images captured by PPSI.

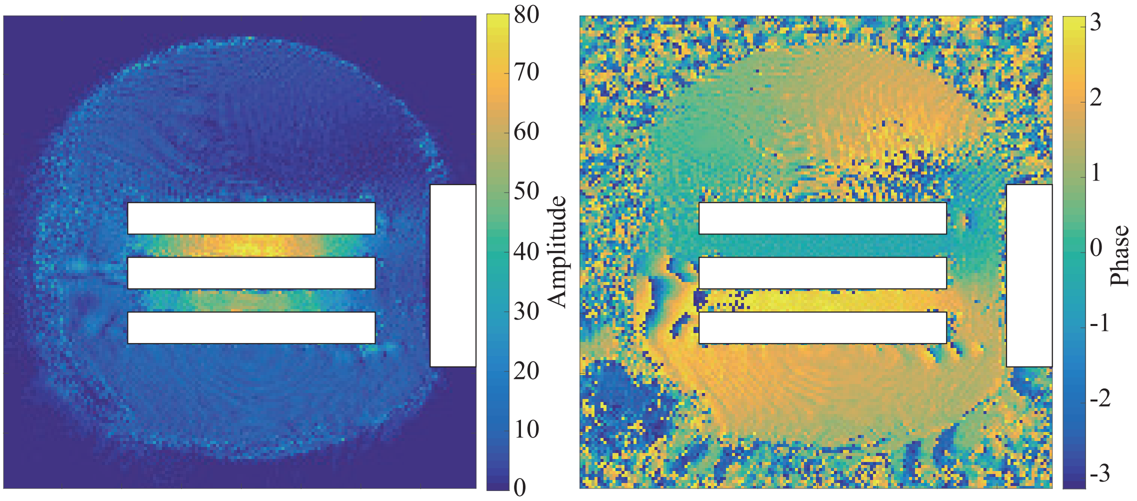

Figure 5: Amplitude and phase of visualized sound field.

features of the observed sound correspond to computer simulations of previous research. Future work includes measuring various aerodynamic sound using PPSI and analyzing visualized data in detail.

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