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NOISE CONTROL FOR QUALITY OF LIFE

Control of Noise from a Cascade of Flat Plates by using DBD Plasma Actuators

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ABSTRACT

The aim of this investigation is to clarify the effectiveness of aerodynamic noise control with a dielectric barrier discharge (DBD) plasma actuator (PA) over the cascade of flat plates. The sound and velocity fields of a flow around a cascade of flat plates were measured with a low noise wind tunnel. The experiments were carried out at the flow velocity from 5 m/s to 20 m/s, with the chord length of 120 mm, the thickness of 2 mm and the distance between plates of 48 mm. The flow around a cascade of flat plates often makes acoustic radiation with resonance at specific freestream velocity. In this case, the most intense tonal noise was observed at the flow velocity of 13.8 m/s. To control this tonal noise, PAs were utilized. The PAs were mounted on both sides near the leading-edge of the vertically central flat plate. At the velocity of 13.5m/s, the maximum reduction of the tonal noise, 10.8 dB was achieved. The tonal noise was reduced by using PAs. The noise reduction level depended on the applied voltage of PAs. Moreover, the frequency of vortex shedding, which causes the acoustic radiation becomes lower when the PAs were driven. As a result, The acoustic resonance was weakened. It indicated that the PAs are useful devices to control of aerodynamic noise.

Keywords: Aeroacoustics, Noise control, Cascade of flat plates

1. INTRODUCTION

Recently, there has been increasing technological trend for comfortable and silent means of transportation. Countermeasures of noise from tires and engines such as automobiles are successful in recent development. Due to the property of aerodynamical noise levels which increases are proportionally to the sixth power of the speed of vehicles, the measures of aerodynamic noise reduction is much difficult in comparison of to the countermeasures of engine and tire noise. Therefore, in order to reduce the noise from automobiles, the measures of the aerodynamic noise reduction is one of the key technologies and it is necessary to develop the comfortable automobiles. Usually, aerodynamic noise reductions are performed by changing body shape or the configurations of parts to change the flow field, especially regarding flow separation and re-attachment. However, there are limits to this method, such as the difficulty of modification from the point of view of commercial values and the regulations of law.

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In the aerodynamical noise, there are cases that aerodynamic noise level is not proportional to the sixth power of the speed. It corresponds to the sound of a cascade of flat plates which we treated in this study, and cavity flows etc. Intense tonal noise radiates at a specific flow velocity. Parker [1] investigated the flow around a cascade of flat plates, and measured the sound pressure level for that. And he clarified that the sound pressure level becomes intense at a specific velocity and that phenomenon is due to the coupling between the vortex shedding in the wakes and the acoustic resonance between plates.

In the field of aircraft technology, active and passive devices are utilized to control the flow separation. For example, vortex generators, suction and blow off controls and so on are performed.

The control using plasma actuators is notable one of the brand new flow control techniques. Figure 1 shows cross-section of conventional PA. It consists of two electrodes made of copper sheets (typical thickness, t = 70 μm) and dielectric layer made of polyimide (t = 80 μm, relative permittivity, $\varepsilon' \approx 3$). Upper electrodes and lower one were arrayed to tuck the dielectric layer in between. By the application of high voltage to the electrodes, air around the electrodes is ionized and generates a strong electric field. As a result, a body force of air is induced around the electrodes. This is the principle of plasma actuators.

The benefits of plasma actuator are the simplicity of constructions, placements, easy-to-output control and wide frequency range of control signal. Jukes [2] investigated the active control of flow separation around a NACA0024 airfoil with PAs. It was shown that PAs could control the flow separation in a high angle of attack. For the aerodynamical noise related to the flow separation, to utilize the separation control techniques using plasma actuator is promising for reducing the aerodynamic noise.

The objective of this investigation is to clarify the possibilities and effects of PA as an actuator of noise control. To do this, we measured the aerodynamical noise from a cascade of flat plates such as front grille of automobiles with and without the PA. The experimental results showed the tonal noise can be reduced with PA. It indicated that the PAs are useful devices to control of aerodynamic noise.

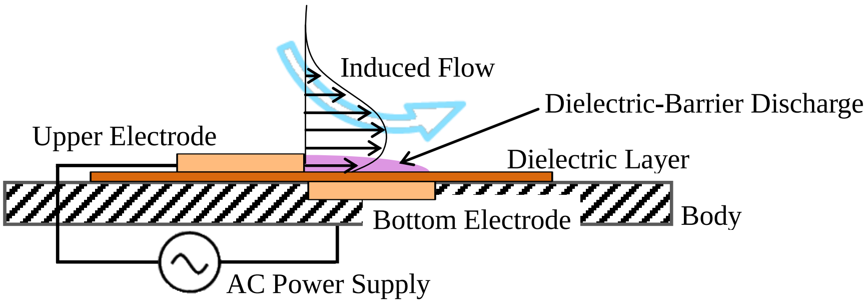


Figure 1 – Schematics of conventional DBD plasma actuator

2. EXPERIMENTAL APPARATUSES

2.1 Experimental Method

Aerodynamic noises from the flat plate cascade were measured by using a low noise wind tunnel that has an open test section with a square section of 300 by 300 mm as shown in Figure 2. The test section of the wind tunnel was placed at an anechoic chamber. The background noise level of this anechoic chamber is less than 30 dB without a freestream and the reverberation time is 0.03 s.

This wind tunnel has an intensity of turbulence of less than 1.0 % and non-uniformity of the mean flow velocity distribution of 1.0 % or less, and the noise of the wind tunnel is less than 65.2 dB at the flow velocity of 30 m/s. The maximum velocity of a freestream in the test section is 30 m/s.

The far field sound pressures were measured at 430 mm from the center of the cascade of flat plates with a non-directional 1/2 inch microphone.

To clarify the effects of the PAs on the flow fields, the flow visualization was performed. For the visualizations of flow around the cascade of flat plates were conducted with a smoke wire method.

The experiments were carried out for the flat plate cascade (the number of flat plates, N = 3) installed as a model of the front grille of automobile as shown in Figure 2. The distance from the nozzle exit to the leading-edge of the flat plate is 260 mm and the height of the center plate is 150 mm from the lower wall of the test section. The x, y, and z axes were set in the flow, normal, and span-wise directions, respectively. The origin of coordinate system is located on the mid span of the trailing edge of the center plate as shown in Figure 2. The uniform flow velocities, U_0, were set from 10 m/s to 20 m/s under these conditions.

The Reynolds number based on the thickness of plates and the freestream velocity of 13.8 m/s for the most intense resonance is 1.8×10^3, and the freestream Mach number is $M = U_0/a_0 = 0.04$, where, a_0 denotes the speed of sound.

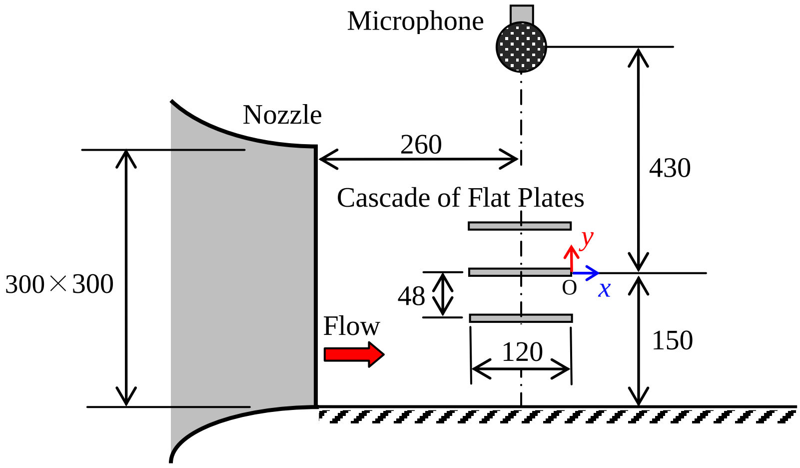


Figure 2 – Schematics of experimental apparatus (unit: mm)

2.2 Plasma Actuator

The basic configuration of PA was shown in Figure 1. The typical thickness of PA for flow separation control is less than 0.5 mm, it is not thicker in comparison with the momentum thickness of non-separated flow. In most cases, PAs are installed in the vicinity of the separation point. In these cases, the boundary layers are very thin.

In the case of the study of aerodynamic noise, the effects of the PAs without actuation are particularly significant problems. For example, for the tonal noise levels of the cascade of flat plates, the levels changes about 10 dB when the PAs are mounted without actuation. It cannot be ignored.

To avoid the influence of PA itself on the flow and noise, Asai and Inasawa [3] developed the flush-mounted PA as shown in Figure 3. In general, it is said that ionization of air cannot occur when the electrodes are flush-mountes on the body and then it cannot induce the body force. However, body forces can be able to be induced by shifting the position of the electrodes as shown in Figure 4.

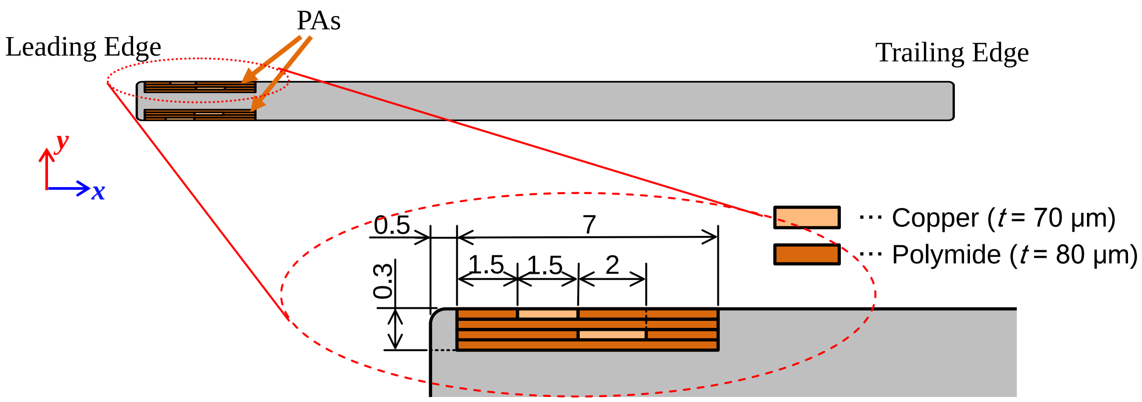
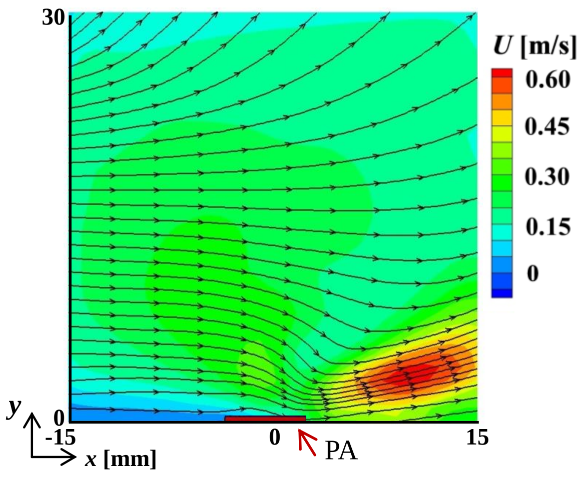
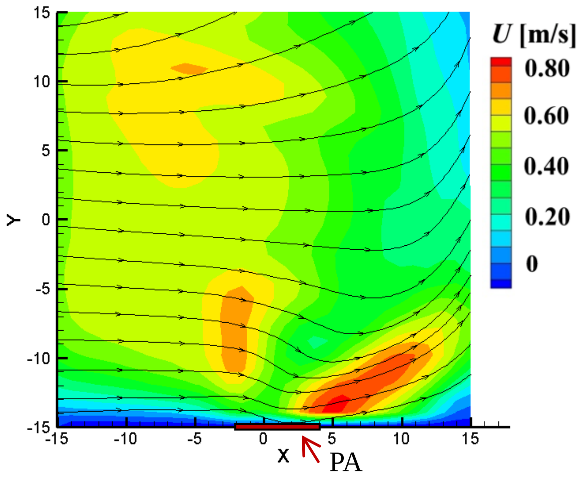


Figure 3 – Schematics of the flush-mounted DBD Plasma Actuators on a flat plate (x-y plane) [unit: mm]



(a) Conventional PA



(b) Flush-mounted PA

Figure 4 – Mean velocity profile of PAs in quiescent air by PIV measurements (E = 2.0 kV, f = 4.0 kHz)

Velocity profile of conventional PA and flush-mounted PA in quiescent air were measured by the Particle Image Velocimetry (PIV). The results were shown in Figure 4. The both applied voltage is 2.0 kV, and the control frequency is 4.0 kHz. In the flush-mounted PA, the body force was induced inside of upper electrode as with conventional PA. Conventional PA has induced maximum flow of 0.6 m/s, while the flush-mounted PA induced that of 0.7 m/s. The jet directions were almost same.

2.3 Cascade of Flat Plates

In this investigation, we attempted to control noise from cascade of flat plates which is model as a front grille of automobiles as show in Figure 5. When these objects installed at high speed flows, sometimes intense tonal noise radiates caused by interaction between the acoustic field and the flow field. The frequency of this tonal noise is narrow-bandwidth and that might cause a discomfort for many people. It is therefore required to develop the reduction and control method of this noise in industrial field.

Table 1 shows parameters of cascade of flat plates in the present experiment. The plate thickness, b, is 2 mm, the chord length, C, is 120 mm, and the span-wise length, Z, is 300 mm. the separation-thickness ratio, s/b, is 24.0 for the cascade of flat plates. Preliminary experiments have confirmed that acoustic resonance occur in a half-wavelength mode along chord length when the vortices shedding frequency is almost the same as the resonance frequency of the flat plate. The resonance frequency can be predicted as follows;

$$f_{\text{res}} = 0.5\left(\frac{a_0}{C}\right) \Bigg/ \left(1+\alpha\left(\frac{s}{C}\right)^{\beta}\right), \alpha = 0.7, \beta = 0.84, \tag{1}$$

Where, the coefficients, α and β denote the empirical constants. In our experimental condition, the fundamental frequency, f_{res}, is estimated 1070 Hz and that of measurement is 1160 Hz at the flow velocity of U_0 = 13.8 m/s. This formula predicts resonance frequency on the basis of chord length plus amount of open-end correction, the coefficients, α and β were tuned for many conditions of cascade of flat plates. In this case, the difference between predicted value and experimental value were caused by small difference of open-end correction.

Table 1 – Parameters of cascade of flat plates

Number of plates	Thickness [m]	Chord length [m]	Separate distance [m]
$N = 3$	$b = 2\times10^{-3}$	$C = 120\times10^{-3}$	$s = 48\times10^{-3}$

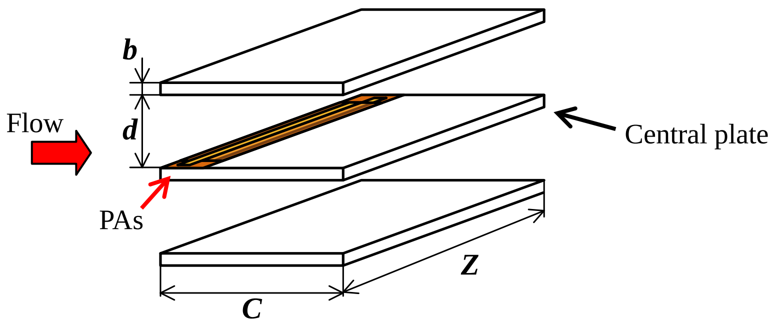


Figure 5 – Schematics of cascade of flat plates with DBD flush-mounted PAs

The PAs were mounted on the both sides of vicinity of leading edge of the plate for the central position. This structure has the presence of salient upper electrode on the surface. Here, in order to make flush surface, PAs were dug into the plate and polyimide sheet was fell around upper electrodes as shown in Figure 3. The inner edges of upper electrodes were located 3.5 mm off the leading edge of the plate surfaces and this location corresponds to the chord position of x/C = 0.03. The amplitude of applied voltage for PAs was changed from E = 2.4 kV$_{p-p}$ to 3.8 kV$_{p-p}$, and control frequency was set to be constant at f = 4 kHz.

3. RESULTS AND DISCUSSION

3.1 Aerodynamic Noise around the Cascade of Flat Plates

Figure 7 shows the peak level of tonal noise from cascade of flat plates. Here, peak SPL means the sound pressure level of tonal noise with acoustic resonance in a half-length mode. The open-circle symbol indicates the peak noise level without a PA. The maximum noise level of 77.1 dB becomes intense was observed at U_0 = 13.8 m/s. In a similar way, the noise level rises around U_0 = 17 m/s. This is smaller than the level at U_0 = 13.8 m/s, and therefore our objective was set for noise around U_0 = 13.8 m/s.

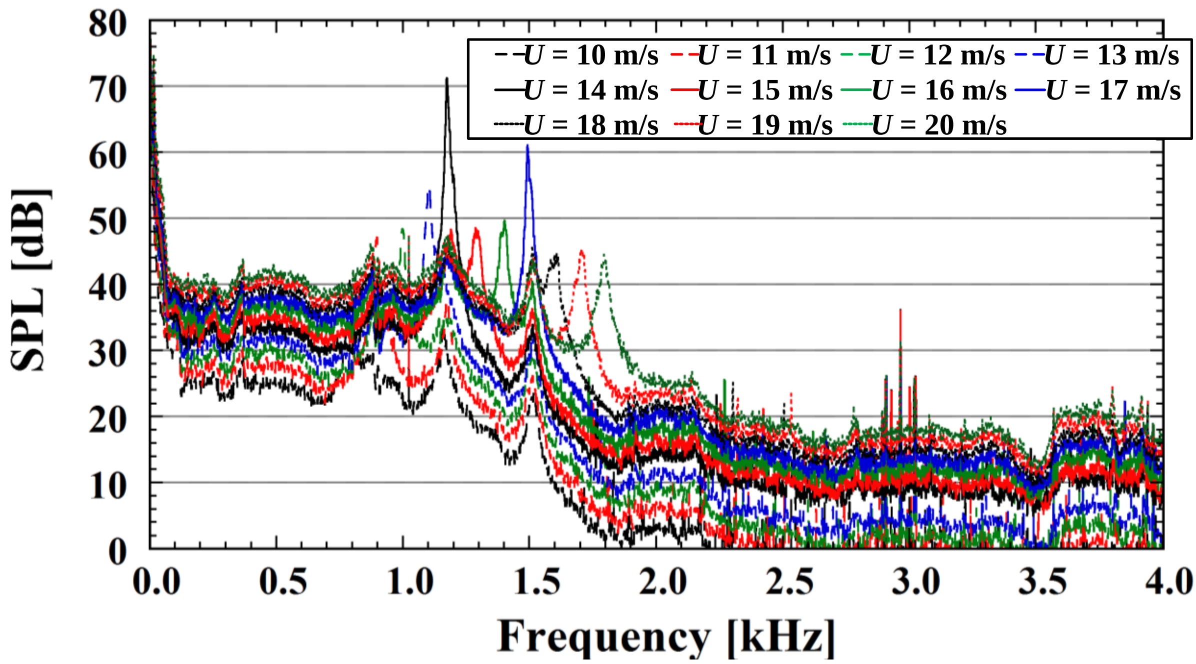


Figure 6 – Spectra of aerodynamic noise radiating from a cascade of flat plates with PA (E = 0 kV), Δf = 1.221 Hz, Averaging number: 72

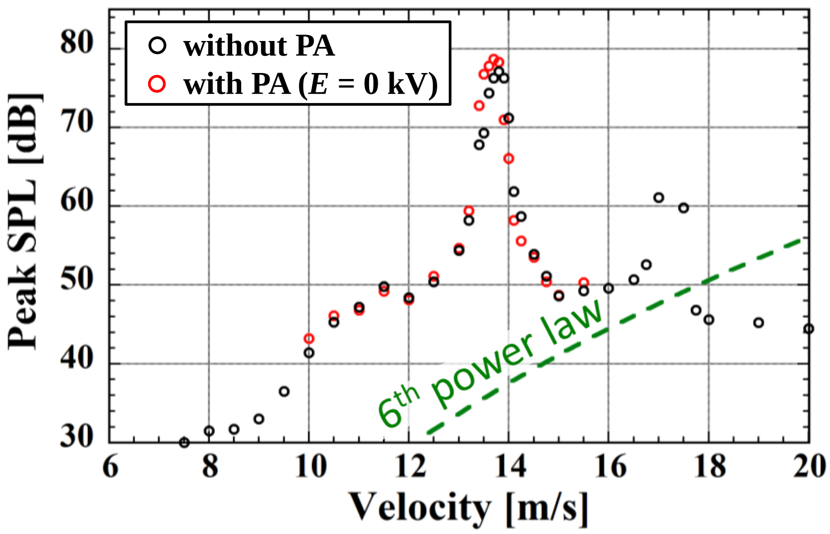


Figure 7 – Comparison of velocity dependency of peak sound pressure level

with and without control of PA, Δf = 1.221 Hz

The closed-circle symbol indicates the noise from cascade of flat plates with PA (E = 0 kV). The maximum noise level at U_0 = 13.8 m/s is 1.2 dB larger than that of cascade of flat plates without PA. According to our preliminary experiments, noise level with conventional PA is around 10 dB smaller. Moreover the tendency of noise against the flow velocity is almost the same as both with and without PA. In addition, a hysteresis of noise generation has not observed in this configuration. It was concluded that that the influence of the flush-mounted PA is negligible small. This result is very useful for those who study the aerodynamic noise.

Figure 6 shows sound pressure spectra of aerodynamic noise from the cascade of flat plates with PA. The first peak can be observed in the frequency range from 800 Hz to 1400 Hz at the flow velocity from 10 m/s to 20 m/s. Since the peak frequency is proportional to the flow velocity, these noises are related to the vortices shedding in the wakes of the plates. Moreover, the maximum sound pressure level can be observed at U_0 = 13.8 m/s where the vortex shedding frequency agrees with the sound resonant frequency between flat pales. Although another peak which is not proportional to the flow velocity near 1500 Hz can be seen, it is thought that this is caused by resonance between the cascade of flat plates and the nozzle.

3.2 Noise Control of PA

Figure 8 shows the effect of PAs on aerodynamic noise control. The black and red open symbols correspond to noise levels of cascade of flat plates for E = 0 kV, and 3.2 kV (f = 4.0 kHz), respectively. The flow velocity of the occurrence of acoustic resonance is increased from 13.8 m/s to 13.9 m/s when PA is actuated. This means the shedding frequency of vortices from cascade of flat plates with PA control is lower than that without control. Due to this change of the frequency of vortex shedding the resonance occurs at higher velocity than conventional conditions.

The difference of noise between the level for E = 0 kV and that for E = 2.2 kV is also shown in Figure 8 as closed symbol. It can be seen that the noise control with PA is successful at the flow velocity from 13.0 m/s to 13.8 m/s. The upper range of controllable velocity is corresponding to the velocity of the resonance condition. The noise control is no longer effective at faster than the above velocity, the noise is therefore increased. Since the vortex shedding frequency becomes lower by the PA as mentioned above, the acoustic resonance occurs faster velocity. Therefore, it is necessary to adjust the velocity range for the PA control to reduce noise in a wide velocity range. For example, we suggest that the PA control should be an active at the velocity range below the velocity of resonance condition under this experimental condition.

3.3 Dependency of Applied Voltage

Figure 10 show the spectra of tonal noise from cascade of flat plates with PA control. Figure 10 also show the effects of the applied voltage on the pressure level of the tonal sound. The effects of noise reduction depend on the applied voltage of the PA. The noise reduction level is almost proportional to applied voltage. The most effectiveness condition is appear in the highest applied voltage of E = 3.6 kV. In that time, Tonal noise can be reduced by 10.8 dB.

3.4 Flow Visualization

Figure 11 (A) to (C) show the visualized flows around the cascade of flat plates. The experiments were carried out under the condition of U_0 = 5 m/s because of limitation of a smoke wire method, although resonance not occurs. However, it is possible to clarify the effects of PA on the flow control. Figure 11 (A) shows the flow around the cascade of flat plates with PA for the applied voltage, E = 0 kV. In this condition, the flow is separated at the leading-edge of the flat plate and soon re-attached near the leading-edge. In the cases with PA controls of E = 2.4 kV (B) and E = 3.2 kV (C), flow separations of the leading-edge are much larger and the stream lines are seems to be observed pushed away from the wall by PA. Moreover, the spread angle of the wake becomes large as the applied voltage becomes higher. Since the induced flow generated by the PA pushed away the separated flow at the leading edge, the flow separations become large. The boundary layer on the surface becomes thick and to broaden the width of the wake.

As a result, the vortices shedding frequency becomes lower with PA control. This result is consistent with the results of the frequency shift and changes the velocity of the resonance condition as shown in Figures 8 and 9.

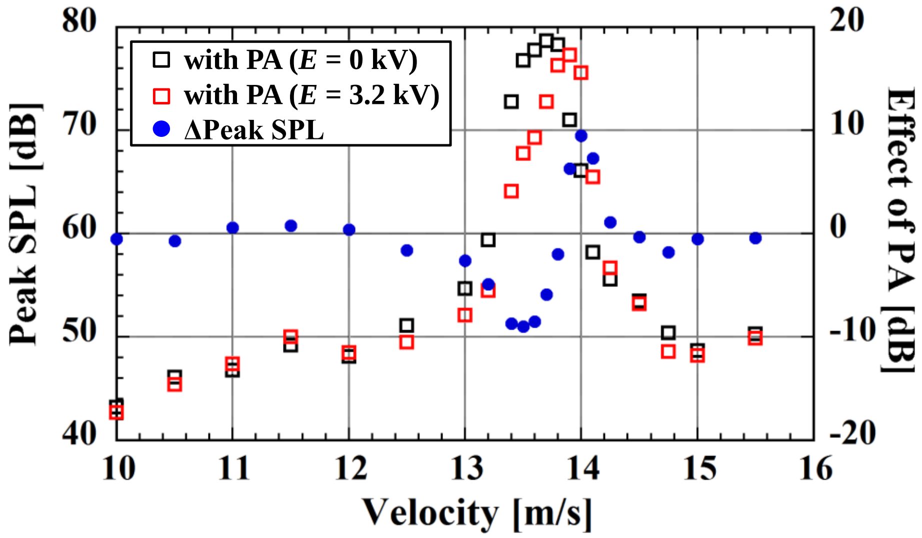
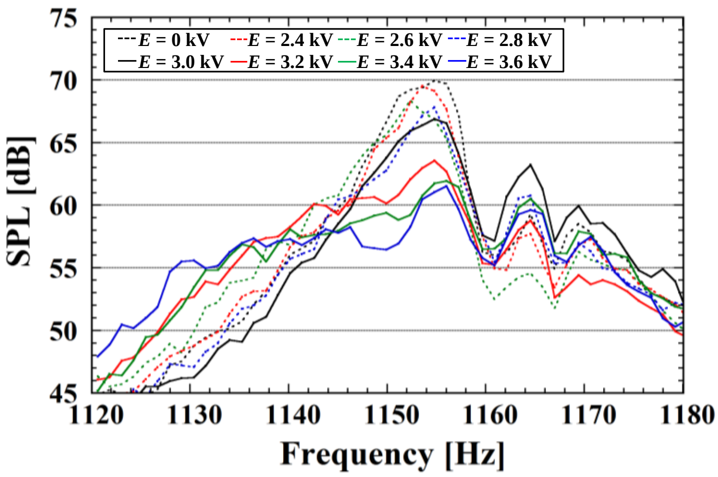


Figure 8 – Effect of PA on tonal noise (f = 4.0 kHz)



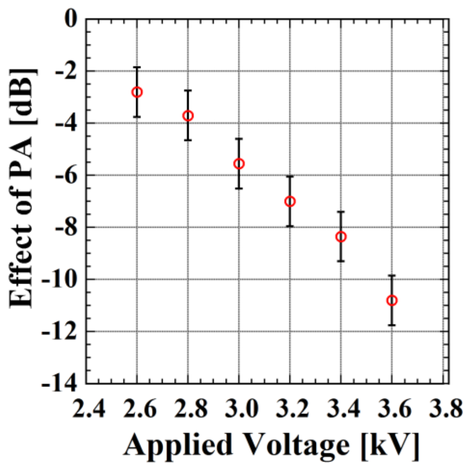
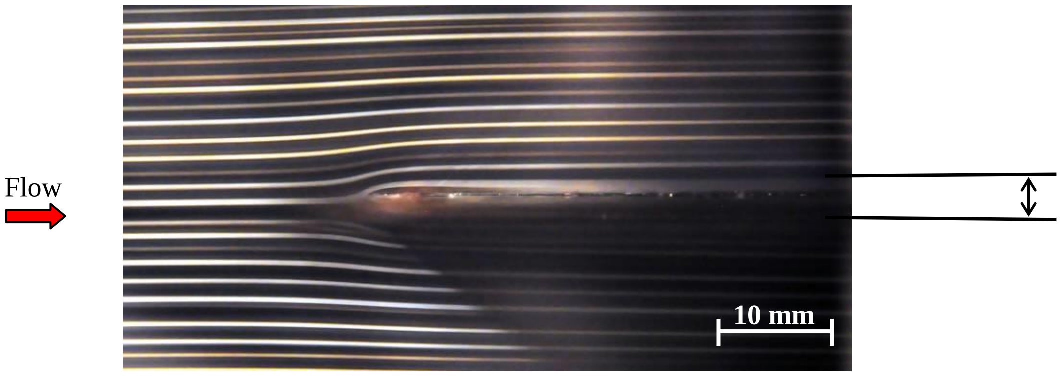
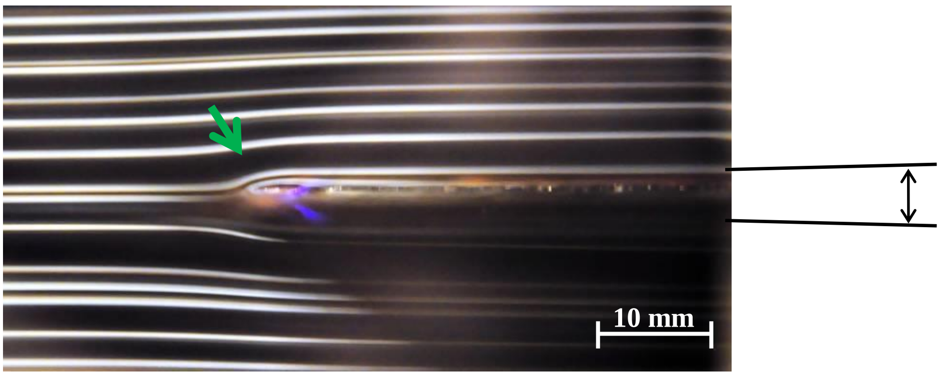


Figure 9 – Comparison of tonal noise with the applied voltage of PA (U_0 = 13.5 m/s, f = 4.0 kHz, Δf = 1.221 Hz)

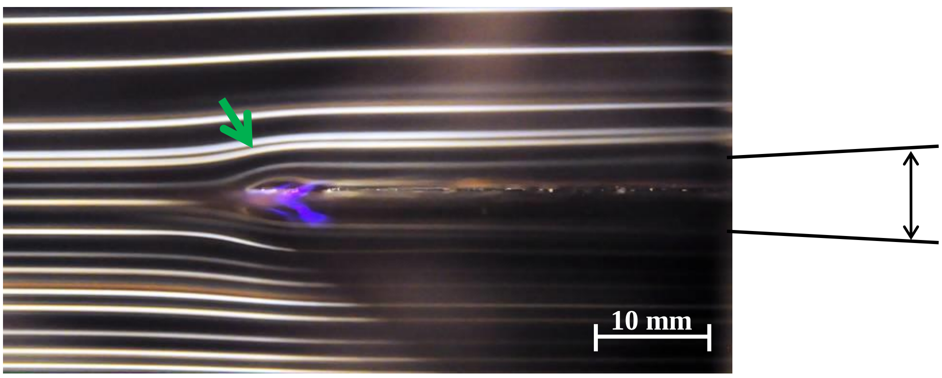
Figure 10 – Dependency of noise reduction of applied voltage of PA control (U_0 = 13.5 m/s, f = 4.0 kHz)



(A) – Flow pattern without PA control (E = 0 kV, f = 4.0 kHz ,U_0 = 5 m/s)



(B) – Flow pattern with PA control (E = 2.4 kV, f = 4.0 kHz, U_0 = 5 m/s)



(C) – Flow pattern with PA control (E = 3.2 kV, f = 4.0 kHz, U_0 = 5 m/s)

Figure 11 – Flow visualization with smoke-wire method

4. CONCLUSIONS

In order to control the tonal noise in flow around a cascade of flat plates, we apply the flush-mounted plasma actuators. The tonal noise becomes weakened when the conventional PA were installed for the cascade of flat plates, because the salient upper electrode which the conventional PA has on the surface affect the flow field, and the acoustic resonance between plates was weakened. Because of that, estimates the effect of noise control by PAs was difficult. There, we install PA for cascade of flat plates without influence on the flow field and the acoustic field by using flush-mounted PAs. The flush-mounted PA produced induced flow as with conventional PAs

In the result, the noise reduction was achieved around the velocity for the resonance such as U_0 = 13.5 m/s. And it turned out that the noise reduction level was proportional to the applied voltage of PAs. The noise reduction up to -10.8dB was achieved where a maximum condition of the applied voltage, E = 3.6 kV.

And the flow visualization made the effects of PAs on flow fields induced by PAs clear. The flow pushed away the separated flow at the leading edge. In that time, the spread angles of the wakes become large by the PA control and the wake becomes broader. This causes the decrease of the frequency of vortex shedding.

As a result, the sound pressure level of the tonal sound was able to be reduced at the velocity for the original resonant condition such as U_0 = 13.5 m/s. Thus the flush-mounted PAs are useful devices to control flow fields and aerodynamic noise.

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