

Suppression of Aerodynamic Tonal Noise from an Automobile Bonnet Using a Plasma Actuator

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ABSTRACT

Intense aeroacoustic feedback noises may radiate from flow around an airfoil, rearview mirror with small gaps and so on. Reductions of these noises are important issues in the development of industrial application. The intense noise from a bonnet of the automobile is one of the typical problems of acoustic feedback noise. In order to reduce this noise, plasma actuator (PA) was utilized to control flow and acoustic fields. The aim of this investigation is to clarify the effects of flow control by the PA on noise reduction and the noise reduction mechanism. Wind tunnel experiments were conducted with a half scale bonnet model and a low noise wind tunnel. Simultaneous measurements of flow and noise fields were conducted to understand the generation mechanism of the bonnet noise. Coherent output power (COP) of the velocity fluctuations with reference to far-field sound pressure was measured to visualize noise source distribution. The result showed the velocity fluctuations around the re-attachment point are strongly related with the tonal acoustic radiation. Moreover, the velocity fluctuation rapidly increased at the downstream of the kink shape with the influence of radiated sound. The measurement result of COP reflects this state and we can found that COP increased from the kink shape to the re-attachment point. This result indicated that the separated flow just behind the kink and reattached flow are key factors to control the bonnet noise. Based on this knowledge, experiments of flow and noise control with PA were conducted. As a result, intense tonal noise can be effectively reduced by the PA control. The mean velocity profile showed that the separation around the kink was suppressed by PA control. COP also showed the velocity fluctuations which were related with the tonal noise become weaker than that of the flow field without PA control.

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INTRODUCTION

In the development of high-speed vehicles, aeroacoustic feedback noise such as trailing-edge noise must be resolved quickly. To understand the mechanism of acoustic feedback noise, many researches have been conducted about trailing-edge noise of airfoils. Paterson *et al.* [1] measured the variation of the fundamental frequency of the tonal noise with the velocity, and they found that the frequency of peak noise varies stepwise or ladder-type with the flow velocity. Tam [2] proposed an aeroacoustic feedback loop consisting of acoustic radiation from disturbances in the wake and generation of disturbances in the upstream boundary layer by reception of the acoustic wave. Arbey *et al.* [3] clarified that the trailing edge noise was composed of broadband noise of the frequency f_s determined by the Tollmien-Schlichting (T-S) instability of the boundary layer and the tonal noise of frequency f_n determined by the aeroacoustic feedback loop. Moreover, the feedback loop is formed between the point for the maximum of velocity on the airfoil and the trailing edge.

The tonal noise may also radiate from automobile bonnets which have a trailing edge and an upstream kink shape. In the preliminary study for noise from the bonnet, it has been clarified that the ladder-type frequency changes with the freestream velocity variations [4]. Yokoyama *et al.* [5] simulated the acoustic field around the

bonnet with direct aeroacoustic simulations based on the three-dimensional compressible Navier-Stokes equations. The results showed that the aeroacoustic feedback loop was formed. At first, two-dimensional vortices were shed from the kink shape and these vortices traveled to the trailing edge. Secondly, the vortices deformed due to interference with the edge of the wall, and acoustic waves were generated around their region. After that, the acoustic waves induced small velocity disturbances around the kink shape where flow separation occurred. Finally, the disturbances synchronized and generated the strong vortices and noise. This is almost same as acoustic feedback system for the edge tone of airfoils. The basic principle of this noise has already been studied.

Recently, dielectric barrier discharged plasma actuators (DBD-PAs or PAs) have attracted attention as a flow control device. The PA has many advantages compared with other flow control actuators, no moving parts; fast time response; low mass and easily attached curved surfaces. Michelis and Kotsonis [6] applied the control by a PA to the flow around an automobile side mirror with guide vane, and showed that the leading edge separation from guide vane was suppressed. Little *et al.* [7] performed the separation control of the flow around a high-lift airfoil (NASA EET) and clarified that the plasma discharge can increase or suppress the size of separated region

over the deflected flap depending on the driving frequency of the PA. Moreover, Tomas *et al.* [8] conducted the reduction of aerodynamic noise radiating from a circular cylinder by the control of the PAs on the cylinder. Also, Inasawa *et al.* [9] performed the control of the flow and noise around an airfoil (NACA0012) using a flush-mounted PA to minimize the effects of protrusion of a PA from the wall on the flow. As a result, it was shown that the tonal trailing-edge noise due to aeroacoustic feedback loop was successfully suppressed. The flush-mounted PA is expected to be effective in aerodynamic noise reduction in the case that the radiated noise is sensitive to the deformation of body configurations.

The aim of this investigation is to clarify the mechanism of the suppression of tonal noise from a bonnet using the PA. Also, the effective conditions of the PA for noise suppression were investigated.

METHODOLOGIES

Experimental Setup

Figure 1 shows the schematics of experimental setup. In order to measure the aerodynamic noise from the bonnet model, experiments were performed by using a low noise wind tunnel. The wind tunnel had an open test section with a square nozzle of 300 mm×300 mm, where the test section was located in an anechoic chamber. The streamwise length of test section was 1250 mm. In this wind tunnel, the turbulence intensity in the freestream was less than 0.5 % and non-uniformity was less than 0.5 %, and the background noise level was 65.2 dB (A) at the freestream velocity of 30 m/s.

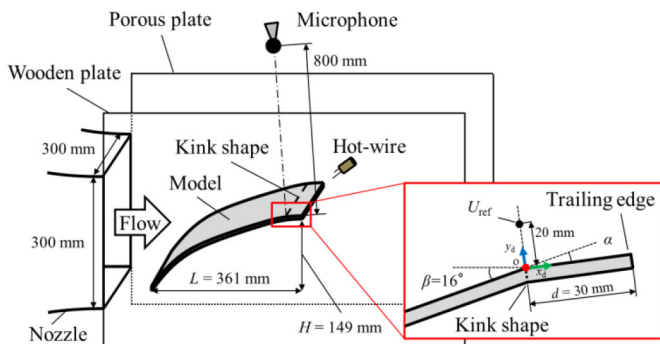


Figure 1. Schematics of experimental setup

A simplified bonnet model (1/2 scale of the automobile) was installed in the test section as shown in Fig. 1. In order to keep the two-dimensionality of flow into spanwise direction, the test section was terminated by two end plates. One of the end plates was made of a porous plate in order to suppress sound reflections and spanwise acoustic resonance. The model length was $L = 361$ mm, the height was $H = 149$ mm, and the distance between the kink and the trailing-edge was $d = 30$ mm. The spanwise non-uniformity of the manufactured model regarding this length d was within 0.1 mm.

Table 1. Experimental parameters

Kink angle, α	1, 6, 7.5, 11, 16°
Installation angle of bonnet, β	16°
Distance between kink and edge, d	30 mm
Reference velocity, U_{ref}	20 - 35 m/s
Reynolds Number, Re_d	4.0×10^5 - 7.0×10^5
Mach Number, M_{ref}	0.058 - 0.102

The origin of the coordinate is set at the center of spanwise direction of the kink. The axis of x_d is defined in the direction from the kink to the trailing edge, the axis of y_d is normal to the wall, and the axis of z_d is along the spanwise direction. Table 1 shows the experimental parameters. The angle α is formed between the upstream tangential line at the kink and the line from the kink to the trailing-edge. To clarify the effects of the angle α on the flow and tonal noise radiation, the experiments were performed at $\alpha = 1, 6, 7.5, 11, 16^\circ$, where the angle β formed between the downstream tangential line at the kink and horizontal line was set to be constant at angle $\beta = 16^\circ$. The reference velocity, U_{ref} measured at a distance of 20 mm from the kink in the y_d direction was changed from 20 m/s to 35 m/s. The error of the freestream velocity was less than 0.1 m/s. Based on the error, the uncertainty of the fundamental frequency was estimated to be 0.7 % at $U_{ref} = 30$ m/s.

Measurement of Sound and Flow Fields

Sound pressure level was measured using a sound level meter (RION Co., Ltd., NL-31) with a non-directional 1/2-inch microphone (RION Co., Ltd., UC-30). The measurement point of sound pressure level was placed at $x_d = 0$ and $y_d/d = 26.7$ as shown in Fig. 1.

The mean velocity and velocity fluctuations around the model were measured using a hot-wire anemometer at the freestream velocity of 30 m/s. Figure 2 shows the measurement lines of the mean velocity and velocity fluctuations. The sampling frequency was 160 kHz and duration time of sampling was 30 s. The frequency resolution in the spectral analysis was $\Delta f = 9.8$ Hz ($\Delta St \equiv \Delta f d / U_{ref} = 0.0098$), and the spectra were averaged 600 times.

Moreover, to clarify the effects of the control of the PA on the flow field related with tonal acoustic radiation, simultaneous measurement of sound pressure and velocity fluctuations were performed and the coherent output power (COP) of velocity fluctuations with reference to the sound pressure was computed by the equation (1).

$$COP(f) = \gamma^2(f) \cdot E_u(f), \quad (1)$$

where $\gamma^2(f)$ is coherent function of sound pressure and velocity fluctuations, and $E_u(f)$ is the power of velocity fluctuations. The distributions of the COP are insightful for identifying the velocity fluctuations that contribute to the tonal sound radiation. In the measurement of the COP distributions, the minimum pitch of measurement in the y_d direction was $\Delta y_d/d = 0.0033$ near the wall.

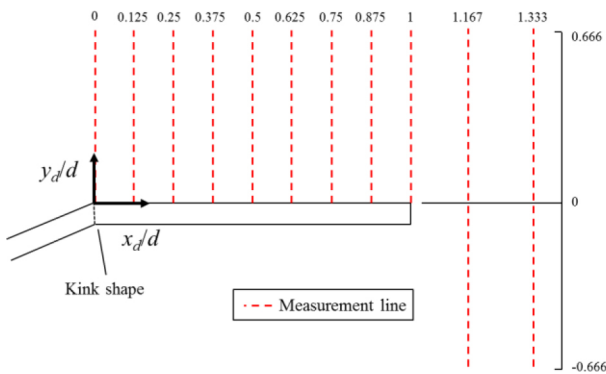


Figure 2. Measurement line of flow field

Control of Plasma Actuator

Figure 3 shows the x_d - y_d cross-section of the configurations of plasma actuator which was installed in the present experiments. The plasma actuator was consisting of top and bottom electrodes (copper) with the thickness of 12 μm and a dielectric material (polyimide) with the thickness of 400 μm . The streamwise lengths of the top and bottom electrodes of the PA are 1 mm and 3 mm, respectively, where the spanwise non-uniformity of both lengths was less than 0.1 mm. The streamwise distance between the top and bottom electrodes was 0.45 mm with the spanwise non-uniformity of less than 0.05 mm. In order to suppress the effects of the protrusion of the PA on the flow, the model surface was covered with polyvinyl chloride (PVC) plate in the region outside of the PA so that the PA was flush-mounted.

To investigate the effects of position of the PA on the flow and sound control, the PA was installed at two streamwise positions of $x_{pa}/d = 0.12, 0.50$, where x_{pa} is the position of the downstream edge of the top electrodes as shown Fig.3. Moreover, the experiments were performed with co-flow and counter-flow forcing configurations about the induced flow by the PA as shown in Fig. 4. To drive PA, it is necessary to supply AC voltage with high-frequency and high-voltage to the two electrodes. In this research, the amplifier of PSI-PG1040F (Ki-Tech Co., Ltd.) was used. The alternating voltage with a quasi-square waveform was set on the PA. The driving voltage of the PA was mainly $E_{pa} = 2.8$ -5.5 kV_{p-p} and the driving frequency was $f_{pa} = 4.1$ -7.0 kHz. Also, the estimation of the power consumption and energy efficiency of the PA is necessary in practical use, where the voltage and current with a phase shift need to be measured with high-frequency sampling due to the spiky waveform of the current. The main objective of the present paper is to clarify the sound reduction mechanism by the PA.

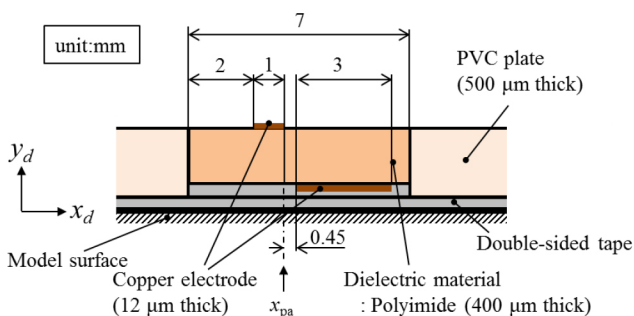


Figure 3. Configurations of plasma actuator

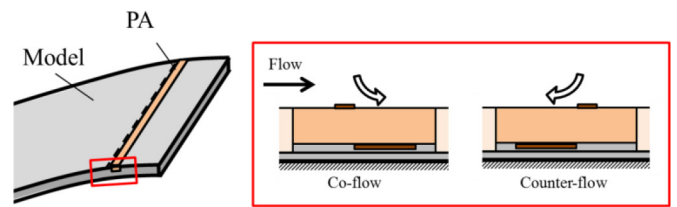


Figure 4. Installation of the PA

Figure 5 shows the light emission from the PA, where the generation of plasma can be confirmed. Also, figure 6 shows the visualization image of induced flow by the PA. The flow is clarified to be induced from the upper electrode to the lower electrode.

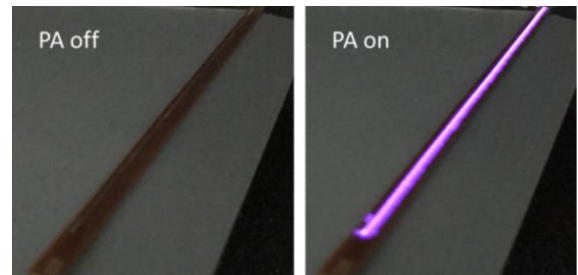
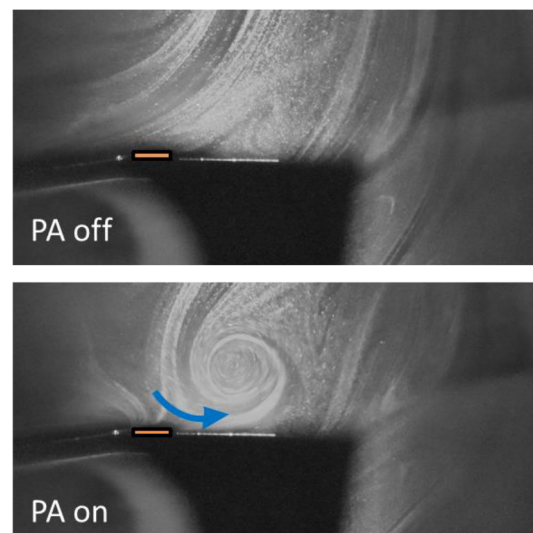


Figure 5. Light emission from the PA

Figure 7 shows the effects of the installation of the PVC plate and PA with driving voltage of $E_{pa} = 0$ kV on the sound spectra at the freestream velocity of $U_{ref} = 30$ m/s. This figure shows that the level of peak frequency of the tonal noise, $St = 2.0$ and spectrum shape, are almost same as that of without PA. This indicates that the effects of the installation of the PA and PVC plate on the fluid-acoustic interaction related with tonal noise radiation are small.

Figure 6. Visualized image of instantaneous field immediately after applying the voltage to the PA without freestream ($E_{pa} = 5.5$ kV_{p-p} , $f_{pa} = 7$ kHz)