A Basic Study on Aerodynamic Noise Reduction Techniques for a Pantograph Head Using Plasma Actuators

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Reducing aerodynamic noise emitted from a pantograph head is an important environmental factor to be examined in the light of increasing the running speed of Shinkansen trains. This paper discusses control of flow around the pantograph head using plasma actuators. The results of the wind tunnel tests show that plasma actuators can prevent flow separation from the pantograph head surface and weaken Karman vortices. In addition, CFD results indicate that the plasma actuators can reduce aerodynamic noise emitted from the pantograph head.

Keywords: pantograph, pantograph head, aerodynamic noise, plasma actuator, flow control, CFD

1. Introduction

In Japan, Shinkansen trains run through densely populated areas. Therefore, reduction of wayside noise caused by Shinkansen trains is necessary to preserve the environment along railway lines. Since the sound power of aerodynamic noise grows in proportion to the 6th and to the 8th power of the train speed, aerodynamic noise is the dominant source of wayside noise along high speed lines. Pantographs, especially pantograph heads (see Fig.1), are one of the dominant sources of aerodynamic noise on Shinkansen trains.

The mechanism generating aerodynamic noise from the pantograph head is known to be as follows: when the pantograph head moves through the air, the flow around it separates from the pantograph head surface and Kármán vortices shed behind the pantograph head cause pressure fluctuations. The pressure fluctuations propagate far-afiel and are known as Aeolian tones. Therefore, if the flow around the pantograph head can be controlled so that the Kármán vortices are weakened, in turn, Aeolian tones from the pantograph head will be reduced.

In previous studies [1][2][3], attempts have been made to abate noise by for example shape optimization and applying porous material. Although these passive methods were effective, a new technique is necessary to achieve further aerodynamic noise reduction. In the present study, the authors focused on an active flow control method: a plasma actuator is applied to the pantograph head surface as a flow control device. Plasma actuators are a relatively new type of flow control device, and are increasingly attracting the attention of aerodynamic researchers. Figure 2 shows a typical configuration of a plasma actuator. The plasma actuator generates plasma on its surface and produces a body force to the surrounding air, inducing local flow. The body force attracts surrounding air and induces tangential flow. Electric power is supplied to the actuator from a dedicated power supply, which outputs several kilovolts voltage with a frequency of several kilohertz. Although the power supply equipment is specially designed, other elements such as the dielectric and electrodes are easily available. In wind tunnel tests conducted for this study, a 0.05 mm thick Kapton® (polyimide) tape was used as a dielectric, and 0.035 mm thick copper foil tape was for the electrodes. In this sense, the plasma actuator has many advantages such as being very thin, having no complex mechanical structure, and being easy to set up. Currently, the plasma actuator can only be used for controlling low speed (several m/s or so) flow because the velocity of its induced flow is insufficient to control relatively high speed flow. It can be claimed however that the plasma actuator, is capable of producing an unprecedented flow control effect and which has provided new ideas about flow control and its mechanisms. In the present study, the plasma actuator was applied to the pantograph head. Two evaluations were carried out to clarify its flow control effect and mechanisms. The first evaluation was in a low speed wind tunnel test. In this wind tunnel test, the flow control effect at low flow speed was confirmed by investigating the flow field around the pantograph head. The second evaluation involved a computational fluid dynamics (CFD) analysis. In this CFD analysis, flow control effect and aerodynamic noise reduction effect at high flow speed were estimated.
2. Wind tunnel test

2.1 Outline of the wind tunnel test

Wind tunnel tests were carried out at RTRI’s small scale low-noise wind tunnel (nozzle size of 760 mm × 600 mm, and maximum flow speed of 150 km/h). The flow control effect of the plasma actuator was verified by evaluating the flow field behind the pantograph head by using particle image velocimetry (PIV), which can obtain simultaneous flow velocity distribution in the two-dimensional plane. In the PIV measurement, the fluid is seeded with oil particles. The particles are irradiated with a laser sheet and image pairs of the particles are taken by a high-performance CCD camera. From the time interval and displacement of the particles between the two snapshots, the flow velocity vector field in the snapshot plane can be obtained. The experimental set up and the coordinate system of the wind tunnel test are shown in Fig. 3.

2.2 Applying the plasma actuator to the pantograph head

The plasma actuator was applied to the half scaled pantograph head model as shown in Fig. 4. The plasma actuator was installed immediately upstream (Case 1, Fig. 4(b)) and immediately downstream (Case 2, Fig. 4(c)) from the flow separation points, i.e. upstream corners of the pantograph head. The plasma actuator was driven by the dedicated electric power supply (KI-Tech., PSI-PG1040F). The voltage and frequency of the AC electric power were 8 kV and 4 kHz respectively. In this experiment, the flow velocity induced by the plasma actuator was about 1 m/s. The span length of the plasma actuator was 100 mm in consideration of the capacity of the electric power supply equipment. Partition plates as shown in Fig. 5 were installed near both ends of the plasma actuator to prevent mixing of the flow between the partition plates where it is controlled by the plasma actuator with the flow outside the partition plates where it is not controlled by the plasma actuator.

Since flow velocity induced by the plasma actuator is relatively low, it was preferable to set a low free-stream velocity and use a small scale model. Therefore, the free-stream velocity was set at 4.6 m/s, which was the minimum flow velocity of the wind tunnel, and the model scale was set at 1/2 so that the span length of the plasma actuator could be sufficiently longer than the cross-sectional scale of the pantograph head. The Reynolds number of this wind tunnel test is approximately 2 million.
tunnel test was about $7.7 \times 10^3$, which is much smaller than that of the real Shinkansen train. However, the flow around the pantograph head is considered to be a fully developed turbulent flow and have little dependence on the Reynolds number; therefore, the essential flow control effect and mechanism observed in this wind tunnel test is considered to be applicable to the real Shinkansen trains.

2.3 Results of wind tunnel test

Figure 6 shows comparisons of the flow fields measured by PIV. Figures 6(a) to (c) show the distribution of the mean velocity in the main flow direction. According to these figures, the wake regions in Case 1 (Fig. 6(b)) and Case 2 (Fig. 6(c)) become longer in the main flow direction compared to the case of “Without PA” (Fig. 6(a)). The plasma actuator is considered to suppress flow separation from the pantograph head surface and stabilize the shear layer. Figures 6(d) to (f) show the distribution of the root-mean-square fluctuations of the velocity vertical to the flow (hereafter referred to as the transverse RMS velocity). According to these figures, the transverse RMS velocities in Case 1 (Fig. 6(e)) and Case 2 (Fig. 6(f)) become smaller compared to that of the case of “Without PA” (Fig. 6(d)). Namely, the plasma actuator weakens the Kármán vortices and reduces unsteady velocity fluctuations. Comparing Case 1 and Case 2, confirms that the flow control effect is more clearly obtained in Case 2. Therefore, applying the plasma actuator to the right and downstream from the separation point is more effective than applying it to the right and upstream from the separation point.

From these results, the mechanism of the flow control by using the plasma actuator can be explained as follows. The tangential jet flow velocity induced by the plasma actuator (about 1 m/s) is much smaller than the free-stream velocity of 4.6 m/s. Therefore, the dominant flow control effect is performed by the flow-attracting effect rather than the tangential jet flow itself. In Case 1, the velocity distribution in the boundary layer is changed by the body force generated by plasma actuator. In contrast, in Case 2, the plasma actuator attracts the separated shear layer and prevents the flow separation from the pantograph head. As a result, the Kármán vortices are weakened. If these effects are obtained in the high speed range, the flow control mechanism obtained by the plasma actuator can reduce aerodynamic noise. The velocity that can be induced by the plasma actuator, however, is not sufficient. Reduction of aerodynamic noise cannot be confirmed with wind tunnel tests. Therefore, CFD analysis was carried out to estimate the flow control effect and the aerodynamic noise reduction effect at high speed.

3. CFD analysis

3.1 Outline of the CFD analysis

CFD analysis was carried out to estimate flow control effect and aerodynamic noise reduction effect obtained by the plasma actuator at high speed. In this CFD analysis, ANSYS Fluent 13 was used and an unsteady flow field was calculated by using Large Eddy Simulation (LES). Figure 7 shows the computational domain and the boundary conditions of this CFD analysis. A flow around a 1/1 scale pantograph head model with the span length of 150mm
was analyzed. The minimum cell size was 0.01mm and the total number of computational cells was 1.43 million. The free stream velocity was 36.1 m/s (130 km/h) and the size of the computational time step was $1.0 \times 10^{-4}$ s. The integration time was 0.45 s (4500 time steps) and the flow fields between 0.05 s and 0.45s were evaluated.

### 3.2 Modeling of the plasma actuator

Effect of the plasma actuator was emulated by using a simplified steady body force model based on the model proposed by Shyy et al. [8]. Figure 8 shows an illustration of the steady body force model. The steady body force given by (1) is applied only to the triangular plasma domain which is formed by point A, point B, and point O shown in Fig.8,

$$F = F_0 \left(1 - \frac{x}{b} - \frac{y}{a}\right)k$$  \hspace{1cm} (1)

where $k$ denotes an unit vector directed from point A to point B, $F_0$ indicates the body force magnitude, and other quantities are as shown in Fig. 8.

The steady body force model was applied to the pantograph head model as shown in Fig. 9. The body force magnitude was set at $F_0 = 8.0 \times 10^6$ N/m$^3$. Figure 10 shows the body force distribution and the induced velocity distribution obtained by this model without a free stream velocity. From Fig. 10, it is confirmed that this model suitably emulates the typical effect of the plasma actuator, that is, attracting the surrounding air and inducing a tangential jet flow.

### 3.3 CFD analysis result

Figures 11 to 13 show the results of CFD analysis. In these figures, the body force magnitude and the induced velocity were $F_0 = 8.0 \times 10^6$ N/m$^3$ and 61 m/s respectively. The induced velocity is about 1.7 times as large as the free stream velocity. Figure 11 shows the distribution of the mean velocity in the main flow direction. The wake region in the case of “With PA” (Fig. 11(b)) is longer in the main flow direction than that in the case of “Without PA” (Fig. 11(a)). Figure 12 shows the distribution of the RMS velocity vertical to the main flow direction. The RMS velocity in the case of “With PA” (Fig. 12(b)) is smaller than that in the case of “Without PA” (Fig. 12(a)). These trends are in accordance with the wind tunnel test results. Figure 13 shows the instantaneous span-direction vorticity distribution. In the case of “With PA” (Fig. 13(b)), flow separation from the pantograph head surface is significantly sup-
pressed and Kármán vortices in the wake region are weakened. From these results, it is conjectured that the flow field around the pantograph head can be controlled even at high speed.

3.4 Estimation of aerodynamic noise

From the unsteady CFD analysis, the aerodynamic noise emitted from the pantograph head was calculated by using the compact approximated Curle’s formulation [9]

$$p_c(x,t) = \frac{1}{4\pi c_0} \int_{S} \frac{\partial}{\partial t} p(y,t) \cdot |x-y| \cdot c_0 n \cdot dS$$  \hspace{1cm} (2)

where \( p_c(x,t) \) is the sound pressure on observation point \( x \) at time \( t \); \( p(y,t) \) is the pressure on point \( y \) on the pantograph head surface \( S \), whose unit normal vector is \( n_i \) at time \( t \). The speed of sound is denoted by \( c_0 \). From the assumption of compact approximation, (2) can only be used to estimate low frequency aerodynamic noise. In this case, the frequency range which can be evaluated by (2) is below 1 kHz.

Figure 14 shows sound pressure levels at observation point \( x=(0m, 5m, 0m) \) obtained by (2). Narrow band peak noise is observed around 80 Hz in the case of “Without PA.” In contrast, this peak noise is drastically reduced in the case of “With PA.” This indicates that the aerodynamic noise emitted from the pantograph head can also be reduced at high speed by means of sufficiently-powerful plasma actuators. However, sufficiently powerful plasma actuators are not easily available at present. Furthermore, the plasma actuator have a number of drawbacks when applied in practice. Consequently, it is necessary to clarify the flow control mechanism performed by the plasma actuator in more detail and propose alternative but practical flow control methods based on the flow control mechanism performed by the plasma actuator.

4. Conclusions

In this study, the plasma actuator was applied to the pantograph head and two evaluations were carried out. The first evaluation was a low-speed wind-tunnel test to confirm flow control effect at lower flow speed. The second evaluation was a CFD analysis to estimate flow control effect and aerodynamic noise reduction effect at higher flow speed. As a result, the following conclusions were drawn:

1. By applying the plasma actuator near the separation point of the pantograph head, flow separation from the pantograph head surface can be controlled, and the Kármán vortices can be weakened.

2. Plasma actuator can control flow field more effectively when it is installed immediately downstream from the separation point of the pantograph head surface rather than immediately upstream from the separation point.

3. The plasma actuator prevents flow separation from the pantograph head surface, weakens Kármán vortices and reduces velocity fluctuations.

4. From CFD analysis result, it is conjectured that the plasma actuator can control flow field around the pantograph head and reduce aerodynamic noise emitted from the pantograph head even at high speed. Based on the flow control mechanisms obtained by the plasma actuator, a proposal will be made for a practical aerodynamic noise reduction method.

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