Paper

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Optimal Shape of Blunt Device for High Speed Vehicle

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Abstract

A contact strip shape of a high speed train pantograph system was optimized with CFD to increase the aerodynamic performance and stability of contact force, and the results were validated by a wind tunnel test. For design of the optimal contact strip shape, a Kriging model and genetic algorithm were used to ensure the global search of the optimal point and reduce the computational cost. To enhance the performance and robustness of the contact strip for high speed pantograph, the drag coefficient and the fluctuation of the lift coefficient along the angle of attack were selected as design objectives. Aerodynamic forces were measured by a load cell and HWA (Hot Wire Anemometer) was used to measure the Strouhal number of wake flow. PIV (Particle Image Velocimetry) was adopted to visualize the flow fields. The optimized contact strip shape was shown a lower drag with smaller fluctuation of vertical lift force than the general shaped contact strip. And the acoustic noise source strength of the optimized contact strip was also reduced. Finally, the reduction amount of drag and noise was assessed when the optimized contact strip was applied to three dimensional pantograph system.

Key words: High speed train, Pantograph contact strip, Design optimization, Wind tunnel experiment, Aerodynamic performance, Acoustic noise source.

1. Introduction

In Korea, new KTX-Double Deck project was developed which runs through the long tunnel under-ground with the speed of 300km/h. And the high speed train named HEMU-430X is being developed with maximum speed of 430km/h and operation speed of 370km/h. As the speed of the train exceeds over 300km/h, aerodynamic problems such as sudden drag increase, severe acoustic noise, pressure variations and instability occur. Aerodynamic issues in high speed train are almost the same as those in aircraft. This is a good example that high technologies in aerospace engineering apply to other engineering field.

Among aerodynamic problems in high speed train, the strong noise from a pantograph system limits the operating speed.[1, 2] A pantograph system which is installed on the roof of a high speed train is an important device that collects electric current from overhead lines. A general pantograph system, which has a complex configuration, is consisted of a contact strip, arm, frame and under-body (electrical insulator) as it is shown in Fig 1. Especially, a contact strip is the major contributor of aerodynamic noise and drag in a pantograph system because it is exposed directly to high speed external flow. Moreover, it determines the lift force,

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which is closely related to the electric current collecting performance between a catenary line and a contact strip. The aerodynamic performance of the pantograph system has been investigated and aerospace engineering technology apply to the pantograph system: In Japan, M. Ikeda et al. had studied a numerical optimization of the crosssectional contact strip shape for low noise and designed a new pantograph system.[3-5] In Europe, C. Noger et al. had investigated acoustical noise of pantograph recess for TGV. [6] T. Dassen et al. had studied the noise of a high speed train pantograph.[7] In Korea, research of applying aerospace engineering technology like airfoil and spoiler to pantograph system was performed for HEMU-430X. With the increase of train speed, the acoustic noise problem has become important issue. Recently, a new pantograph system suitable for the operational speed of 370km/h has been required for decreasing noise level by 5~10 dB.

In regard to the acoustic noise of the contact strip, a dipole source is caused by an unsteady pressure fluctuation and due to the train speed less than Mach number of 0.3 proportional to the train speed by a power of 6.[8]

In regard to the robustness of the contact strip, the current collecting performance can be estimated by lift fluctuation and $\frac{dC_l}{d\alpha}$. Under the constant speed condition without any disturbance, the amplitude of vertical force fluctuations of the contact strip needs to be small at a given angle of attack. In the constant speed condition with disturbances such as crosswind or gust, the vertical lift forces need to be small with the variations of angle of attack, $\frac{dC_l}{d\alpha}$; this means that the current collecting performance becomes stable.

In this research, to reduce acoustic noise and drag and to increase robustness of the contact strip against flow disturbances, the aerodynamic shape of the contact strip is optimized by minimization of c_d and $\frac{dC_l}{dq}$.

Following the introduction, in section 2, design optimization process and the method for selecting the final optimization shape are described. The values of c_d and the fluctuation of c_1 are compared between the rectangular shaped contact strip and the final optimized contact strip. In section 3, experimental setup and condition are introduced for flow visualization, Strouhal number and aerodynamic force measurements. And, the final optimized contact strip shape is validated. Finally in section 4, concluding remarks are drawn.

2. Design and optimization of contact strip

A new Korean high speed train named HEMU-430X is being developed for maximum speed of 430km/h and operation speed of 370km/h. Accordingly, high speed pantograph for lower noise and contact force is being developed.

Generally, a contact strip cross-section of high speed train pantograph is in rectangular shape. A rectangular shape has a higher drag and a larger amplitude of lift fluctuation because of the vortex in the rear field. If a rectangular shape is changed to a streamlined shape, drag and amplitude of lift fluctuation can be remarkably reduced. [3] And acoustic noise due to a vortex can also be reduced.

2.1 Design condition

The operation speed of HEMU-430X is 370km/h. Acoustic noise and drag are expected to increase significantly as the operation speed increases from 300km/h which is the speed of KTX(Korean Train eXpress) to 370km/h. Therefore, a high priority is to design a new contact strip producing minimum acoustic noise and drag for the normal close knee condition as it is shown in Fig. 2. The open knee condition, which is an



Fig. 1. Pantograph for HEMU-430X and optimized Contact strip shape

emergency condition, was not considered because the train speed was much lower than the operation speed of the close knee condition.

2.2 Design objective

As mentioned, the existing rectangular shaped contact strip has a higher drag and higher unsteady pressure fluctuation as well due to a vortex. On the other hand, in the case of a streamlined contact strip, when the angle of attack is small, drag and pressure fluctuation is quite small and the flow around the streamlined shape is almost steady. Thus, in the case of the contact strip shape, c_d can be achieved the design objective because the acoustic noise of the contact strip could be reduced simultaneously when the drag and pressure fluctuation (Strouhal number) is decreased. [9-11]

The current collecting performance is influenced by the lift fluctuation of the contact strip itself when there are no disturbances. For a streamlined contact strip shape, the reduction of c_d means the decrease of the pressure drag and consequently, it causes the decrease of the pressure fluctuation (lift fluctuation). Thus, the reduction of c_d of contact strip may lead to a stable current collecting performance. On the other hand, when there are disturbances, the current collecting performance is affected by the changes of lift force as the variations of the angle of attack $(\frac{dC_l}{d\alpha})$ rather than a lift fluctuation of contact strip itself.

Finally, the objective functions were c_d and $\frac{dC_l}{d\alpha}$, which were minimized to achieve lower drag, lower acoustic noise and higher robustness against disturbances.

2.3 Design variables

The shape of the contact strip was controlled by design variables n, m, a_1 , a_2 which were the front curvature, rear curvature, length of axis and thickness on the basic elliptical curve as it is shown in Fig 3. The definition functions are equation (1) and equation (2). The thickness 2b was fixed. Defining shape by equation is very effective for the shape optimization since it is possible to create a variety of shapes with less variation. [12]

$$\left(\frac{x}{a_1}\right)^n + \left(\frac{y}{b}\right)^n = 1; \ (x \le 0) \tag{1}$$

$$\left(\frac{x}{a_2}\right)^m + \left(\frac{y}{b}\right)^m = 1; \ (x > 0) \tag{2}$$

2.4 Design constraints

Design constraint was a lift force of the contact strip to be less than 200N which was given from the operation regulation of HEMU-430X. It came from maximum contact force between pantograph and catenary line. The conditions of the design optimization are summarized in table 1.

2.5 Optimization process

The contact strip shape optimization procedure is shown in Fig 4. First, the initial sample points are selected for construction of a response surface. Then, CFD calculations are performed according to the design variables of the sampling points and a response surface model is constructed by Kriging model.[13,14] This approximated surface is optimized with GA(Genetic Algorithm) and EI(Estimated Improvement) values are calculated.[15] Based on the EI values, additional points are added to the set of sampling points. Then, the overall process is iterated again until adequate results are obtained. The details of each process



Fig. 3. Unsymmetrical elliptic cylinder [15]



Fig. 2. Pantograph setup condition

are as follows;

For selecting the initial sampling points, the Latin Hypercube method is used and 30 sampling points are selected and distributed uniformly in the design space. The example grid shapes of the sampling points are shown in Fig 5.

The grid system is the structured O type with the far boundary located at as far as 20 times of contact strip length (a_1+a_2) from the contact strip. The free-stream velocity is

Table 1. Summary of design optimization

370km/h, and the angle of attack (α), is set as -10 ~ 10 degrees to investigate the robustness of the designed results.

Based on the calculations, a response surface model was constructed via the Kriging model. The GA optimization was performed with the RS (Response Surface) to find the minimum of c_d and $\frac{dC_1}{d\alpha}$. Even with GA optimization, the GA values may miss the global optimum points because the predicted points by the Kriging model contain uncertainty.



Fig. 5. The example grid shapes of sampling points

optimized contact strip were 35mm, 25mm, and 65mm. And

their spans were 500mm. End plates were clearly installed

to avoid three dimensional effects. The models were made

by wood with accuracy of 1/100 using CNC(Computerized

Wind tunnel tests were conducted in Seoul National University (SNU) and Korea Air Force Academy (KAFA)

under the same experimental condition. Aerodynamic force

and Strouhal number were measured in the wind tunnel

of SNU. And Flow visualization was conducted with PIV

(Particle Image Velocimetry) in the wind tunnel of KAFA.

The wind tunnel of Seoul National University has the test

Thus, we calculated the EI values and added additional sampling points to the initial points. We iterated this process three times.

The final optimized shape was selected on a palette set, as it is shown in the left of Fig 6. This palette set shows that the two objective functions conflict with each other. Here, c_d and c_l were non-dimensionalized by height of each shape. The final optimized shape was selected from the point which has the smallest values of cd and $\left|\frac{dC_l}{d\alpha}\right|$ as shown in the left of Fig 6.

The detailed geometries on the optimized shape of the contact strip are shown in table 2. Lift and drag of the final optimized contact strip shape are shown in Fig 7 and table 3. From the test results, c_d of optimized contact strip shape was decreased by about 90%, from that of the rectangular shaped contact strip. $\left|\frac{dC_l}{d\alpha}\right|$ was decreased by about 42%. Amplitude of lift decreased from 0.695 to 0.085 by about 87%.

3. Wind tunnel tests for validation

3.1 Experimental models for contact strip shape

To validate the optimized contact strip shape and to compare aerodynamic performances, experimental models of a rectangular shaped contact strip, a circular shaped contact strip and the optimized contact strip shape were selected. Generally, a typical contact strip is in rectangular and circular shapes, as it is shown in Fig 8. Each model has the same height of 25mm. The chord length of the rectangular shaped contact strip, the circular shaped contact strip and



section of $0.97m (H) \times 1.3m(W) \times 2.4m(L)$ in size; its maximum speed is 75m/s with turbulent intensity of less than 0.2%. The wind tunnel of the Korea Air Force Academy has test section of 0.9m (H) $\times 0.9m(W) \times 2m(L)$ in size; its maximum speed is about 50m/s with turbulent intensity of less than 0.25%.

3.2 Experimental setup and condition

3.3 Flow visualization

Numerical Control).

Flow visualization was performed with PIV. The PIV system used for present study was made by the TSI Company: the CCD camera has the maximum frames per second of 30, pixel resolution of $1K \times 1K$, dynamic range of 8 bit and sampling rate fixed to 15 Hz. For seeding, a particle generator driven by pneumatic power evaporates the olive oil and seeds it to the collector of the wind tunnel. The experimental Reynolds number was about 50,000.



Fig. 6. Palette set(Left) and the optimized shape(final optimization, Right)

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Final Optimization	1.75 X 10 ⁻²	3.36 X 10 ⁻²	3.5	1.5	Fig. 6(Right)

3.4 Strouhal number measurement

A hot wire probe (KANOMAX Constant Temperature Anemometer) was used to measure the Strouhal number. The measuring position was 2D (diameters) after the experimental models. The measurement frequency was 10 kHz for 2 minutes. Strouhal number is given by $\text{St}=\frac{fD}{U}$. (Where, f: frequency, D: diameter, U: freestream velocity). Experimental Reynolds numbers ranged from about 25,000~50,000. The frequency for the calculation of the Strouhal number was acquired by Fast Fourier Transform.

3.5 Force measurement

The aerodynamic forces for two dimensional experimental models were measured by two-axis load cell, as it is shown in Fig 9. The two-axis load cell was made by CAS Korea, and



Fig. 7. Aerodynamic coefficients of the optimized shape at angle of attack is 0 degree

Table 3. Comparison of cd and $\left| \frac{dc_l}{d\alpha} \right|$ of the optimized contact strip

its accuracy was $\pm 0.05\%$. Experimental Reynolds numbers were in the range of about 25,000~50,000 and the sampling frequency was 1 kHz. Aerodynamic data were acquired by averaging during 30 seconds. The blockage ratio of experimental models was less than 3%.

3.6 Experimental results and analysis

3.6.1 Flow visualization and Strouhal number for two dimensional contact strip shape

Flow visualizations were performed to investigate vortex formation, which is one of the causes of acoustic noise. The results of flow visualization with PIV are shown in Fig 10~12. In the model of a rectangular shaped contact strip, flow separation occurs at both front corners and recirculation regions are observed at both the upper side and the lower side. Also, the rectangular contact strip shows the strongest and largest wake region among the three models. The circular shaped contact strip also shows a vortex and has a large wake region compared to that of the optimized shape. On the other hand, the optimized



Fig. 9. Force measurement set up



Fig. 8. Experimental contact strip models (Rectangular shaped contact strip(left), circular shaped contact strip(middle), optimized contact strip shape(right))

contact strip shape has a more stable flow than those of both the rectangular shaped contact strip and the circular shaped structure. The optimized contact strip shape does not show separations or vortex. PIV experiments also show seemingly steady flow around the optimized contact strip. To confirm the results of PIV, the Strouhal number



Fig. 10. Flow around rectangular shape (Re=50,000)



Fig. 11. Flow around circular shape (Re=50,000)

Table 4. Strouhal number of contact strip models

of each experimental model was measured by a hot wire anemometer. Measured Strouhal numbers by HWA are shown in table 4. They are very close to the typical value. [16, 17] The optimized contact strip shape did not have a Strouhal number because the flow around the optimized contact strip was almost steady.

3.6.2 Force results for two dimensional contact strip shape

Mean lift and drag coefficients for the rectangular shaped contact strip, the circular shaped contact strip and the optimized contact strip shape are shown in table 5.

Lift and drag coefficients of the rectangular shaped contact strip, the circular shaped contact strip, and the optimized contact strip shape showed typical results in Reynolds number range of apprx. 25,000~50,000.[18~20] Among the experimental models, the optimized contact strip shape showed the smallest drag.

The drag coefficients of the optimized contact strip were reduced about 89% and 87% from those of the rectangular shaped contact strip and the circular shaped contact strip respectively. Amplitudes of lift and drag fluctuations are



Fig. 12. Flow around the optimized shape (Re=50,000)

Experimental models	Reynolds number	Strouhal number	Reference	
Rectangular shaped	25000	0.143	0.14	
contact strip	50000	0.142	0.14	
Circular shaped	25000	0.206	0.2	
contact strip	50000	0.191	0.2	
Final optimized	25000	N/A		
contact strip	50000	N/A	-	

shown in table 6. The optimized contact strip shape showed 87% reduction in amplitude of lift fluctuation from that of the rectangular shaped contact strip, which meant that the pressure fluctuation has decreased in the optimized contact strip.

In the real operational condition of HEMU-430X, the Reynolds number of the flow around the contact strip is about 4×10⁵. For this Reynolds number, the circular shape may give different aerodynamic characteristics compared to those for the Reynolds number of 4×10⁵ because of the turbulent effect. Over the critical Reynolds number for turbulent flow, the flow separation point moves toward the rear because of the increase of the flow momentum near the surface. Thus, the drag coefficient is expected to be smaller in a real condition. On the other hand, in the cases of the rectangular contact strip and a streamlined contact strip, although the Reynolds number increases from 50,000 to 4×10^5 , the drag coefficient of the rectangular shape changes little because the separation point does not move and a vortex is still generated in high Reynolds number regions. Also, the drag coefficient of the streamlined contact strip is almost constant even in high Reynolds number regions, unlike to that of the rectangular shape.[21] Therefore, it is reasonable that the results of the general rectangular contact strip and the optimized contact strip at the Reynolds number of 50,000 would still remain valid in the real condition.

The strength of a noise source on a contact strip surface can be estimated by the pressure fluctuation on the contact strip surface.

$$SPL (dBZ) = 20 \log(\frac{\Delta P}{P_{ref.}})$$
(3)

where, SPL (dBZ) is the un-weighted SPL and P_{ref} is 2×10^{-5} .

The difference of source strength between the rectangular shape and the optimized shape is

$$\Delta \text{SPL}(dBZ) = 20 \log \left(\frac{\Delta P_{rect.}}{2 \times 10^{-5}}\right) - 20 \log \left(\frac{\Delta P_{opt.}}{2 \times 10^{-5}}\right) = -17.72 \text{dB} \quad (4)$$

where ΔP_{rect} and ΔP_{opt} are the pressure fluctuations on surface of the rectangular shaped contact strip and the optimized contact strip respectively.

The amplitude of the pressure fluctuation of the optimized contact strip, ΔP_{opt} , was about 13% of the rectangular contact strip because the pressure fluctuation is directly determined by lift fluctuation and viscous force does not affect lift fluctuation in the streamlined shape. Thus, acoustic noise source strength of the optimized contact strip may be reduced by 17.72dB from that of the rectangular shaped contact strip.

In regard to current collecting performance, the lift amplitude of the optimized contact strip was about 29N when the operation speed of the train was 370km/h. The lift amplitude of the optimized contact strip was much smaller than the rectangular shaped contact strip and the circular shaped contact strip, so the optimized contact strip will show much more stable current collecting performance than the rectangular and circular shaped

Table 5. Mean c_l and c_d

Model	Reynolds number	Mean c _l	<i>Mean</i> c_d
Rectangular shaped contact strip	25000	0.002	1.427
Rectangular shaped contact ship	50000	0.002	1.426
Circular shared contact strip	25000	0.002	1.103
Circular shaped contact strip	50000	0.002	1.107
The final antimized contact strin	25000	0.001	0.152
The final optimized contact strip	50000	0.002	0.155

Table 6. Amplitudes of c_l and c_d fluctuations

	Amplitude of c_l	Amplitude of c_d
Rectangular shaped contact strip	0.7(-0%)	0.025
Circular shaped contact strip	0.55(-22%)	0.011
Final optimized contact strip	0.09(-87%)	0.002

contact strips.

3.6.3 Application of contact strip shape to three dimensional pantograph system.

To investigate the enhanced overall performance when the optimized contact strip is applied to a pantograph system, CFD on a three dimensional pantograph system is performed and also results from wind tunnel experiment [22] is referred.



Fig. 13. One-quarter scale model of single arm and double head pantograph



Fig. 14. Drag forces generated by a single-arm pantograph attached to a rectangular or optimized panhead

For CFD study, full scale computational model of single arm and single head type pantograph in Fig. 15 was used. Velocity condition of the CFD was 45, 60 and 77m/s. For analyzing turbulent flow, LES (Large Eddy Simulation) is applied and the result of turbulent flow is analyzed by Ffowcs Williams-Hawkings (FW-H) acoustics model. As shown in Fig. 16, the flow field in the pantograph with the optimized contact strip is more stable than that of the pantograph with rectangular contact strip. The drag of the optimized contact strip pantograph system decreased by 26% and acoustic noise decreased by 2.0 dB.

In reference 22, one-quarter scale model of single arm and double head type pantograph in Fig. 13 was experimented. The experimental velocity conditions were 20, 40, 60 and 65 m/s. The experimental Reynolds number based on the length between the front and rear of the panhead ranged from 2.05x10⁵ to 6.67x10⁵. The drag of the optimized contact strip pantograph system decreased by 35% as shown in Fig.14 and lift fluctuation decreased by 28%. The acoustic noise source strength of the optimized system may be reduced by 2.85 dB from that with the rectangular shaped contact strip.[22]

$$\Delta \text{SPL} (dBZ) = 20 \log \left(\frac{\Delta P_{rect.}}{2 \times 10^{-5}}\right) - 20 \log \left(\frac{\Delta P_{opt.}}{2 \times 10^{-5}}\right) = -2.85 \text{dB}$$

Because a double head type system has two heads, it is



Fig. 15. Computational model of single arm and single head pantograph



Fig. 16. Velocity contour of rectangular (left) and optimized(right) contact strip pantograph

slightly more efficient than a single head type system.

The drag and acoustic noise reduction of three dimensional experiment and CFD is even less than the reduction of contact strip itself, 17.72 dB because the arm of pantograph and the linkage also generate high level of acoustic noise. For realization of operating speed of 350 km/h, the overall level of acoustic noise has to be reduced by 5~10 dB. Accordingly, the arm and linkage design should be as well as the contact strip.

4. Concluding Remarks

The contact strip shape of a pantograph system for a high speed train was optimized and validated by wind tunnel tests to improve the aerodynamic performance and stability of a pantograph system.

From the design optimization of the contact strip shape, the final optimized contact strip shape was acquired with various CFD methods. For optimizing a robust and lower drag contact strip, design optimizations were carried out rapidly and effectively with GA and EI. Finally, the optimized contact strip shape for lower acoustic noise and drag were selected in the palette set by minimizing both c_d and $|\frac{dC_l}{d\alpha}|$.

In wind tunnel tests, PIV, aerodynamic forces and Strouhal number were measured to validate the optimized contact strip shape. From the test results, the optimized contact strip shape had the smallest drag with lower vertical lift force fluctuation than the rectangular shape and the circular shape. The flow around the optimized contact strip is almost steady without fluctuations. The optimized contact strip gave 89% less drag and 87% less amplitude of lift fluctuation than the rectangular shaped contact strip. We can expect the acoustic noise source strength on the optimized contact strip surface to decrease by about 17.72dB from that of the rectangular shape. When optimized contact strip shape is applied to the pantograph system, the drag and acoustic noise were reduced by 26% and and 2 dB respectively. It is evident to optimize the arm and linkage design as well as the contact strip in order to reduce the level of acoustic noise by 5~10 dB which is required for the realization of the operational speed of 350 km/h.

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