Analysis of Aerodynamic Noise at Inter-coach Space of High Speed Trains

Tae-Min Kim† and Jung-So Kim*  

Abstract

A numerical analysis method for predicting aerodynamic noise at inter-coach space of high-speed trains, validated by wind-tunnel experiments for limited speed range, is proposed. The wind-tunnel testing measurements of the train aerodynamic sound pressure level for the new generation Korean high-speed train have suggested that the inter-coach space aerodynamic noise varies approximately to the 7.7th power of the train speed. The observed high sensitivity serves as a motivation for the present investigation on elucidating the characteristics of noise emission at inter-coach space. As train speed increases, the effect of turbulent flows and vortex shedding is amplified, with concomitant increase in the aerodynamic noise. The turbulent flow field analysis demonstrates that vortex formation indeed causes generation of aerodynamic sound. For validation, numerical simulation and wind tunnel measurements are performed under identical conditions. The results show close correlation between the numerically derived and measured values, and with some adjustment, the results are found to be in good agreement. Thus validated, the numerical analysis procedure is applied to predict the aerodynamic noise level at inter-coach space. As the train gains speed, numerical simulation predicts increase in the overall aerodynamic sound emission level accompanied by an upward shift in the main frequency components of the sound. A contour mapping of the aerodynamic sound for the region enclosing the inter-coach space is presented.

Keywords: Aerodynamic noise, Computational fluid dynamics, High speed train, Inter-coach space

1. Introduction

In recent years, high-speed trains have come to enjoy wide acceptance as swift, convenient, and environment-friendly means of transportation. At the same time, increase in the operating speed poses additional challenges. One of the main challenges is how to cope with the predominance of aerodynamic noise. As train speed increases, the aerodynamic noise level rapidly increases due to turbulent flow and vortex shedding. The parts of the train that significantly contribute toward aerodynamic noise are the pantograph and inter-coach space. The pantograph which supplies electric power to the train during operation is located on top of the train and acts as a source of aerodynamic noise due to vortex shedding. The inter-coach space between the adjacent cars disturbs the air flow, leading to flow separation which also causes vortex shedding [1]. The vortex then impinges on the exterior surface of the train car which in turn transmits noise into the cabin. Research works on reducing inter-coach space noise by adjusting the gap at the inter-coach space, for instance, have been reported [2,3].

The speed dependence of aerodynamic noise can be conveniently expressed via power law relationships with power law coefficients serving as indicators of sensitivity. Data on aerodynamic noise for various train systems operating worldwide today are presented via appropriate power law coefficients. The sound level measurements for new generation Korean high-speed trains during test runs have been taken, and power law coefficients are determined for each test case. The test result suggests the overall aerodynamic noise power law coefficient of 4.4, but the noise emission of different parts of the train such as inter-coach space and pantograph could significantly differ. Detailed analysis of the characteristics of the aerodynamic noise at
The present study extends the previous work by the authors on turbulent flow and aerodynamic noise analyses [4]. A numerical simulation method is developed to elucidate the aerodynamic noise generation mechanism. The turbulent flow analysis that incorporates unsteady flow is performed to gain understanding of the mechanism whereby the vortex formation leads to aerodynamic noise. The noise level is then numerically computed by applying the acoustic analogy methodology.

For characterizing aerodynamic noise at inter-coach space in Korean high-speed trains, a full-scale mock-up of inter-coach space is constructed and tested in the wind tunnel. The same set of conditions as the experimental testing is numerically modeled for turbulent fluid flow and aerodynamic noise analysis. Where feasible, the numerically obtained noise level is compared with the wind tunnel test measurement results under similar conditions in an effort to validate numerical analysis process employed in the present study.

The organization of the paper is as follows: Section 2 presents power law relationships between the aerodynamic noise emission level and the train speed, and serves to motivate the remainder of the present study. Section 3 presents the flow field analysis and subsequent aerodynamic noise analysis based on acoustic analogy method. Validation of the numerical simulation results is sought by comparing with the wind tunnel test measurements. Section 4 presents numerically predicted aerodynamic noise as the train speed is varied. A display of spatial distribution of sound in the form of contour sound map is presented.

### 2. Dependence of Aerodynamic Noise on Train Speed

#### 2.1 Power Law Relationships

The dependence of aerodynamic sound pressure level on train speed can be encapsulated by the following power law relationship.

\[
\text{Sound Pressure Level (dB)} \propto 10\log(\text{train speed}^\alpha)
\]

\(1\)

One of the more commonly known analytical expressions on aerodynamic sound pressure level in high speed trains stipulates that the sound pressure level increases in proportion to the 6th power of the train speed. Aerodynamic noise occurs due to vortex shedding at the boundary layer on the exterior surface of the train as well as due to a mixing shear zone. In contrast to structure-borne noise arising from wheel/rail interactions, aerodynamic noise can be accurately predicted if the material characteristics and surface profile of the train exterior are known. In the case of magnetically levitated trains in which the structure-borne noise due to wheel/rail interactions can be safely neglected, a fairly accurate correlation between analytically predicted and experimentally measured values has been obtained. The main finding along this line of investigation has been the 6th power law relationship between aerodynamic noise and train speed found in MAGLEV.

In contrast to the 6th power law relationship found in MAGLEV as a whole, the operators of the more conventional high speed trains have attempted to derive their own proportionality relationships between the aerodynamic noise and train speed for different parts of the train [5-7]. Table 1 summarizes the power law relationships derived for different parts of TGV-A which served as the base model for Korean high speed train furnish particularly useful reference values.

The theoretical relationship relevant to the present purpose can be derived from the following equations due to Brooks, which shows the aerodynamic sound pressure level as a function of the train speed [8].

#### Table 1: Power law coefficients for high speed train systems

<table>
<thead>
<tr>
<th>Noise type</th>
<th>Train system</th>
<th>Proportionality ((\propto \text{t}^\alpha))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locomotive</td>
<td>TGV</td>
<td>3 (up to 300km/h)</td>
</tr>
<tr>
<td></td>
<td>Coach</td>
<td>3 (up to 300 km/h)</td>
</tr>
<tr>
<td></td>
<td>TGV-A</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>ICE</td>
<td>6–8</td>
</tr>
<tr>
<td></td>
<td>TR70 (MAGLEV)</td>
<td>6 (fluid separation)</td>
</tr>
<tr>
<td></td>
<td>Shinkansen</td>
<td>6</td>
</tr>
<tr>
<td>Wheel</td>
<td>middle coach</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>front locomotive</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>rear locomotive</td>
<td>3.0</td>
</tr>
<tr>
<td>Pantograph(rear locomotive)</td>
<td>5.7</td>
<td></td>
</tr>
<tr>
<td>Cooling fan</td>
<td>front locomotive</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>rear locomotive</td>
<td>4.6</td>
</tr>
<tr>
<td>Front window (front locomotive)</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>Between coaches</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>Bogie</td>
<td>6.1</td>
<td></td>
</tr>
<tr>
<td>Turbulent boundary layer(per square meter)</td>
<td>4.3</td>
<td></td>
</tr>
</tbody>
</table>
For narrow band:

\[ p^2(f) = 8.7 \times 10^{-8} \rho^2 \delta^* U_0^3 \left[ 1 + (\pi S)^2 \right]^3 \frac{1}{2} \]  \hspace{1cm} (2)

For broad band:

\[ p^2(f) = \int_0^\infty p^2(f) df \]

\[ = 8.7 \times 10^{-8} \rho^2 \delta^* U_0^3 \int_0^\infty \left[ 1 + (\pi S)^2 \right]^3 df \]  \hspace{1cm} (3)

For calculating the bandwidth noise, the constant 8.7 \times 10^{-8} represents a value derived from data measured at 25 m distance from the center of the railroad track, \( \rho \) denotes the air density, \( \delta^* \) denotes the equivalent boundary thickness, and \( S \) denotes the Strouhal number.

### 2.2 Determination of Power Law Relationships

Different power law coefficients listed in Table 1 hints that 4.4th power law relationship between the aerodynamic noise and the train speed may be due to a combined effect of the aerodynamic noise characteristics of different parts of the train with distinct power law relationships of their own.

The two parts of the train that contribute significantly to the aerodynamic sound pressure level are the inter-coach space and pantograph.

To obtain the aerodynamic noise characteristics of inter-coach space and pantograph, wind-tunnel test runs were taken by using full-scale models of inter-coach space and pantograph. The train operating speed range was 185 km/hr to 235 km/hr for inter-coach space and 250 km/h to 400 km/h for pantograph. The data were obtained by taking measurements at horizontal distance of 300 mm for inter-coach space and at 5 m distance for pantograph. The mock up for inter-coach space is shown in Fig. 1 [4] while the mock up for pantograph is shown in Fig. 2 [9].

Figs. 3 and 4 represent wind-tunnel sound pressure measurements and the associated best fit power-law curves for inter-coach space and pantograph, respectively. The 4.4 power-law estimation for the whole train is also shown for comparison.

Fig. 3 shows that the wind-tunnel sound pressure measurements at the inter-coach space show the best fit with the curve representing the 7.7th power law given by the solid line. This line is clearly different from the reference value of 4.4th power law suggested for the train as a whole. In contrast, the sound pressure measurements for pantograph of Fig. 4 show more gradual increase with the train speed, showing the best fit with the curve representing the 3.7th power law. The results confirm the early hypothesis that different parts of the train may have distinct power law coefficients. The power law coefficient of 4.4 for the train as a whole can thus be regarded as a weighted average value. The 7.7th power law suggested for inter-coach space means that at higher train speed, this aerodynamic noise component could very well dominate noise emission from the train. The remainder of this paper focuses on investigation of the noise emission characteristics at train inter-coach space.
3. Numerical Analysis and Experimental Validation of Aerodynamic Noise at Inter-coach Space

3.1 Wind Tunnel Test Setup

For validating numerical prediction of aerodynamic noise level at inter-coach space in Korean high-speed train, a full-scale mock-up of inter-coach space is constructed and tested in the wind tunnel. The mock-up is made of acryl, and the dimension of the inter-coach space is set at 300 mm. The experimental setup of the inter-coach space mock-up is shown in Fig. 1.

A suction-type wind tunnel with medium size subsonic speed open-loop control has been utilized for sound measurements. The inlet wind speed is varied from 185 km/h to 235 km/h with measurements taken for each speed. The inlet velocity is equivalent to the train velocity. For noise measurement, a DAT recorder and a sound-level meter NL-20, a calibrator and a tripod are used. As shown in Fig. 1, the sound-level meter is placed at a location 300 mm from the end of the inter-coach space in the downstream direction [10].

3.2 Numerical Analysis of Aerodynamic Noise

3.2.1 Fluid Flow Analysis

The same set of conditions as the wind tunnel test is duplicated in a numerical model and turbulent flow simulation performed by applying appropriate computational fluid dynamics techniques. For minimizing the number of meshes, only 1/2 of the domain is modeled by utilizing the symmetry. For the flow analysis results to be useful as inputs to the subsequent aerodynamic noise analysis, the mesh size has to be determined by considering the smallest wavelength of the sound wave of interest, and also requires appropriately small time step. For the sound frequency in the range of 50 Hz to 2,000 Hz, the mesh size has been set to be 1/10 of the wavelength corresponding to the upper limit frequency of 2,000 Hz. Approximately six hundred thousand tetrahedral meshes with the size range of 1~34 mm have been generated in constructing a CFD model as shown in Fig. 5.

The fluid flow associated with the aerodynamic noise is dominated by unsteady-state flow. In the present study, unsteady fluid motion analysis of three dimensional incompressible flow has been carried out using commercially available fluid analysis software FLUENT. For computational efficiency, steady-state fluid motion analysis based on K−ω equation turbulent flow model is first carried out and the result subsequently fed as the initial condition for unsteady-state fluid motion analysis. Fig. 6 shows the side view and top view contours of the vortices distributions obtained by steady-state fluid flow analysis. The figure shows the generation of periodic vortices that lead to large vortices generated at the tip [11].
For obtaining the unsteady-state turbulent flow, Large-Eddy Simulation (LES) method is employed, and Smagorinsky-Lilly model is selected for computing subgrid scale viscous model [12]. For comparison with wind tunnel testing results, the inlet wind speed has been set at 185 km/h, 200 km/h and 235 km/h, respectively.

A second order implicit finite difference method is used in conjunction with double decision. To ensure sufficient accuracy, the time step of 0.05 ms which is less than 1/10th the period corresponding to 2,000 Hz has been selected. The flow duration of 0~3 s is chosen so that the time duration exceeds 10 periods of 50 Hz. Table 2 summarizes the parameters used.

### 3.2.2 Aerodynamic Noise Analysis

Acoustic analogy method based on FW-H (Frioucs-Williams Hawking) equation is applied to estimate aerodynamic noise from the fluid flow. The equation is cast in the form of a wave equation developed from the continuity equation and the Navier-Stokes equation, and has proven quite useful in problems involving fluid flow. FW-H equation is expressed in terms of sound sources, which include two surface sources (monopole and dipole) and one volume source (quadrupole), as shown below:

\[
p'(x, t) = p'_T(x, t) + p'_L(x, t) + p'_O(x, t)
\]

Equation 4 contains the thickness noise dependent on the shape and kinematic conditions (monopole: \( p'_T \)), the loading noise engendered from friction between the body and the surrounding fluid (dipole: \( p'_L \)), and quadrupole noise (\( p'_O \)) source due to nonlinear wave propagation, shock waves, and turbulence in the fluid flow field. For low Ma fluid motion, the effect of the quadrupole noise source is negligibly small. The present study employs FW-H module in FLUENT that includes the thickness noise and the loading noise sources only. Just like in the wind tunnel test, the sound measurement point during all numerical simulation runs is located 300 mm from the end of the inter-coach space in the downstream direction.

### 3.3 Validation of Aerodynamic Noise

To validate numerical simulation results, comparison with wind tunnel experiment under identical boundary conditions and at the identical inlet wind speed in the range of 185 km/h ~ 235 km/h is performed. The effect of the blower which is related to the number of the turbine blades in the blower has been calculated and deleted from the wind tunnel measurement data. Fig. 7 compares the numerically derived sound pressure level of inter-coach space with the wind tunnel measurement data. Fig. 7 shows that except for the first frequency peak, the magnitudes of the other peaks are comparable but frequency at which the peak is observed is somewhat different. This discrepancy is thought to be due to differences in the conditions inputted into the numerical simulation and the actual conditions existing in the wind tunnel experiment. When the fluid flow speed input to the simulation runs is uni-
formly increased by 10 m/s, a much better fit with the experimental results is obtained.

The effect of the cavity flow arises from the flow feedback phenomenon that starts with the formation of the vortices due to the desquamation of the flow as it passes over the front edge of the mud-flap and the cavity. The flow then crashes into the rear edge and generates a sound wave. The sound wave is in turn transmitted to the front edge and engenders yet additional vortices. During wind tunnel testing, severe vibration of the mock-up was observed due to this phenomenon. The frequency of the vibration within the cavity engendered by acoustic pressure feedback mechanism can be predicted by empirically based Rossiter’s equation derived by considering the cavity flow and acoustic pressure feedback phenomena, as given by Eq. (5).

\[
\frac{L}{U_c} + \frac{L}{c} = \frac{n-\beta}{f_n}, \quad n = 1, 2, 3, \ldots
\]

where \(L\) denotes the length of the cavity, \(U_c\) denotes the convection velocity, \(c\) is the sound velocity, and \(\beta\) is the phase lag set to 0.25. The convection velocity used in Rossiter's equation is approximately 60% of the flow velocity.

Fig. 8 shows the frequency components for different fluid flow speeds corresponding to the train speed in the range of 185 km/h ~ 235 km/h and based on Rossiter’s equation. During numerical simulation, fluid flow speed is adjusted by 10 m/s to obtain a better fit with the wind tunnel test results. With this adjustment, the figure shows good agreement between the numerically predicted aerodynamic noise level and the experimentally determined noise level.

4. Numerical Simulation of Aerodynamic Noise at Inter-coach Space

4.1 Simulation Results for Different Train Speed

The characteristics of aerodynamic noise at inter-coach space of the new generation Korean high speed train are numerically investigated for the train speed of 200 km/h, 300 km/h and 400 km/h. As described in the previous section, the numerical scheme has been validated by wind-tunnel test results for the train speed in the range of 185 km/h ~ 235 km/h. Fig. 9 presents sound pressure level in the time domain. Although direct comparison is not possible due to vastly different measurement conditions, a fairly steep increase in the sound level with train speed shown in Fig. 9 is consistent with the high sensitivity shown in Fig. 3.

The noise spectrum taken for the flow time interval of 0.1 ~ 0.3 seconds is shown in Fig. 10, while the same data are shown in 1/3 octave band form in Fig 10. Both figures
show that as train speed is increased, there is a corresponding upward shift in the peak frequency components. For the train speed of 400 km/h for instance, substantial portion of the overall noise level can be attributed to frequency components in excess of 500 Hz.

**Fig. 11** Noise level vs. train speed in frequency domain (1/3 octave band)

**Fig. 12** Map of overall aerodynamic noise

**Fig. 13** Map of aerodynamic noise by octave bands
4.2 Spatial Distribution of Aerodynamic Noise

Numerical simulation also allows display of spatial distribution of aerodynamic noise within the inter-coach cavity and the adjacent region. Fig. 12 represents the contour map of the overall sound pressure level in the frequency range of 250 Hz ~ 4,000 Hz for the train speed of 200 km/h. It shows that the maximum sound pressure level exists within the cavity. It also shows not insignificant noise at the mouth of the cavity toward the downstream of the flow.

Fig. 13 shows the contour map of the sound pressure level by octave bands. There tend to be large variations in the sound pressure level at lower frequency bands. At higher frequency bands, spatial variation of the sound pressure level as well as the absolute sound level is diminished. Spatial distribution of the particular frequency component can also be obtained for more detailed analysis. Fig. 14 shows the map of the sound pressure level for the peak frequency component of 315 Hz, where large spatial variation is evident.

5. Conclusion

The present study proposes a numerical analysis method for predicting aerodynamic noise at inter-coach space of high-speed trains. The turbulent flow field analysis incorporating unsteady state fluid flow is carried out to determine vortex formation. The acoustic analogy method is then applied to determine the emitted aerodynamic sound. The proposed numerical simulation method is validated for a selected range of train speed by comparing the simulation results with the wind tunnel test measurement results subject to similar boundary conditions. The proposed method is used to predict the characteristics of the aerodynamic noise at inter-coach space of high speed trains.

Acknowledgement

This research (Title: Development of Biomimetic Design Methodology) was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2010-0007670) and 2012 Hongik University Research Fund.

References
