

# CHARACTERISTICS OF AERODYNAMIC NOISE FROM THE INTER-COACH SPACING OF A HIGH-SPEED TRAIN

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#### Abstract

As the speed of high speed trains increases, the aerodynamic noise tends to dominate all other noise sources. Several measurements for high-speed trains in Korea confirmed that aerodynamically generated noise is significant when the train speed exceeds 250km/h. This phenomenon becomes prominent in the low frequency range below 200Hz, especially, when the train passes tunnels. It has a baneful influence upon interior noise because the sound insulation characteristic of the car-body structure is very weak in this low-frequency range. In this paper, experiments were performed in order to investigate the characteristics of aerodynamic noise sources generated from the inter-coach spacing of a high-speed train. It has been found that the low frequency noise is strongly dependent on the size of the inter-coach spacing that increases the turbulent intensity of the flow along the train surface and also inside the cavity. These pressure fluctuations excite the train structure which in turn radiates noise inside the passenger cabin. Measurements of both the inside and outside of the cabin are carried out to investigate the characteristics of the noise. Also performed is an array measurement to locate different noise sources from the high-speed train. Finally efforts have been made to reduce the interior noise level by varying the width of mud-flaps, rubber curtains used to prevent inter-coach components from contamination, and the results show significant decrease in the interior noise for the optimized width of mud-flaps.

# **1. INTRODUCTION**

Noise sources of a high-speed train can be classified into categories such as rolling noise equipment noise, and aerodynamic noise. Contributions from these sources are dependent on the speed of a train and it is well known that the aerodynamic noise becomes dominant when the train speed exceeds 250~300km/h [1]. Aerodynamic noise originates from various sources: vortex shedding due to a pantograph and turbulent boundary layer or flow separation from the head of a train, bogies, and intercoach-spacings. It contributes not only to outdoor noise by radiating into far-field but also to interior noise by acting on the vehicle structure and re-radiating in to the inside of the cabin. This structure-borne noise has its dominant

components below 200Hz [2]. Usual panel structures used for a passenger coach of a train show good transmission loss characteristics in the mid-to-high frequency range but they are relatively ineffective in the low frequency range. Hence low frequency noise sources have a baneful influence upon the interior noise of a train.

High-speed trains with the maximum speed of 300 km/h, named as Korea Train eXpress (KTX), have started revenue services since April 2004. In addition to the introduction of KTX trains, which are based on TGV models, Korea Railroad Research Institute has been developing a high-speed train system named as HSR-350x. A number of noise measurement campaigns for KTX trains revealed that interior noise has excessive components below 200Hz range and it became the cause of public grievance during commercial operation. One of the special features of KTX and HSR-350x trains are an articulated bogie which connects two coaches and hence it significantly lowers the degree of rolling noise and vibration inside the passenger coach. However it is difficult to avoid inter-coach spacing that creates aerodynamic noise.

This paper deals with experimental results to examine characteristics of noise generated from high-speed trains, especially from the inter-coach spacing. First the noise measured inside the KTX and HSR-350x trains have been investigated to show the effect of mud-flaps, rubber curtains used to prevent inter-coach equipment from contamination. Wind tunnel tests are carried out to examine mechanism and spectral characteristics of noise generation from a cavity. Experiments show that flow feed-back between the edges of a cavity results in excessive noise from the cavity at particular frequencies depending on the size of the cavity. Efforts have been made to reduce the interior noise level by varying the width of mud-flaps. Also performed is an array measurement to locate noise sources. A spiral array with 48 microphones has been used to investigate noise sources from the outside of high-speed trains at the speed of 300km/h.

## 2. INTERIOR NOISE OF KOREAN HIGH-SPEED TRAINS

A KTX train consists of 20 compartments, including 2 power cars, 2 motorized cars and 16 passenger coaches. In order to investigate the effect of inter-coach spacing mud-flaps for the half of passenger coaches were replaced with wider ones, i.e., the size of the gap was reduced by 12cm. Noise measured in two coaches with different mud-flaps have been compared in figure 1. The figure shows time history of equivalent sound pressure levels measured at the center of coaches, 1.2m above the floor. Interior noise level increases approximately 5~7 dB(A) when the train passes a tunnel and it is clearly observed in the figure. Also found is the effect of changes in mud-flap width. Interior noise level has been decreased approximately 2~3dB(A) on open field and 3~5dB(A) in tunnels, respectively. The aerodynamically generated noise has greater influence in tunnels because the radiated wave reflects from tunnel walls and returns to the train. Shown in figure 2 is the frequency spectrum of interior noise. It is found that noise from wide inter-coach spacing has dominant component below 100Hz and this low frequency component is dramatically reduced in case of the narrower gap.

For the HSR-350x interior noise measured before and after replacement of mud-flaps has been compared. Equivalent noise levels averaged over 5 seconds have been calculated along with average train speed over the same time span. Shown in figures 3 and 4 are noise level in open field and tunnels, respectively. Variations in noise level are observed for the same speed range because measurements were not carried out on the same day. Considering theses facts, the effect of changes in mud-flap width is seen to be rather small compared to the case of KTX trains. It is presumed that the difference in the effect of mud-flap width in the two trains is due to the difference in sound transmission loss characteristics of the car-body structures. Although exterior shapes are almost same for both the KTX and HSR-350x trains there are several differences in car-body structures. HSR-350x uses doubled walled aluminum-extrusion composite materials for the car-body instead of the mild steel for KTX. The windows of HSR-350x uses 4 layers of glasses and gaps are filled with films and argon gas while those of KTX uses 3 layers filled with dry air. Hence the sound insulation characteristics of HSR-350x is better, especially for low frequency noise sources.



Figure 1. Time history of interior noise measured in KTX coaches with wide and narrow inter-coach gaps.



Figure 3. Interior noise of HSR-350x in open field measured before and after the changes in mud-flaps.



Figure 2. 1/3 Octave band frequency spectrum of interior noise measured in KTX coaches with wide and narrow inter-coach gaps.



Figure 4. Interior noise of HSR-350x in tunnels measured before and after the changes in mud-flaps.

#### **3. WIND TUNNEL TEST**

A model for the inter-coach spacing and mud-flaps has been used in a wind tunnel test to examine mechanism and spectral characteristics of noise generation from a cavity. Figure 5 shows a schematic diagram of the wind tunnel test model. Mud-flaps are attached at the mouth of a cavity made of a doubled walled acryl box. Dimension of the box is 0.8m×0.8m×1.6m and the gap between the acryl layers are filled with sand to reduce unwanted vibration. The spacing between mud-flaps is adjustable and six microphones (B&K Type 4951) are located on the downstream of the flow to measure wall pressure and blocked pressure according.

Shown in figure 6 are variations of blocked pressure according to changes in the gap size between mud-flaps. Flow speed was 180km/h and pressure has been measured for the size of the gap from 0cm to 30cm. Results show that blocked pressure is proportional to the size of the gap. When the spacing becomes larger than 20cm strong vibration of the cavity box has been observed and some peaks in the blocked pressure are found in the low frequency range. Uniform flow separates at the leading edge

of the cavity and creates turbulence. It is transferred to the direction of downstream, reflected from the trailing edge, and then interacts with the flow from the opposite direction. Frequencies of this flow feedback phenomenon can be found from the Rossiter's equation [3] as shown in equation (1).

$$\frac{L}{U_c} + \frac{L}{c} = \frac{n - \beta}{f_n}, n = 1, 2, 3L$$
(1)

In this equation L is the spacing of the cavity opening,  $U_c$  is convection speed, c is sound speed, and  $\beta$  is the phase lag. Convection speed has been calculated from phase differences of the cross-spectrum obtained from pressure measured by two microphones [4]. The first term in equation (1) is time for the flow to travel from the leading edge to the trailing edge and the second term is time for the reflected wave from the trailing edge to reach the leading edge. The right-hand side term represents *n*-th order resonant frequency for the flow and sound wave. For the time delay  $\beta$  experimental value of 0.25 is used in general. For the experiment shown in figure 6 the first resonant frequency calculated from the Rossiter's equation is 65Hz, which is pretty close to the frequency of the first peak, 63Hz, shown in figure 6. Errors between experimental results and calculated results become bigger for higher order resonances.



Figure 5. A schematic diagram of a wind tunnel test.

Figure 6. Variations of blocked pressure according to changes in the spacing between mud-flaps.

## 4. MICROPHONE ARRAY MEASUREMRNT

Microphone array measurement has been carried out using a spiral array with 48 microphones to investigate noise sources from the outside of high-speed trains. The measurement took place along the *Kyungbu* high-speed line near Osong depot in Korea. Figure 7 and 8 show the microphone array used for the experiment and the measurement site. The diameter of the array is 2.4m and each microphone locates  $0.1m \sim 0.2m$  apart. Sampling frequency for data acquisition was 16kHz and a low pass filter (3.4Hz) and a anti-aliasing filter (7.3kHz) were applied using National Instruments PXI-4472. Distance between the array and the rail was 5m and the height of the array was 1.6m ~ 2.0m. Resolution of an array measurement is determined from a beam width *b*:

$$b = r_0 \frac{\lambda/2}{D}, \qquad (2)$$

where  $\lambda$  is the wavelength,  $r_0$  is the distance between the source and the array, and D is the diameter of the array. Sources at least 2b apart can be separated from the array measurement.

In order to validate the microphone array and analysis results the first measurement was carried out with two horns, generating 700Hz harmonic sound, placed at the 5<sup>th</sup> and 6<sup>th</sup> bogies from the left of HSR-350x. Figure 9 shows reproduced sound field at 600Hz ~ 800Hz range and the microphone array exactly locates the two horns.



Figure 7. The spiral array with 48 microphones.



Figure 8. KTX train passing by the measurement site.



Figure 9. Noise from 700Hz horns at 5<sup>th</sup> and 6<sup>th</sup> bodies.

Shown in figure 10 is noise source map for 70~90Hz for HSR-350x at 297km/h. The color map represents relative source levels at the specified location and difference between the maximum and the minimum levels is denoted by the depth. Resolution at this frequency is approximately 9m, and hence it is difficult to separate closely located noise sources. However the lengthwise location of the noise sources can be separated from the result because the coaches are approximately 19m long. As shown in figure 10 HSR-350x has 2 power cars at each end, 2 motorized trailers next to them, and 3 passenger's coaches in the middle. Mud-flaps at the end of the  $3^{rd}$  car from the left ( $1^{st}$  passenger's coach) were replaced with narrower ones (*i.e.* smaller inter-coach spacing) before the measurement. Major noise sources are found at the

head of the first car, at the trailing bogie of the last car, and between cars. It is interesting to notice that no source has been found at the end of the  $3^{rd}$  car. Because wheels of HSR-350x are well maintained contributions from rolling noise can be assumed similar for all wheels. Therefore it is possible to infer that the discrepancy of the noise sources of the  $3^{rd}$  car is attributed to the difference in the mud-flap length. This result confirms the spectral characteristic of noise generated from the inter-coach spacing shown in figure 2. Figure 11 shows noise sources at 300Hz ~ 1kHz range. In this figure resolution is 0.4~1.2m and noise sources from the head, bogies, and the pantograph are clearly seen.



Figure 10. Noise sources map of the HSR-350x at 297km/h (70~90Hz). Max 39.1dB, depth 6dB.



Figure 11. Noise sources map of the HSR-350x at 297km/h (300Hz~1kHz). Max 34.5dB, depth 12dB.

# **5. CONCLUSIONS**

This paper deals with experiments to investigate the characteristics of aerodynamic noise sources generated from the inter-coach spacing of a high-speed train. The inter-coach spacing creates flow separation and the resulting turbulent pressure fluctuations excite the train structure which in turn radiates noise inside the passenger cabin. This aerodynamically generated noise has dominant component near 80Hz range and it has been reduced by narrowing the inter-coach spacing. Wind tunnel test shows that flow feed-back between the edges of a cavity results in excessive noise and the frequency is dependent on the cavity length. Also performed is a microphone array measurement using 48 microphones. The measurement results confirm low frequency noise generation from the inter-coach spacing.

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