INTERIOR NOISE OF A KOREAN HIGH-SPEED TRAIN IN TUNNELS

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Abstract

High-speed trains with the maximum speed of 300 km/h, named as Korea Train Express (KTX), have started revenue services since April 2004. Because of the geomorphologic conditions of Korea a large portion of the 'Kyung-Bu' line is comprised of tunnels or bridges, which may cause excessive noise in a vehicle. The vibration generated by the trains propagates into the tunnel and the vehicle structure and it can be radiated as noise inside the vehicle interior. This noise can usually be heard as low frequency structure-borne noise. Measurement of the noise and vibration inside the KTX vehicle confirmed that the noise comprises of frequencies below 250 Hz with a couple of broad peaks. In this study the analysis has been presented to reveal the cause of the excessive noise level and the correlation between the vehicle interior noise and the vibration of the tunnel structure.

Introduction

The Korea Train Express (KTX), started its revenue services since April 2004 have brought a radical change in lives of Koreans. The train sets are based on TGV technology and the maximum commercial speed is 300km/h. Although the overall performance of the KTX vehicle has been estimated to be successful after a few months of the commercial operation, some technical problems have been raised including the interior noise of the vehicle.

One of the most significant reasons for the interior noise of the train is the vibration that is created due to the contact of the wheel and the rail, especially when the train passes over the joints in railway tracks. However, KTX rails have no joints, and thus produce less noise and vibration despite the significantly greater speed of operation. For KTX, the 300m long rails were made using a special welding technique. The individual rails were then connected together to create a continuously welded track. Besides, KTX trains are designed with wheels installed between the compartments rather than below each compartment, which significantly lowers the degree of noise and vibration caused by the wheels.

After a few months of revenue service, it has been found that most of the KTX vehicles satisfy the interior noise specification for the ordinary operating condition. However, the interior nose level passes the specification when the train passes some tunnels. The Korean high-speed line consists of 412km double track, including 112km (27%) of at-grade sections, 109km (27%) of viaducts and 191km (46%) of tunnels. Hence a quick counter-plan should be considered to reduce interior noise levels inside tunnels. The noise level inside tunnels is expected to increase due to the reflections of sound waves from the wall. Table 1 shows some specifications for the interior noise of high-speed trains. It is shown that the interior noise level inside the tunnel is 5~7dB higher than those of the open field. The noise specification for the KTX vehicle is more stringent than that of the other high-speed trains.

Table 1. Interior noise specification for high-speed vehicles

Vehicle	Max. Speed (km/h)	Noise level [dB(A)]	
		Open field	Tunnel
KTX	300	66	73
TGV	300	66	71
Shinkansen	240	69	74
ICE	250	65~68	70~73

This paper deals with the status of the interior noise of the KTX vehicles during the commercial operation. Sound pressure levels are measured in a vehicle while it is passing through tunnels and the results are compared with those measured on a viaduct and an open field. It has been found that the interior noise of the passenger's compartment is larger for the tunnel with slab tracks than that for ballasted tracks. Also shown are the noise levels measured under the vehicle and vibration levels for some points on the tunnel and vehicle structures. The measurement data are analyzed to predict the cause of the excessive interior noise in tunnels, especially in those with slab tracks.

Interior noise of high-speed trains

The sources of the vehicle interior noise can be classified into categories such as equipment noise, airborne noise, aerodynamic noise, and the structure-borne noise. Equipment such as air-conditioners and ventilation systems are responsible for the equipment noise. Aerodynamic noise originates from the turbulent boundary layer or flow separation acting on the vehicle structure. The air-borne noise, generated from various sources, propagates into the interior of the train through the vehicle structure or through the gaps in gangways or windows and its components are usually above 200Hz. On the other hand, the structure-borne noise has its dominant components below 200Hz, results from the re-radiation of the vehicle structures that are excited by vibro-acoustic sources [1,2]. Rather often, when the frequencies of interests are low, the terms "structure-borne noise" and "vibration emission" are used interchangeably. Usual panel structures used for the vehicle show good transmission loss characteristics in the mid-to-high frequency range but they are relatively ineffective in the low frequency range. Figure 1 shows the typical transmission loss characteristics of some materials including the floor structure of the KTX vehicle [3]. Usually it is very difficult to reduce the low frequency structure-borne noise by using conventional noise insulation methods.

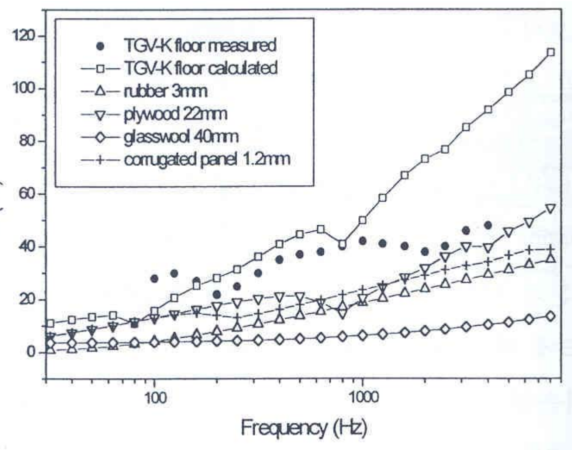


Figure 1. Transmission loss of panel structures.

There have been a number of works regarding ground-borne noise of tunnel structure [4, 5], however, references for the interior noise in tunnels are relatively rare. There are often instances of passengers suffering from a ringing-in-the-ears effect while using express trains or airplanes. Such an effect is caused by the difference in atmospheric pressure between the inside and outside of the passenger compartments. With express trains, this effect is mainly generated while passing through a tunnel. For the Japanese Sinkansen, the wavelength of the pressure wave has found to be 17m for a tunnel of 9m in diameter and the corresponding acoustic energy is distributed below 20Hz [6]. However, for KTX vehicles, computers in the passenger compartments deliver an order to cut-off external air by expanding rubber tubes inserted around the entrance doors when the speed of the train exceeds 5km/h. In particular, the passenger compartment ventilation facility is automatically closed while passing through a tunnel, which prevents changes in air pressure inside the passenger compartments to eliminate the ringing in the ears. In case of German trains, interior noise increases approximately 10dB when a train passes a tunnel with a ballasted track at the speed of 200 km/h [1]. For a ballast-free track without absorption, the increase is 7dB larger than that of the ballast track. In these cases the increase in the interior noise is inferred from the air-borne noise in the mid-to high frequency ranges rather than the structure-borne noise.

Interior Noise of KTX in tunnels

As it was mentioned earlier, noise inside tunnels is of great interest because of many tunnels in the Korean high-speed line. Although ballasted tracks are still popular, slab tracks have drawn much attentions recently because they have some significant advantages such as low maintenance, high availability, low structure height, and low weight. The conventional ballast tract is adopted for the majority portion of the Korean high-speed line. However slab tracks are used for some long tunnels because of the convenience in maintenance works. Shown in Table 2 are the general characteristics of the ballasted and the slab track used in KTX line.

Table 2. General track characteristics

	Ballasted	Slab
	Crushed stone 31.5/50mm Thickness min. 350mm	BTS height = 340mm width = 3160mm
Sleeper	Pre-stressed concrete block L = 2.6m, Weight = 3kN	Rheda Type concrete sleeper Weight = 2.5kN
Sleeper spacing	0.625m	0.63m
Fastening	Elastic Pandrol e-clip 25kN/rail	Vossloh 330 system
Rail	UIC 60	UIC 60
Rail pad	Studded rubber pad t = 10mm, k = 65~95kN/mm	t = 10mm 1) Rail Pad = 100kN/mm 2) Baseplate pad = 22.5kN ± 2.5kN

Each KTX train consists of 20 compartments in total, including 2 power cars, 2 motorized cars and 16 passenger compartments. Measurements of the interior noise were performed in the motorized car and the 2nd passenger compartment. Microphones (B&K) and a recorder (SONY SIR-1000) were used for the measurement. The microphones are placed 1.6m high, at the center of the compartment as described in an international standard [7].

Figure 2 shows the equivalent sound pressure level in the passenger compartment versus the train speed measured in some tunnels of the KTX line. More than 10 seconds of record was used to calculate each equivalent noise level. Noise level increases steadily as the train speed increases, although some variation exists. Noise level ranges from 72 to 80dB(A) when the velocity is above 295km/h. It is noticeable that the interior noise level inside the slab tunnel is larger than that of the ballasted track. The differences are approximately 5dB(A).

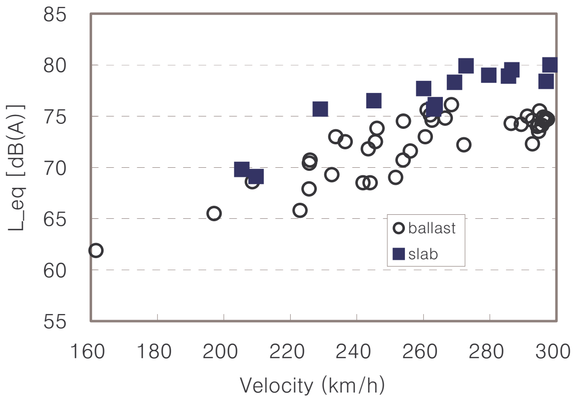


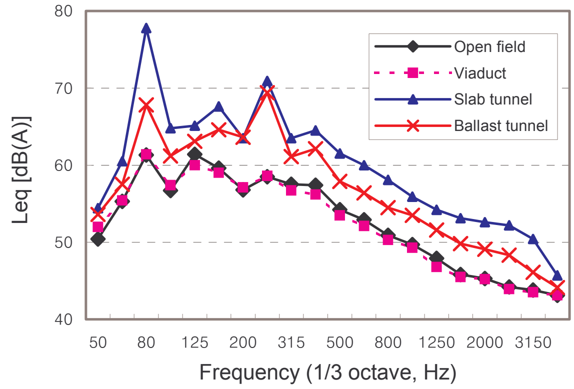
Figure 2 Interior noise of the passenger's compartment inside tunnels with ballasted and slab tracks.

For a complete description of the interior noise, frequency spectrum of the interior noise in the tunnel has been compared with those measured in an open field, on a viaduct, and in a ballasted tunnel. We selected a 3km long section without any noise barrier for an open field measurement. The length of the viaduct, the slab tunnel, and the ballasted tunnel chosen for the measurement are 6.3km, 10.0km, and 1.8km, respectively. Beside the speed of the vehicle, there are many factors that affect the interior noise such as the grade of the track and the acceleration of the vehicle. For data given in the table 3, we selected sections where the influence of the grade and speed variation is minimum. Noise levels measured in a passenger compartment and a motorized car are compared. Also shown are exterior noise levels measured using a microphone placed under a vehicle body near a bogie. Shown in Figure 2 are frequency spectra for these measurement data.

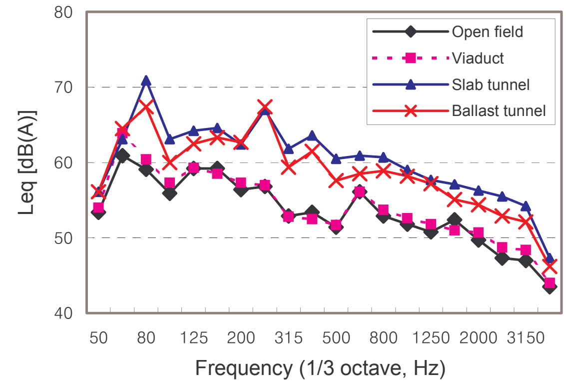
Table 3. Comparison of interior and under-body noise level

Section	Avg. Speed (km/h)	Noise level [dB(A)]		
		Passenger car	Motorized Car	Under body
Open field	297	69	69	115
Viaduct	296	69	70	121
Slab tunnel	289	80	76	125
Ballasted tunnel	297	75	74	123

(a)



(b)



(c)

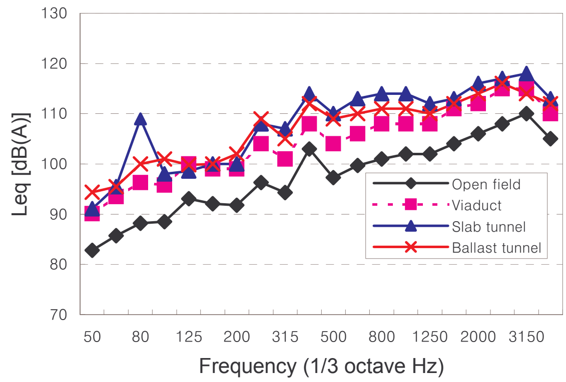


Figure 3 Frequency spectra of interior noise; (a) passenger compartment, (b) motorized car, (c) under car body.

Results show that the difference in interior noise levels measured in the open field and on the viaduct is not noticeable, although the under body noise level on the viaduct is approximately 6dB higher. We presume that the structure-borne noise from the viaduct structure is one of the causes of the increment of the under body noise. Furthermore rails on bridges or viaducts have joints that create impact noise when wheels pass them. However interior noise spectra for the open field and the viaduct are very similar to each other as shown in Fig 3(a) and 3(b). It shows that an increase of the under body noise does not affect the interior noise on the viaduct. Also found is that, for an open field and a viaduct, the noise level in a motorized car is usually higher than that in a passenger car due to noise from the power car. This can be observed as an increase of high frequency components above 500Hz in Fig. 3(b).

A remarkable aspect of the frequency spectra is the peak in the low frequency region. It can be seen that the noise component with its center frequency at 80Hz is as much as 10dB higher than those of the adjacent bands. It is most noticeable in the passenger compartment and inside the slab tunnel. For the motorized car in the open field and on the viaduct, peaks are found at 63Hz band. It is also interesting to note that in tunnels, noise level in a passenger car is higher than that in a motorized car. The bogies for the power and motorized cars are located below each car unlike the passenger compartment where they are placed between the cars. Hence one can expect that the motorized car and passenger car will show different vibrational and acoustic characteristics.

For further understanding of the phenomena acceleration data have been measured at some positions in tunnels. The acceleration level of the sleeper in a ballasted track is much higher because it's motion is relatively free compared to that of a slab track. Figure 4(a) shows high level of acceleration between 50 to 250Hz region that corresponds to the source of the structure-borne noise. Besides, the resonance of the slab structure has been observed below 30Hz. One can expect that there is strong coupling between the track and the vehicle and a further analysis is necessary.

Vibration level (power spectral density) measured at the side of the passenger compartment in a slab tunnel is shown in Fig. 5. A significant increase of vibrational energy near 75Hz can be seen which is in accordance with the noise spectra given in Fig. 3. From several measurements in tunnels, we have experienced that noise level near the window side of the passenger car is much greater (up to 10dB(A)) than that measured in the center. It is presumed that a fundamental acoustic mode across the width of the compartment is created with its maximum at each side of the vehicle and minimum at the center. Hence the noise level heard by passengers might be even higher than that reported. It should be noted that the increase of a noise level near the window side was less than 5dB(A) in the open field. We infer that reflected sound from the wall of the tunnel is transmitted through the structure of the vehicle and contributes to the interior sound field.

(a)

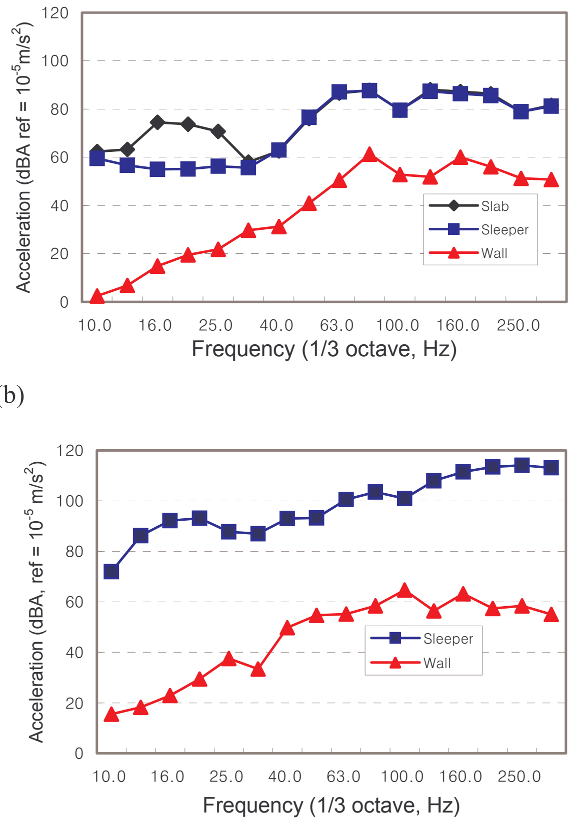


Figure 4 Acceleration measured in tunnel structures; (a) slab tunnel, (b) ballasted tunnel.

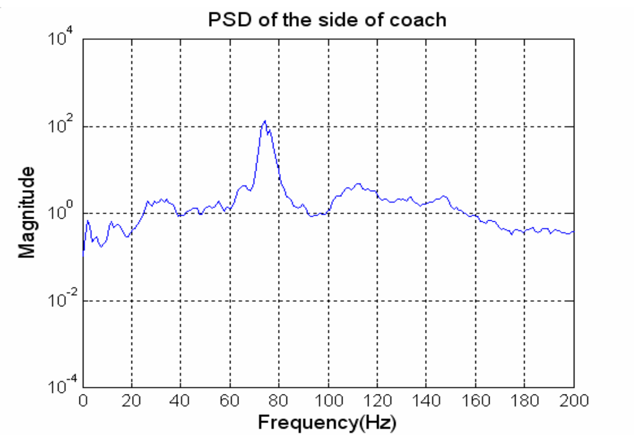


Figure 5 Vibration level measured at the side of the passenger compartment in a slab tunnel.

Conclusions

The present work has dealt with the interior noise of the KTX vehicle in tunnels. Interior noise has been measured and analyzed in vehicles running through tunnels. The results have been compared with those measured in an open field, on a viaduct and in a ballasted tunnel. It has been found that interior noise increases as much as 10dB(A) in tunnels. The increase is larger in tunnels with slab tracks compared to those with ballasted tracks. A major increment of noise has been observed in the 80Hz band that corresponds to the increase of vibration of the side panel of the vehicle and the structure-borne noise from the track structure.

Further measurements and analyses are being carried out to reveal the cause of the excessive noise level in slab tunnels.

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