A Correlation Study of Vibration and Noise Signals by Analyzing Its Responses for Monitoring of High-Speed Trains

SIU-KAI LAI, YI-QING NI and LIN-HAO ZHANG

ABSTRACT

In high-speed trains, vibration has long been an inevitable problem caused by many ambient effects, including wheel polygonization, rail defects, imperfect suspension systems, aerodynamic instabilities, meteorological conditions, and topographical variations, which can disturb the dynamic response and interior noise levels. These factors can be either correlated with or independent of each other. Excessive vibration levels of high-speed trains can lead to a series of problems related to ride comfort, train stability and track deterioration. Naturally, vibration and noise are interacted with each other, in which noise can be transmitted through air-borne and structure-borne paths to the interior of high-speed trains. The variation of noise levels is very sensitive as high-speed trains pass through various topographical terrains. Besides, aerodynamic noise becomes dominant as the speed of trains increases or trains travel through tunnels. Tracing the source that generates anomaly noise responses can give an important clue for monitoring operational safety and detecting adverse status. Pilot studies for the online monitoring of noise in the bogie of a high-speed train running on a railway in China have been conducted. The present study aims to investigate the relationship between ambient vibration induced by the rail-wheel interaction and noise measured from the bogie. The dynamic behaviour of high-speed trains is analysed in relation to the topographical variations (e.g., tunnels, viaducts, and plain area). Noise levels of the bogie are also investigated among various types of environmental conditions. Furthermore, the frequency response function is adopted to explore the correlation between the detected noise and ambient vibration using those on-board monitoring data.

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INTRODUCTION

The rapid development in high-speed rail technology and expansion of the high-speed railway network in China commit with a great prospect in time and resources to unite national and regional activities. Apart from the benefits of its excellent carrying capacity and time-saving, the high-speed railway also contributes to the sustainability of environment and energy without the direct consumption of fossil fuels as the driving energy. Nevertheless, there are also imperative concerns relating to safety and ride comfort because of the demand for increasing the speed of high-speed trains and the high frequency of passenger service in China (about 2500 running high-speed trains per day). Therefore, a better understanding that aims at practical and challenging issues induced by train dynamics and helps enhancing operational safety and quality of high-speed trains is of paramount importance.

Technically, the vibration response of high-speed trains is an inevitable and important issue caused by nonlinear wheel/rail contact forces and imperfect suspension systems [1-2]. The comfort of passengers is directly affected by exposing to the vibration of train vehicles, especially for long distance and frequent journeys. Indeed, ambient environments such as complex meteorological conditions and topographical variations can also affect the dynamic response and interior noise levels of high-speed trains. These influencing factors are either correlated with or independent of each other. Although it is only to pose a mild risk of motion sickness given sufficiently good design practice of high-speed trains, low-frequency vibration inside passenger coaches is still omnipresent inside train vehicles. Furthermore, vibration and noise are interacted in nature. Noise that is another crucial indicator of ride comfort is radiated into train cabins through both structure-borne and air-borne paths at low frequencies and higher frequencies, respectively. More importantly, noise spectra inside modern high-speed train vehicles are particularly dominated by low-frequency sound effects [3]. In the literature, it is found that humans are susceptible to low-frequency noise under long-term exposure which may induce anxiety disorders, vasoconstriction, and heart ailment [4, 5]. Hence, this is a crucial issue to be investigated in high-speed trains.

In high-speed trains, bogies are the major mechanical component to support rail vehicle bodies [6]. It includes a frame, wheelsets, axle-boxes and other mechanical accessories to compose a vehicle suspension system. It is used to maintain the stability of trains on straight and curved tracks. Besides, it can minimise the impact of centrifugal forces when turning curve tracks at a high speed. During the operation of high-speed trains, the vibration of bogies can induce the structure-borne noise to the interior of train vehicles. The variation of noise is very sensitive as high-speed trains pass through different topographical sections, including tunnels, bridges, and plain areas [7, 8]. Aerodynamic noise becomes significant as the speed of trains increases or trains pass through tunnels [9, 10].

To investigate the correlation between ambient vibration induced by the rail-wheel interaction and noise measured from the bogie, experimental studies of in-service monitoring have been conducted in a high-speed train running on a railway in China. This type of high-speed train can work efficiently under extreme cold weather and various topographical terrains (e.g., tunnels, bridges, mountains, and plains). The running speed of the train used as a test bed for real-time measurements was 200-250 km/h, and the ambient temperature was approximately –10 °C to 4°C. The present work provides a correlation analysis between noise and vibration during the train operation.

Based on the on-board monitoring data, the frequency response function is adopted to analyse the correlation between the detected noise and ambient vibration. A strong correlation between two sets of signals (i.e., vibration and noise) is found at the low and medium frequency bandwidths.

MEASUREMENT SET-UP

In this research, an online data acquisition system was deployed on an in-service high-speed train. In Figure 1, the system composed of sensors (i.e., accelerometer and microphone) was used to measure acceleration amplitudes and noise signals, respectively. In the course of measurements, two computer laptops and one interrogator were simultaneously adopted for data logging and recording the dynamic amplitudes and noise levels of the high-speed train.

Making use of the online monitoring system, two sets of data can be recorded accordingly. Both the accelerometer and microphone were mounted on the axle box and bogie frame, respectively. The accelerometer was used to record the data of vibration levels of the axle box in both lateral and vertical directions, as illustrated in Figure 2. The measured acceleration and acoustical signals of the high-speed train were stored in the interrogator with a sampling rate of 5000 Hz for data analysis.

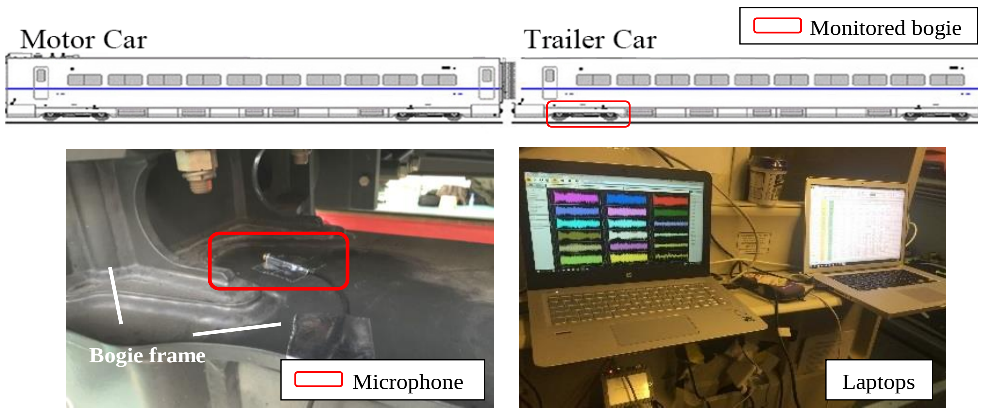

Figure 1. Data acquisition system deployed on a high-speed train.

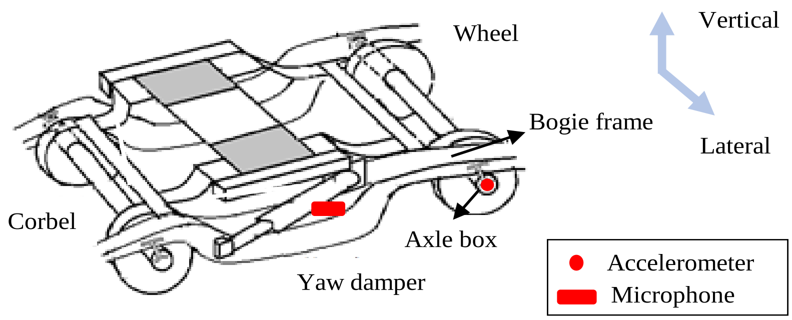

Figure 2. Sensor locations on the bogie.

DATA PROCESSING AND ANALYSIS

Understanding the dynamic characteristics of a high-speed train requires a set of stable and effective data, the online monitoring system was conducted for a couple of days during the routine operations. The measured lateral and vertical accelerations on the axle box as well as the simultaneously collected noise signals on the bogie frame are analysed in this section. With the help of the frequency response function, the correlation between the generated noise and vibration data is also investigated herein.

Figure 3 presents the measured noise data on the bogie frame in the time domain and frequency domain during the operation of the high-speed train. In Figure 3(a), we observe that the variation of noise levels among each sampling point changes within 100 dB. The general mean noise level in this monitoring process for the whole rail line is about 115.6 dB. It should be noted that the regions highlighted by the red dash lines show a greater variation of noise levels in the time history response. Since the variation of train speeds may induce different air flows and ambient vibrations, it makes a significant impact on the noise level in the bogie frame. Meanwhile, it is found that the acceleration amplitudes of the axle box relate to the running speed of the train. In this work, we studied the measured data at approximately 200 km/hr. On the other hand, the peak frequencies of noise signals dominate around 10 Hz and 640 Hz as shown in Figure 3(c). This is different for the case of vibration on the axle box as presented in Figure 3(d).

To explore the relationship between the noise levels and ambient vibrations, the frequency response function (FRF) is applied to find out its correlation. In this part, the measured lateral and vertical accelerations on the axle box are set as input signals, while the noise signals are performed as output signals to obtain the FRF, as shown in Figures 4(a) and (b). The results indicate that the noise levels on the bogie frame have a good correlation with the ambient vibrations at around 10 Hz and 643 Hz. According to the previous results, these frequency values can be found in both PSD domains of the noise and vibration levels in Figure 3(c) and 3(d). In other words, the lateral and vertical vibrations are the major contributors on the generation of noise in the bogie frame.

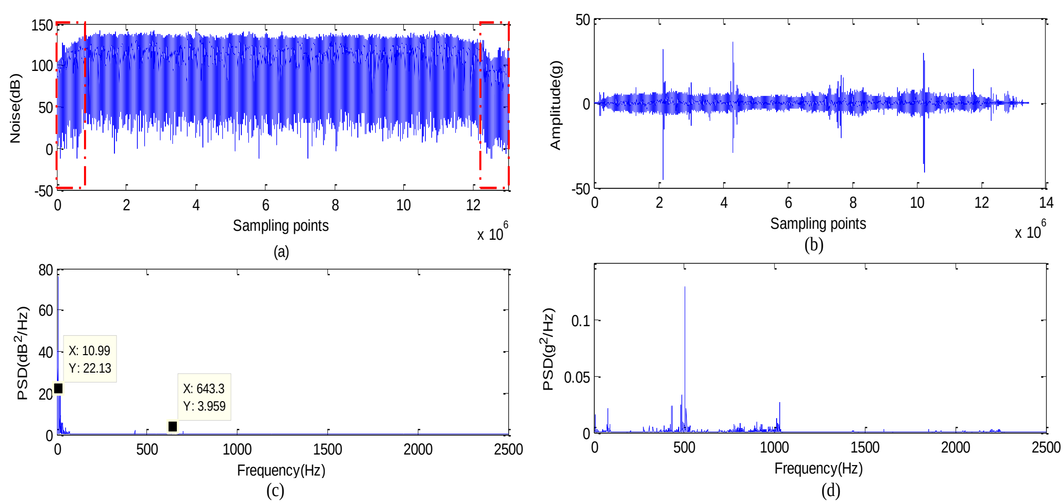

Figure 3. Noise data on the bogie frame and vibration signals on the axle box: (a)-(b) time history and (c)-(d) power spectral density.

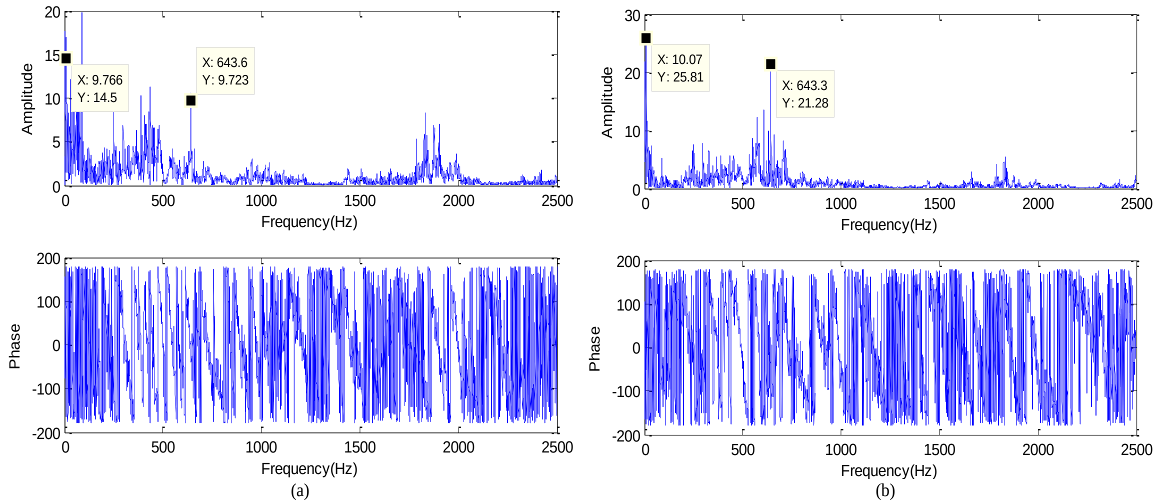

Figure 4. The frequency response function (FRF):
(a) Input: the lateral acceleration on the axle box, Output: the noise signals on the bogie frame; and
(b) Input: the vertical acceleration on the axle box, Output: the noise signals on the bogie frame.

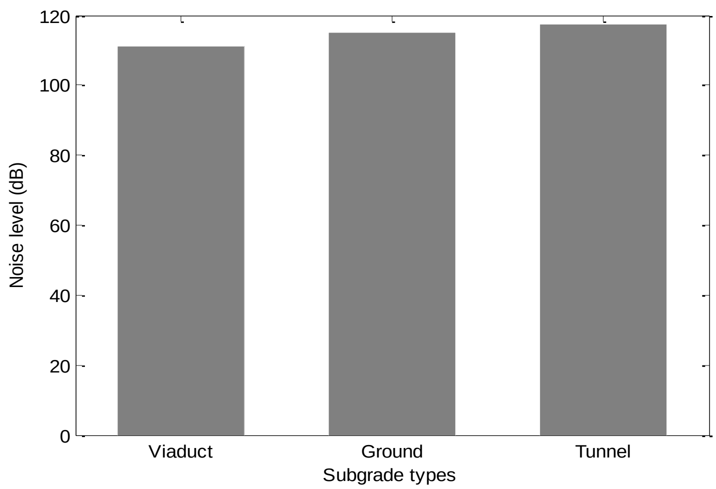

Figure 5. Mean noise levels on the bogie frame corresponding to different type subgrades.

TABLE I. MEAN NOISE LEVEL OF THE BOGIE FRAME ON DIFFERENT SUBGRADES

	Subgrade types		
Noise level (dB)	Viaduct	Ground	Tunnel
	111.2	115.0	117.5

In this study, the high-speed railway line is categorised into three types, namely viaduct, ground and tunnel. Since various noise levels can be induced due to the variation of topographical conditions, we attempted to use the microphone to collect the noise signals on the bogie frame as the train travelled through these three subgrades. As presented in Figure 5 and Table I, the variation among them has been successfully highlighted. The mean noise level of the tunnel case achieves the highest level among others. This finding is mainly due to the fact that the propagation of pressure waves is generated in a small and enclosed space, and it may also be induced by the variation of ambient vibration.

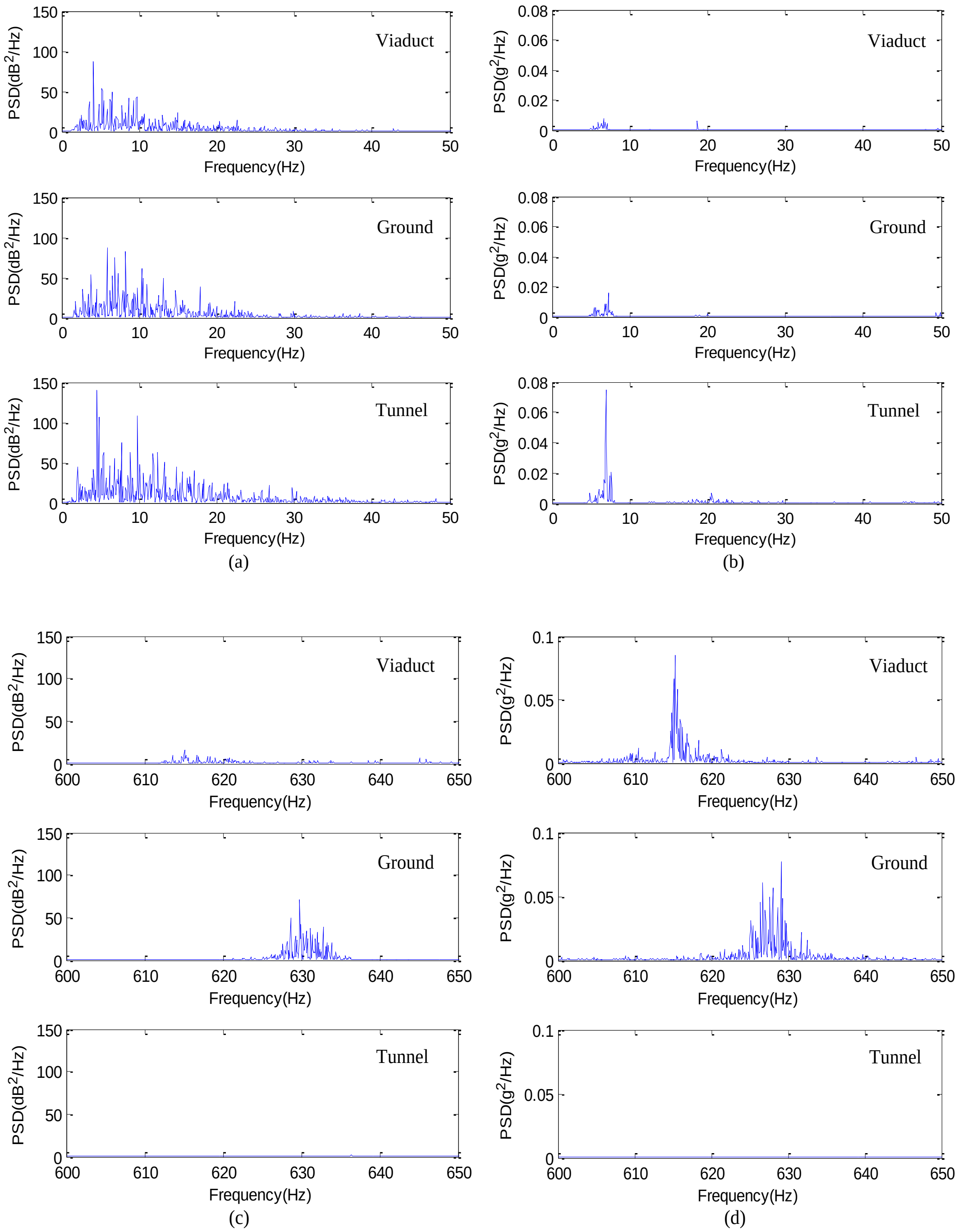

Figure 6. Noise signals on the bogie frame and accelerations on the axle box under different subgrades: (a)-(b) 0-50 Hz and (c)-(d) 600-650 Hz.

Based on the measured noise data, a comparison is presented for the train travelling through different subgrades in two frequency ranges (i.e., 0-50 Hz and 600-650 Hz). As illustrated in Figure 6, it is obvious that the ambient vibration has a great influence on the noise generation even on different subgrade conditions. The variation of noise signals in the frequency domain mainly occurs at the ranges of 0-50 Hz and 600-650 Hz, which govern a well correspondence to the ambient vibration. Specifically, the noise effect measured on the bogie frame shows a similar distribution in the frequency range 0-50 Hz. In the tunnel case, the mean noise level is slightly higher than the two other conditions. By comparing these conditions at the frequency range of 600-650 Hz, it is found that the noise dominates at about 630 Hz, which is induced by the vibration of the axle box when driving on the ground structure. In Figure 6 (c)-(d), there is nearly no signal detected, not only noise but also vibration, in the tunnel case in this freqnecy range. The reason may be due to the strong impact of ambient vibration and aerodynamic force on the high-speed train to change its dynamic behaviour.

CONCLUSIONS

In this work, the variation of noise and vibration levels of a high-speed train running through different subgrade conditions (i.e., tunnels, viaducts, and ground structure) is investigated. The results show that the mean noise level on the bogie frame reaches to 115.6 dB for the whole rail line. In addition, the mean noise level is up to 117.5 dB in the tunnel case. A comparison study in the frequency domain indicates that the generation of noise in the bogie frame has a close relationship to the ambient vibration when the train running on different subgrades. Based on the frequency response function, a strong correlation between two sets of signals (i.e., vibration and noise) is found at approximately 10 Hz and 643 Hz (see Figure 4).

In the future work, the blind source separation of structural vibration causing low-frequency noise inside high-speed trains will be investigated to develop a self-updatable and self-adaptable data-driven model. This is a crucial topic of inferring the nature of unknown endogenous sources from exogenous measurements. Because of the uniqueness of the vibration and noise patterns inside high-speed trains induced by various uncertainties, the reconstruction of the origin and strength of the relevant component responses can be highly useful for the identification and assessment of the individual source conditions.

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REFERENCES

1. Ni, Y.Q., Ye, S.Q., and Song, S.D. 2016. "An experimental study on constructing MR secondary suspension for high-speed trains to improve lateral ride comfort," *Smart. Struct. Syst.*, 18: 53-74.
2. Wang, J., Song, C., Wu, P., and Dai, H. 2016. "Wheel reprofiling interval optimization based on dynamic behavior evolution for high speed trains," *Wear*, 366-367: 316-324.
3. Thompson, D.J. 2009. "Railway Noise and Vibration: Mechanisms, Modelling and Means of Control," Elsevier, Amsterdam.
4. Berglund, B., Hassmén, P., and Soames Job, R.F. 1996. "Sources and effects of low-frequency noise," *J. Acoust. Soc. Am.*, 99: 2985-3002.
5. Leventhall, H.G. 2004. "Low frequency noise and annoyance," *Noise Health*, 6: 59-72.
6. Hong. M., Wang, Q., Su, Z., and Cheng, L. 2014. "In situ health monitoring for bogie systems of CRH380 train on Beijing–Shanghai high-speed railway," *Mech. Syst. Signal Proc.*, 45: 378-395.
7. Soeta, Y. and Shimokura, R. 2013. "Survey of interior noise characteristics in various types of trains," *Appl. Acoust.*, 74: 1160-1166.
8. Park, B., Jeon, J.Y., Choi, S., Park, J. 2015. "Short-term noise annoyance assessment in passenger compartments of high-speed trains under sudden variation, *Appl. Acoust.*, 97: 46-53.
9. Gilbert, T., Baker, C.J., and Quinn, A. 2013. "Gusts caused by high-speed trains in confined spaces and tunnels," *J. Wing Eng. Ind. Aerodyn*., 121: 39-48.
10. Liu, T.H., Chen, Z.W., Chen, X.D., Xie, T.Z., and Zhang, J. 2017. "Transient loads and their influence on the dynamic responses of trains in a tunnel," *Tunn. Undergr. Space Technol.*, 66: 121-133.