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Experimental research on identification of ground-borne noise from subway lines based on partial coherence analysis

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Abstract

The definition of how ground-borne noise is radiated into rooms in surrounding buildings due to underground subway lines is diverse in different countries, especially in the dominant frequency range. In the present paper, a set of field tests were carried out in Suzhou city, China to obtain ground vibration induced by subway vehicles and radiated noise in buildings. Preliminary analysis of frequency range is 1-300Hz based on the strength of frequency domain analysis of the ground-borne vibration and noise and attenuation of vibration along propagation path. Furthermore, the ground-borne noise is recognized from the measured data by partial coherence function. Based on this theory, the contributions of different vibration sources to the noise are distinguished. The analyzed result shows that the recognized dominant frequency range of the ground-borne noise is between 20~310Hz. This research also indicates a difference of A-weighted sound levels between the tested result and contrasting criterions.

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Keywords: Experiment ; Vibration ; Ground-borne Noise ; Partial Coherence Analysis

1. Introduction

Subway lines are becoming important and bringing a multiplicity of benefits for citizens in urban area. However, air-borne and ground-borne noise emitted from vibration generated by wheel-rail interaction is transmitted through the tunnel structure and enclosures of buildings, which is one of the main causes of environmental disruption from

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urban rail transit systems. The secondary radiation noise can induce increasing annoyance to the inhabitants of surrounding buildings and sensitive structures such as residences, office buildings, museums, schools, and so on. Therefore, the accurate assessment on the range of noise in different frequency domains is the basis of effective reduction of vibration and noise, which is also a great challenge. Vibration is induced by wheel-rail interaction and propagated into the tunnel and through the stratified ground layers with different ground material properties, resulting in vibration of floors and walls. [1] The flexural resonance of floors and walls of buildings caused by the track-train interactional vertical vibration at 30-200Hz frequency, generally emit the secondary radiation sound. There is a broad peak around 50-80Hz in the vibration frequency domain in most cases. A-weighted sound pressure level of the secondary radiation noise commonly ranges from 35dB to 45dB. The decrease in sound levels radiation by the room's floor with increasing height in buildings is 1dB/floor. In some cases, sound levels on the upper floors can be amplified due to floor resonances.

But the frequency range of radiation noise differs greatly in the noise impact criteria for transit projects in China as well as other countries. [1,2,3] The noise levels for general assessment is suggested to be the maximum sound level (L_{max}) during a single noise event without having to consider the interest frequency range in "Guidelines for Design of Rapid Transit Facilities" from the Department of Public Security in USA, and is the same as in "Memorandum on Vibration and Noise" from London Underground. Since the targeted frequency range is relatively low for typical room in buildings, A-weighted sound level at 10-160Hz frequency range ($L_{pa,LF}$) is adopted to evaluate secondary radiation noise in Danish, without the sound of something beating against doors and windows. In China, "JGJT 170-2009 Standard for limit and measuring method of building vibration and secondary noise caused by urban rail transit" ("JGJT 170-2009") provides for the dominant frequency scales of noise which varies between 16Hz and 200Hz. With the different frequency ranges of secondary radiation noise, the above standards are not reasonably accounted for disturbance of residents in buildings. In a word, there is not an effective frequency scale of ground-borne noise in most countries.

Compared to the air-borne noise, researches relevant to the ground-borne noise is far from well- documented. [4,5, 6,7,8,9]K. W. Ngai and C. F. Ng (2002) studied the dominant frequency range for vibration of concrete box structure and rail viaduct. Xiaozhen Li et al. (2015) studied the peak bridge-borne noise frequency on single-track box-girder bridges by experimental research. The numerical computation of the structural and acoustic response of a building to an incoming wave field generated by high-speed surface railway traffic was presented by P. Fiala et al. (2007). However, partial coherence analysis is a new developing method in recent years, and lots of research on identification of ground-borne noise sources by this method are introduced later. Rongping Fan et al. (2013) used partial coherence methods to identify the most significant interior noise sources in high speed train. A noise-identification method for bridge local vibration based on coherence analysis is proposed by Li Xiao-zhen et al. (2014). An experiment was conducted by Choi, Ki-Soo et al. (2009) on an evaporator that caused the principal noise of a refrigerator on the basis of OCF(ordinary coherence function) and PCF(partial coherence function) analysis.

This paper presents a set of field test carried out in Suzhou city, China. The testing results including the vibration and noise signals are obtained. The relationship between the propagated vibration and ground-borne noise radiated from subway lines are discussed through the analysis of frequency domain method. The ground-borne noise radiated from subway lines is separated and identified from the measured data by partial coherence analysis. As stated above, the present paper discusses the comparison between the values of noise assessment in different criteria and A-weighted sound level of this experiment within the frequency range identified on the basis of partial coherence analysis, which can provide theoretical guidance for assessment regarding secondary radiation noise.

2. Test site information

Experimental data from enclosures of buildings was examined on account of the noise and vibration complaints by urban inhabitants who live in residential dwelling near subway lines. This line was buried nearly 14 meters depth and the investigated dwelling was a three-story masonry building located almost 23 meters away from the ground above tested line. The measurement site is shown in Figure1.

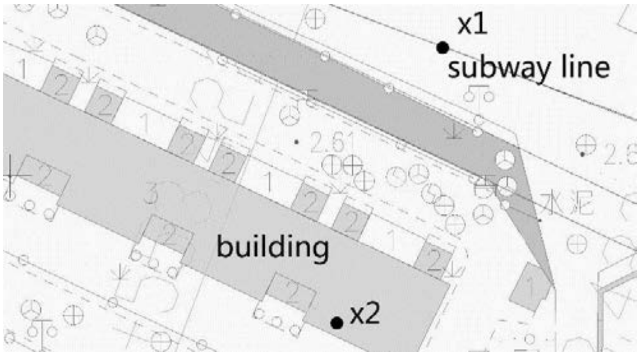

Fig. 1. Sketch map of the measurement site (point x1: above the subway line, point x2: center of the first floor).

In the experiment, measured points x1 and x2 are applied to investigate the vibration propagation. There are two accelerometers placed on each point, recording vertical and horizontal (perpendicular to tested subway line) component vibration signals. They are arrayed in the same transverse section in order to prevent weakening of wave propagation from the rail transit system. All the microphones are settled on each floor of the test dwelling (Figure 2) where all doors and windows are closed for reducing the impact of other noises from environment. Each of them is set at least 1.2m off the ground and 1.0m off the walls to avoid reflection of the first order standing wave and reverberation in the room. To ensure the reliability of this experiment, the number of tested train is no less than ten and all the accelerometers and microphones must be integrated into a synchronous acquisition system.

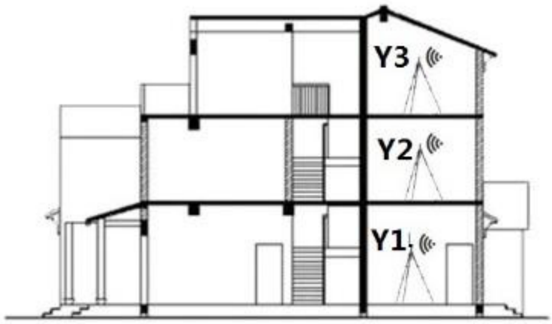

Fig. 2. Measured points of noise in tested building.

The tested vibration of the floor in the room of building is transmitted from both surface traffic and underground, radiating the tested noise. As the vibration acceleration grows, A-weighted sound level of tested noise becomes much higher. Hence, noise source identification method is important to recognize the vibration generated from the rail-wheel interaction.

3. Experimental analysis

3.1. The vibration response

As the aim of this study was to analyse propagation of vibration, the most commonly used metric for scoping assessment is VL_{max} (Table 1), according to the standard of "JGJT 170-2009". VL_{max} is the maximum value of Z-weighted vibration acceleration level in one-third octave within 4-200Hz.

Table 1. Vibration acceleration level of the test result.

VL_{max}	x1(dB)		x2(dB)	
Number	vertical	horizontal	vertical	horizontal
1	64.15	55.63	60.80	55.26
2	64.97	57.31	60.91	55.77
3	64.30	55.11	61.22	56.63
4	63.51	52.78	59.87	55.91
5	64.50	53.99	61.41	55.40
6	64.12	56.52	59.71	54.51
7	63.55	59.62	60.87	55.93
8	63.90	56.09	61.14	55.88
9	64.32	58.41	61.33	55.29
10	64.50	58.00	62.43	56.23
Average	64.18	56.35	60.97	55.68

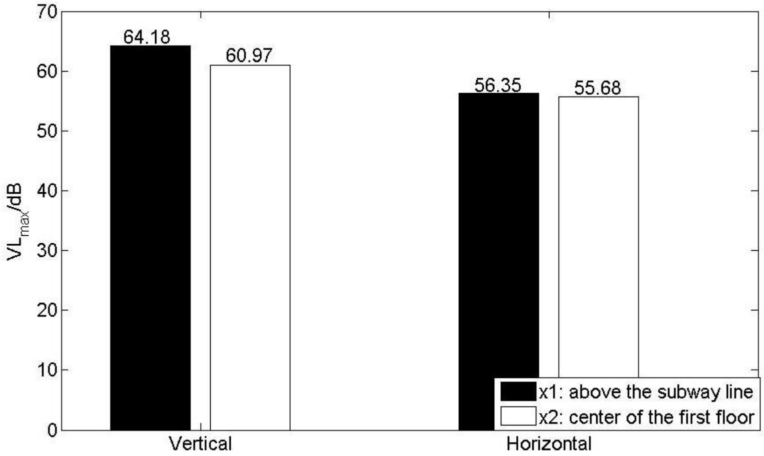

Fig. 3. Mean value of vibration acceleration level.

Vertical vibrations are higher than horizontal components above the subway line as the tested train passes by, shown in Figure 2. [1] It indicates that the composition of mechanical vibration waves generated from rail-wheel interaction primarily consists of R-waves, mixed with some S-waves and P-waves. In addition, attenuation of vertical vibrations is more predominant. However, vertical vibration in the center of the first floor in building is still higher even if the immediate attenuation. The attenuation rate of horizontal component is 0.14dB/m.

3.2. The noise response

The tested noise is made up of not only air-borne noise but also secondary ground-borne noise, which radiated from the coupling vibration excitation produced by road traffic and rail train passing through. This paper presents the tested noise in frequency domain at 0-500Hz due to the general frequency range of secondary radiation noise (approximately 20-200Hz).

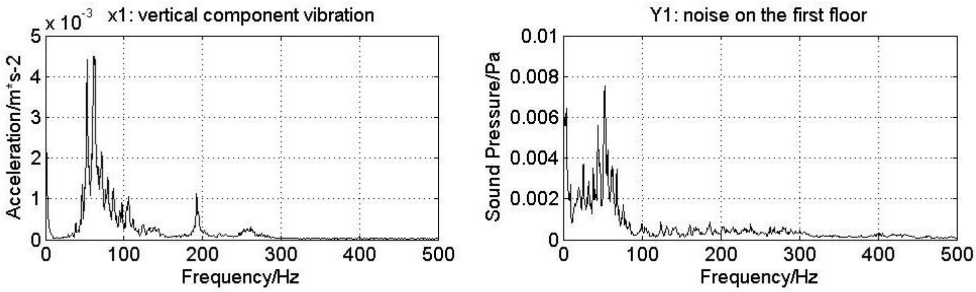

Fig. 4. Vibration and noise in frequency domain.

Figure 4 displays the frequency domain of the vertical component vibration above the subway line and the sound pressure on the first floor. The figure shows the dominant frequency of noise ranges from 40Hz to 70Hz and the peak sound pressure within 50-60Hz, which is consistent with the frequency of vibration. It reveals the frequency dependency of radiation noise and noise source. However, there are low sound pressure extent to 300Hz beyond prescribed range of every criteria. Clause 4 will explain the discrepancy among them by partial coherence analysis.

Sound levels of noise radiated from the room's floor decline with increasing height in buildings regardless of weight method which modifies the sound pressure of tested noise. A-weighted sound pressure on the 3rd floor has an absolute decrease of 1dB relative to the 1st floor. But results of the 2nd floor are a little higher than the 1st floor, which is related to the interior structure of this building. The 1st floor is connected with 2nd through a spiral stair without any barrier and the tested noise on the 2nd floor could be considered as a sound which also includes air-borne noise on the 1st floor.

Table 2. Sound pressure of noise on each floor of tested building

Sound pressure	Noise(dB)		
	1st floor	2nd floor	3rd floor
A-weighted	33.73	34.04	32.02
Linear-weighted	58.61	59.41	57.55

4. Partial coherence analysis

4.1. Theory of partial coherence function

In this paper, it is a trivial matter to identify various multiple correlated vibration radiating secondary noise. [10]This acoustics and vibration problem can be simplified as a general multiple input/single output model to recognize response effects caused by the combination of various sources. The evaluation of results requires practical iterative formulas like ordinary coherence analysis, partial coherence analysis, etc. Definition for ordinary coherence function is as follows,

$$\gamma_{xy}^{2}(f)=\frac{\left|S_{xy}(f)\right|^{2}}{S_{xx}(f)S_{yy}(f)}\qquad\left(0\le\gamma_{xy}^{2}(f)\le 1\right)\tag{1}$$

where $x(t)$ denotes the input signal as an arbitrary stationary random record in time domain and $y(t)$ denotes the output signal as an arbitrary stationary random record in time domain. The S's here denotes two-sided spectral density functions of frequency f . $S_{xx}(f)$ and $S_{yy}(f)$ are auto spectral density functions of $x(t)$ and $y(t)$, respectively. $S_{xy}(f)$ is cross-spectral density function between $x(t)$ and $y(t)$ .Perfect correlation between noise and noise source in certain frequency is 1 while 0 means there is no relationship between these signals.

Although the response in frequency domain is obtained to interpret the degree of correlation between single input and total output, it is not clear here how much of the spectral output is caused by this input independently when the original input records are mutually coherent with each other in multiple input/single output model. Thus ordinary coherence analysis is more applicable to models with uncorrelated inputs. In this context, it is essential to compute associated conditional output spectral density function which leaves in conditional output after removing the linear effects of one input by partial coherence analysis. Definitions for the partial coherence functions are as follows,

$$\gamma^2_{x_2y-x_1}(f) = \frac{\left|S_{x_2y-x_1}(f)\right|^2}{S_{x_2x_2-x_1}(f)\,S_{yy-x_1}(f)} \tag{2}$$

Where $S_{ij\text{-}z}(f)$'s here denote conditional auto spectral density function of record i by removing the coherent part of record z when $i = j$ and conditional cross-spectral density function of record i and j by removing the coherent part of record z when $i \neq j$.

Combined with Eq. (1), Eq. (2) shows that partial coherence function is fully consistent with ordinary coherence function with no connection among inputs. It indicates that the relevant portion of inputs can be eliminated on the basis of partial coherence analysis. By considering x_1 as one input and x_2 as the second input, it is important to define their order of them in a specific way which decides how results are explained. The linear effects of x_1 from x_2 are removed so as to better allow the prediction of y without x_1.

4.2. Identification of tested noise source

This paper applies vertical vibration above subway lines as noise source to identify radiation noise because the dominant frequency range of secondary noise is almost the same as that of vertical vibration which is defined as frequency dependency of radiation noise outlined in Clause 3.2. The simplified experiment model which is using a two inputs/single output model is shown in Figure 5.

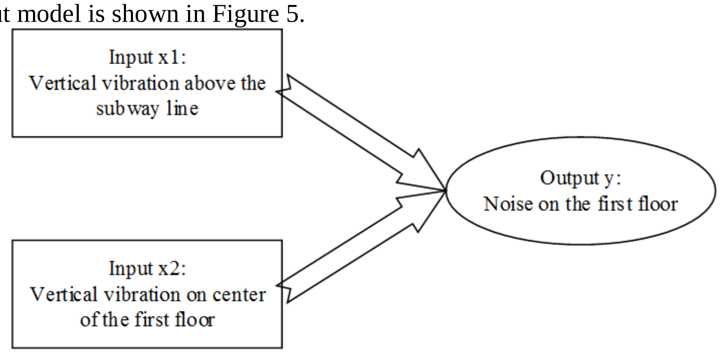

Fig. 5. Simplified model of the experiment.

The lower bound of noise source (vertical vibration above subway lines) generated from rail-wheel interaction is interpreted as 20Hz for the reason that vibration on the ground under 20Hz generally results from road traffic according to research.

It is known that x_2 should follow x_1, then x_1 should be chosen as the first record and $x_{2\text{-}1}$ (x_2 removing the linear effects of the stronger x_1 from x_2) becomes the second record. Figure 6 shows the difference between overall auto spectral density function of output y and conditional auto spectral density function of record y by removing the coherent part of record x_1 as follows,

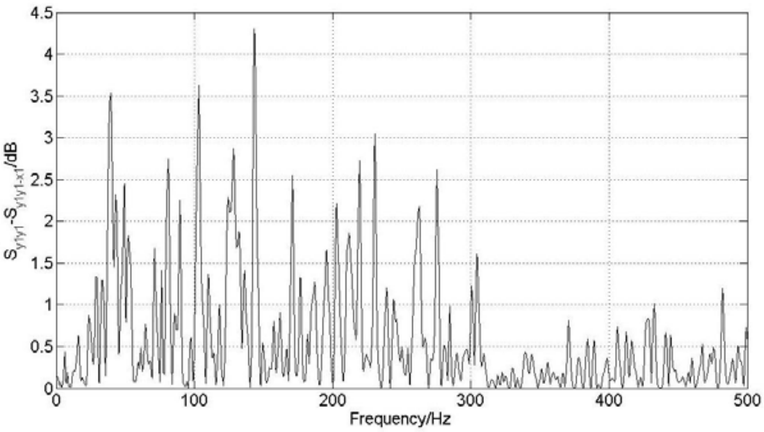

Fig. 6. Difference between overall auto spectrum and conditional auto spectrum.

It can be seen that the dominant frequency range of noise contributed from the input x_1 is 20-310Hz evenly distributed. The peak value of the frequency is 4.3dB at 143Hz. There are also some inconspicuous contributions among 310-500Hz range. Within this range, the maximum value is just 1.2dB. The secondary radiation noise generated from train-track interaction of test ranges from 20Hz to 310Hz, which differs greatly from frequency range of the criteria as previously mentioned.

5. Comparison of criteria

A-weighted sound level of this experiment at 20-310Hz is calculated in comparison to the noise assessment value of criteria in some countries, as shown in Table 3. We can clearly see that the result of this paper is the largest due to its widest frequency range, closely followed by the maximum sound level (L_{max}) in the USA & Britain, with Danish at the bottom of the list. It is also 2.5dB higher than the noise assessment value of criteria in China.

Table 3. Comparison of noise assessment values

Sound level of ground-borne noise in the building				
	the USA/ Britain	Danish	China	the Result of test
Noise Assessment Value	34.84(1000Hz)	31.27	33.73	36.23

6. Coclusion

The measurement data presented in this work is analyzed to predict the frequency range of secondary noise radiated from vibration caused by subway lines. The key findings are:

- Mechanical vibration waves generated from rail-wheel interaction are primarily consists of P-waves mixed with some S-waves and R-waves because the vertical vibration in measuring experiment propagates most obviously.
- Attenuation of vertical vibrations is more predominant than that of horizontal component. The attenuation rate of horizontal vibration is 0.14dB/m.
- Radiation noise is frequency dependent for the dominant frequency range of secondary noise is almost the same as that of vertical vibration.
- The secondary radiation noise generated from train-track interaction of the test ranges from 20Hz to 310Hz using partial coherence analysis.

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