Experimental Study on Environmental Vibration Induced by Streetcar

Tian Zhang, Fei Du and Gang Yang

Abstract The environmental vibration tests by streetcar were carried out on a certain section along Line 202 in Dalian City, and the ground acceleration time history curve was obtained. Time-domain and frequency-domain analysis methods were used for processing the acceleration data, then draw the 1/3 octave spectrum of the vibration acceleration and obtain the vibration level of the environmental vibration so as to assess the environmental vibration effect and study the propagation law of the vibration response induced by the tram car. The measured result shows that the main frequency band of the environmental vibration by the tram car is 30–70 Hz; the maximum vibration level at different measuring points is 75–93 dB, and in winter the effective value of vibration acceleration is greater than the value in summer. This is because the low temperature increases the strength and stiffness of the subgrade, which leads to an increase in the effective value of the acceleration in the longitudinal direction. In addition, the vibration response is reduced with the increase in distance from the vibration source. The maximum vibration level at 10 m from the central line of the downlink track is about 93 dB when the speed of the vehicle is 40 km/h, about 77 dB at 30 m, so it can meet the vibration standard of urban environment.

Keywords Streetcar · In situ test · Environmental vibration response · Spectrum analysis · Vibration level

With the rapid development of urbanization in China, urban population is growing rapidly, so the demand for urban public transportation is also increasing. To a large extent, rail transit can share the urban traveling pressure because of its huge passenger volume. Compared with other public transports, rail transit has many advantages: it is convenient, efficient, low energy consumption, low pollution and can promote the development of social and economic development along the line. At the same time, rail transit will also bring some negative effects. The environ-

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mental vibration and noise generated by train operations will have a significant impact on the health of citizens, the use of precision instruments in universities, hospitals and research institutes, and the life of old buildings near the line [1–6]. In situ test, as one of the most important methods for studying environmental vibration, has important theoretical and social significance. The measurement results can reflect the vibration response of the train as a vibration source intuitively and can be used to verify the correctness of the theoretical analysis model, confirm the rationality of the numerical simulation model and provide data for evaluating the environmental vibration caused by the rail transit system [7]. The accumulation of a large amount of measured data can lay the foundation for the study of the propagation law and mechanism of environmental vibration.

Common rail transit system includes subway, light rail, tram car and so on. As a public transport system with a large passenger volume, the subway has the characteristics with closed lines and dedicated signals. Lines generally consist of underground tunnels, closed-surface lines, elevated bridges and underground or elevated stations. However, the construction cost of subways exceeds RMB 1 billion/km, which has deterred the subway construction in many cities. At the same time, the maintenance and repair costs of subways have remained high, which has become a heavy burden on subway operators. Even in cities with large passenger traffic, such as Beijing, the subway is hard to make profit. Of course, as a public transport means, the ticket price of the subway cannot be too high. The cost of the new streetcar system is much lower (about 200–300 million/km), and the economy is good, but the passenger traffic is lower than the subway and higher than the bus; the one-way capacity is about 15,000 person/h. So the streetcar is very suitable public transportation means for small- and medium-sized cities. The line is generally in the form of all terrain or ground + elevated [8].

From the above perspectives, it is very necessary to research the environmental vibration caused by streetcar. Therefore, the environmental vibration tests were carried out on a certain section along Line 202 in Dalian and the ground acceleration time history curve was obtained. Time-domain and frequency-domain analysis methods were used for processing the acceleration data so as to assess the environmental vibration effect and study the propagation law of the vibration response induced by the tram car.

1 Test Equipment and Test Site Layout

Line 202 in Dalian streetcar is divided into Uplink (Xiaopingdao Front Station–Xinggong Street Station) and Downlink (Xinggong Street Station–Xiaopingdao Front Station), passing through Dalian Maritime University, the Second Hospital of Dalian Medical University, Dalian Institute of Chemical Physics and so on. The train lines are close to these venues, and the resulting vibrations are bound to affect them. Tram forms are shown in Fig. 1. In order to study the vibration characteristics induced by the streetcar, and to minimize the influence of other forms of

Fig. 1 Line 202 streetcar in Dalian

transportation, a site near Star Sea Square is selected for in situ test place. The site is wide and close to the side of the tram line, far from the urban major road. From the test results, the vibration caused by road traffic does not interfere the result.

In the in situ tests, there are some experiment instruments, including the piezoelectric acceleration sensor with sampling frequency 0.2–2.5 kHz, four-channel intelligent data acquisition instrument and analysis system with sampling frequency of 10.24 kHz, and the hand-held speedometer. In order to research the environmental vibration response and propagation law caused by trams, four measuring points were set at the distances of 10, 15, 20 and 30 m from the centerline of the track to lay out vibration acceleration sensors. Data collection will be performed when the tram is coming, and a hand-held speedometer will be used to record the speed and save the measured data. The measuring point position is shown in Fig. 2.

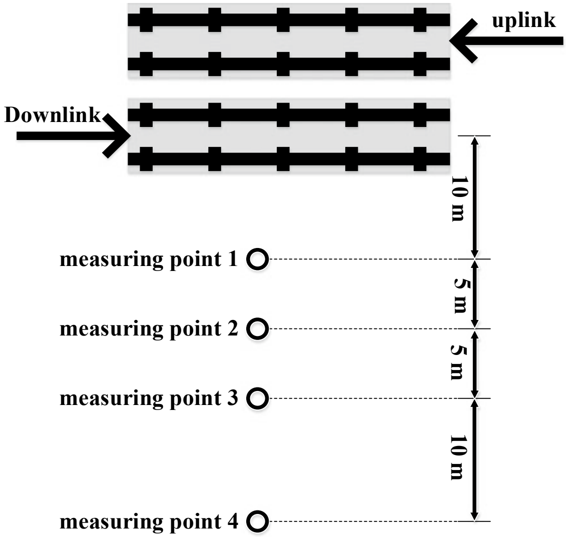


Fig. 2 Layout plan of measuring points

2 Data Analysis and Processing Methods

The ground vibration response is evaluated by the vibration acceleration in this test. Therefore, this article mainly discusses the Z vibration level [9] and 1/3 octave frequency vibration acceleration and variation law caused by the tram. In the "*Urban Area Environmental Vibration Standard*" (GB 10070-1988), when evaluating the magnitude of two different frequency vibrations, vibration acceleration levels are commonly used, which do not take into account the weighting correction of different frequencies. So-called vibration acceleration level, that is, the average energy of the vibration is represented by the effective value of the acceleration [10, 11]. The effective value a_e of the acceleration is defined as the square root of the average value of the square of instantaneous acceleration value a with respect to time T

$$a_e = \sqrt{\frac{1}{T}\int_0^T a^2 \mathrm{d}t} \tag{1}$$

The above formula can be applied for the known acceleration function. For the discrete data in experiment test, Eq. (1) can be transformed into:

$$a_e = \sqrt{\frac{1}{n}\sum_{i=1}^{n} a_i^2} \tag{2}$$

where n is the sample number, and a_i is the value of acceleration. The vibration acceleration level can be defined as follows:

$$\mathrm{VAL} = 20 \cdot \lg\frac{a_e}{a_0} \tag{3}$$

where a_0 is the reference value of the acceleration vibration level, $a_0 = 1 \times 10^{-6}$ m/s^2.

Research indicates that the vertical vibration response is a major factor affecting the daily lives of residents. According to the provisions of "*Urban Area Environmental Vibration Standard*" and ISO 2631, the vibration acceleration level obtained by modifying the whole body vibration with different frequency weighting factors is called vibration level. The indicator of environmental vibration caused by urban rail transit is the vertical Z vibration level. The vibration level is calculated by 1/3 frequency octave method, that is, the index evaluating the environmental vibration is obtained by correcting the acceleration effective value according to the following formula:

$$\mathrm{VL} = 10 \cdot \lg\left[\sum_{i=1}^{20} 10^{(\mathrm{VAL}_i + \mathrm{cf})/10}\right] \tag{4}$$

Table 1 Correction value of 1/3 octave center frequency

Octave center frequency *f* (Hz)	1	2	4	8	16	31.5	63	80
Vertical correction cf	−6	−3	0	0	−6	−12	−18	−20

In the above formula, VAL_i is the vibration acceleration level of the center frequency *f*; cf is the correction value shown in Table 1.

3 Analysis of Experimental Results

During in situ test, eight tests were performed on the uplink and downlink vehicles of Line 202 in Dalian, and six groups of data were selected for comparative analysis. The collected vibration acceleration signals are analyzed in time domain and frequency domain. In order to compare and analyze the effects of different soil properties in different seasons on the environmental vibration response caused by trams, the in situ tests were conducted on the same place in the summer and winter.

3.1 Time-Domain Analysis

The in situ tests were carried out to obtain the ground vibration response; in order to avoid the impact of other ground traffic, the acceleration response is collected in every test when the tram goes alone. After several tests in the field, it was found that the vibration acceleration responses are approximately equal at the same distance from the vibration source when the uplink vehicle and the downlink vehicle pass at the same speed. Therefore, only the vibration response by the downlink vehicle is used as the analysis research.

In order to ensure the authenticity and accuracy of the data, the acquisition time for every test is more than 15 s, and the acceleration curve can show the vibration response by passing trains well. For the downlink direction, the measured data for the measuring point 1, 2, 3 and 4 are shown in Fig. 3 during the summer and winter at a tram speed of 40 km/h.

From Fig. 3, we can find acceleration peaks of ground vibration at the four measuring points when the tram passes. The distance from the center of the track increases, the peak value of the generated vibration acceleration decreases. The closer the distance from the track center is, the faster the vibration acceleration decays. Comparing the time histories of vibration accelerations in summer and winter, it was found that the measured results are similar at the same speed of the streetcar and measuring points.

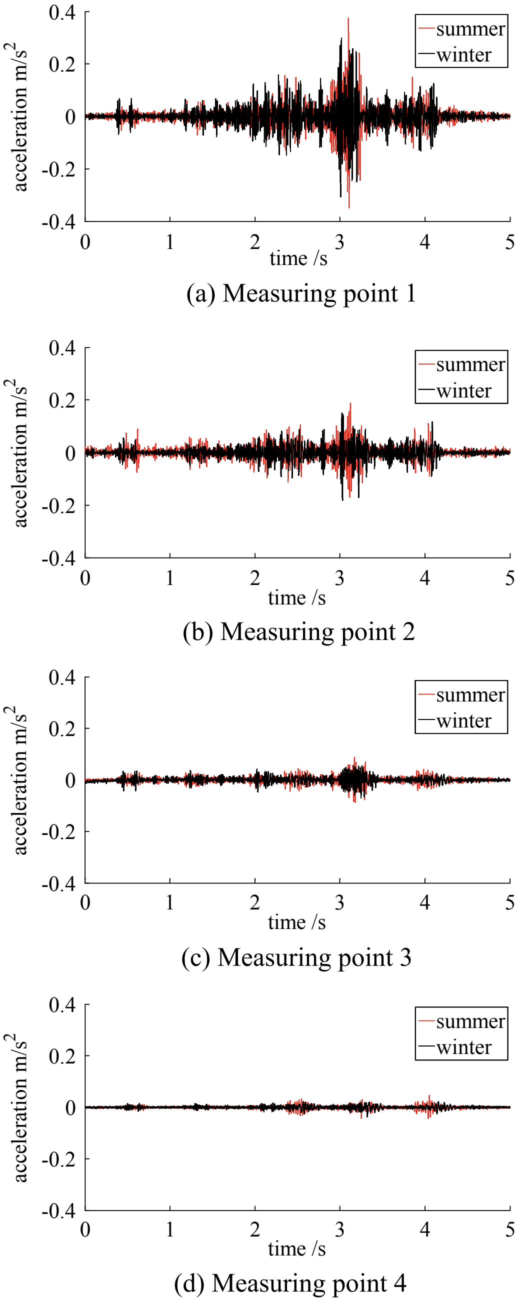


Fig. 3 Vibration acceleration time history curves of different measured points

3.2 Frequency-Domain Analysis

In order to study the characteristics of environmental vibration induced by trams in the frequency domain, the vibration acceleration time histories in field measurement were analyzed in frequency domain, and the vibration acceleration spectrum was obtained.

For the downlink vehicle at a speed of 40 km/h, the measured results in the summer and winter are transformed to frequency domain, as shown in Fig. 4.

It can be seen from the vibration acceleration spectrum of each measuring point that the main frequency band of the environmental vibration response is between 30 and 70 Hz, and the acceleration peaks at different measuring points all are in the same frequency range.

The distribution of the vibration acceleration at the same speed in summer and winter is similar, and the peak value is almost the same. From Figs. 3 and 4 in the time domain or frequency domain, it can be found that seasonal changes do not have much influence on the environmental vibration response, but the frequency distribution has some different at the high-frequency section, such as 55–75 Hz.

3.3 1/3 Octave Analysis

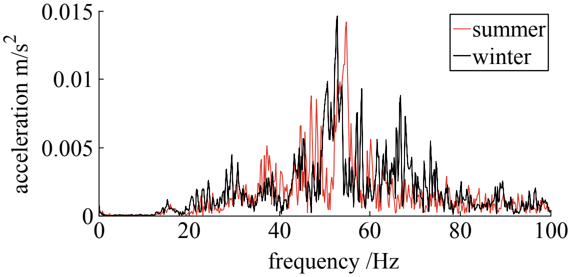
The measured vibration acceleration is analyzed by 1/3 octave spectrum, and the vibration acceleration level is finally obtained to evaluate the standard of the environmental vibration. The 1/3 octave spectrum of vibration acceleration for different measuring points is compared at the different streetcar speed for the results in summer, as shown in Fig. 5, where the abscissa is the center frequency of octave, and the ordinate is the division frequency vibration acceleration level VAL (dB).

It can be seen from Fig. 5 that the vibration level of these four measuring points caused by passing streetcar are in the range of 70 dB to 90 dB when the speed are 35–40 km/h. At the same time, Fig. 5 shows the maximum vibration level at different driving speed and measuring points, and dispalys the change law of vibration level. It can be found that the vibration level changes are the same with the time-domain analysis. For the same measuring point, the higher the streetcar operating speed is, the higher the vibration level is. For the same speed, the farther the distance from the measurement point to the centerline of the track is, the smaller the vibration level is and the change is nonlinear.

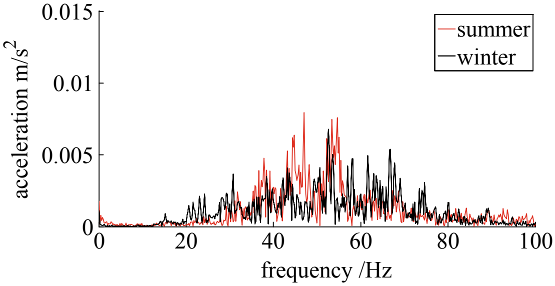
3.4 Effective Value of Vibration Acceleration

According to Eq. (4), the effective value of vibration acceleration at different measuring points for downlink tram at different speeds was analyzed. There are

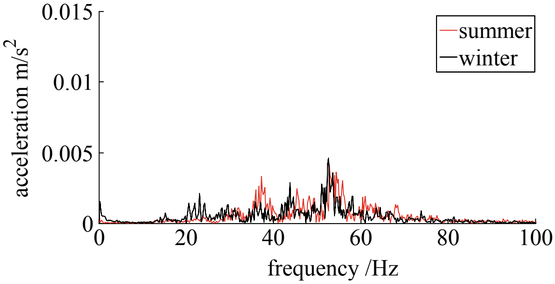
Fig. 4 Spectrum of measured vibration acceleration



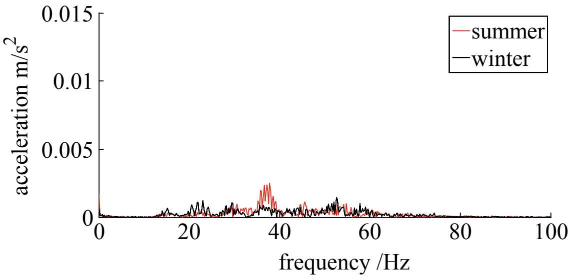
(a) Measuring point 1



(b) Measuring point 2

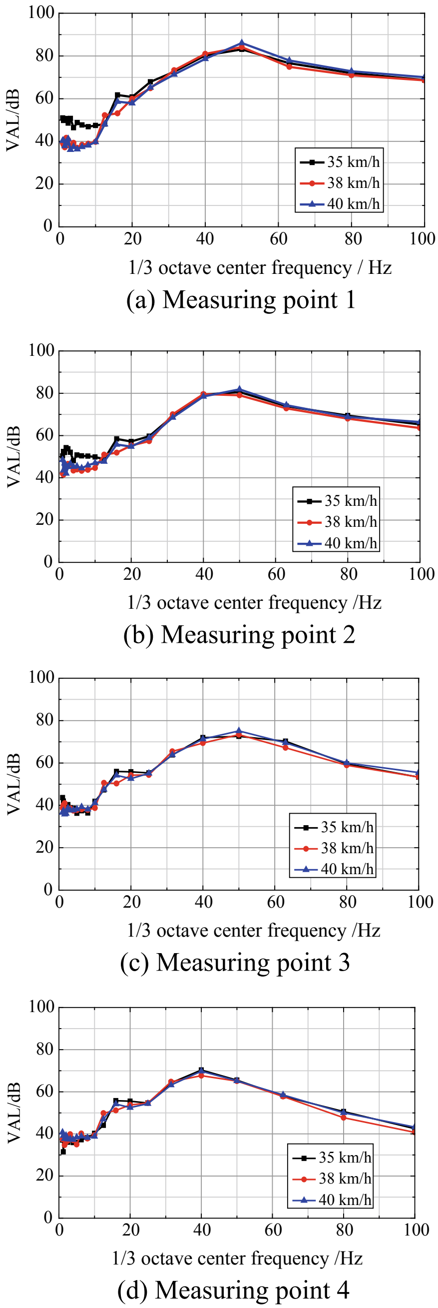


(c) Measuring point 3



(d) Measuring point 4

Fig. 5 Division frequency *Z* vibration level curve of measuring points



three cases for different tram speeds, that is, the speed of the tram 35, 38 and 40 km/h, and the effective value of vibration acceleration for the results in summer is shown in Fig. 6.

According to the variation curve of the effective value of acceleration at different speeds, the faster the train speed is, the greater the ground vibration is. And the farther the distance from the center of the track is, the smaller the vibration is, but the vibration attenuates and changes nonlinearly, and the attenuation gradually becomes slower.

The measured data are processed at the speed of 40 km/h in summer and winter, and the changing curve of the vibration acceleration is shown in Fig. 7. The effective value of the ground vibration acceleration in winter is greater than that in summer near the track, but the result is opposite at greater distance.

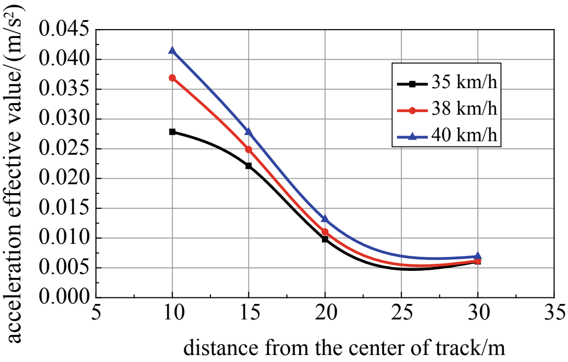


Fig. 6 Effective value of ground vibration acceleration at the different tram speeds

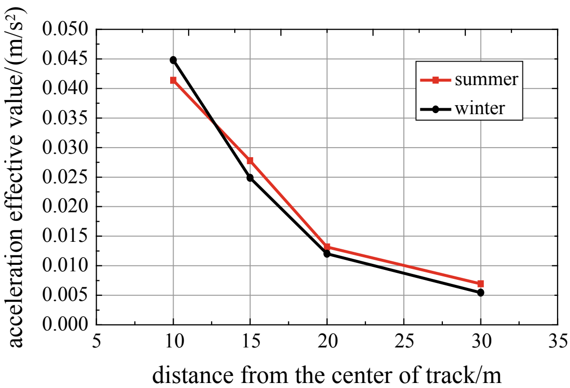


Fig. 7 Effective value curve of acceleration in different seasons

4 Evaluation of Environmental Vibration Caused by Tram

The "*Urban Area Environmental Vibration Standard*" (GB 10070-1988) formulated by China is an environmental vibration evaluation standard, which relates to the peak of vibration level. It evaluates the vibration level of the surrounding ground and building vibration in different areas. The vibration level in different regions should not exceed the values listed in Table 2 [12].

The division frequency *Z* vibration level is calculated, and the vertical total vibration level of each measuring point under different driving speeds is obtained. Then the environmental vibration which is induced by Line 202 Tram in Dalian is evaluated according to the criteria in Table 2. As shown in Fig. 8, it is the total vibration level curve summarized by the division frequency vibration level.

In Table 2, the ground vibration level outside the 30 m on both sides of the railway line shall not be more than 80 dB. According to the arrangement of on-site measurement points, the distance is 30 m from the measuring point 4 to the center line of the track. From Fig. 8, when the tram passes, at measuring point 4 the maximum value of total vibration level is 76.72 dB and the minimum value is 75.65 dB, not more than 80 dB. This shows that the vibration level is regulated in accordance with the urban environmental vibration standard.

Table 2 Standard of vibration in urban area environment

Area of application	Day	Night
Special residential area	65	65
Residential, cultural, educational area	70	67
Mixed area, commercial district	75	72
Industrial district	75	72
Both sides of main road lines	75	72
Both sides of main railway lines	80	80

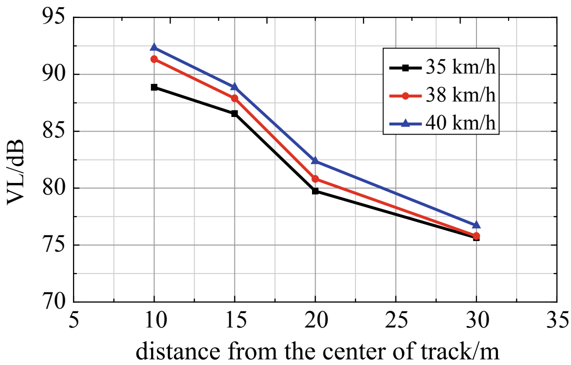
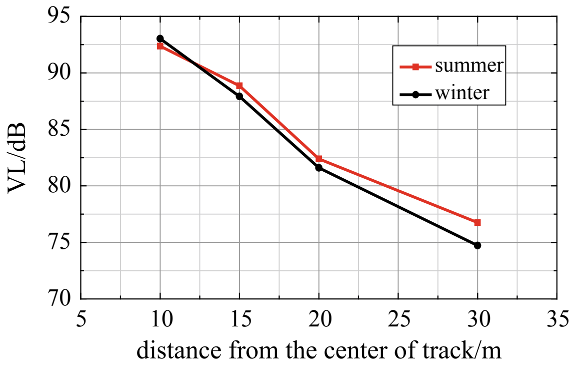


Fig. 8 Vibration level curve of measuring points

Fig. 9 Vibration level curve in different seasons



The measured data are processed at the speed of 40 km/h in summer and winter, and the changing curve of the total vibration level is shown in Fig. 9. Similar to the effective value of vibration acceleration, in the winter the total vibration level of the ground vibration near the track is greater than the value in the summer, but the result is opposite at greater distance. This phenomenon is due to the effect of the ambient temperature change, and the temperature is too low to increase stiffness of the subgrade, which leads to an increase in the effective value of the vertical acceleration.

5 Conclusions

Taking Line 202 in Dalian as the research object, the environmental vibration response caused by trams was studied by means of the in site measurement of the ground vibration acceleration, and the measured results were analyzed in the time-frequency domain. The following conclusions were obtained:

(1) The main frequency band of the environmental vibration by the tram car is 30–70 Hz; the total vibration level is about 75–93 dB.
(2) The vibration acceleration response caused by a tram increases with the tram speed and decreases with the distance from the track centerline, but the vibration attenuates and changes nonlinearly, and the attenuation rate gradually decreases. The change law of the vibration level is similar to the vibration acceleration.
(3) The environmental vibration caused by trams is affected by seasonal changes. In the winter, the temperature is too low and the roadbed stiffness is increased. As a result, the effective acceleration value and total vibration level is different between summer and winter.
(4) The total vibration level of environmental vibration caused by trams is less than 80 dB away from 30 m which is the distance from the measuring point 4 to the track centerline, meeting the vibration standard of urban environment.

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