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RESEARCH ARTICLE

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Running train induced vibrations and noises of elevated railway structures and their influences on environment

Abstract The vibrations and noises of elevated railway structures have been cause for concern due to their effects on the environment and the people living near elevated lines. In this paper, the main structural features of some new elevated bridges and station hall were introduced. The generation mechanism of vibrations and noise of elevated structures induced by trains were investigated. The noise induced by different types of elevated bridges, their influences on the environment and the theoretical method for the analysis of structure borne noise was analyzed. Finally, several field measurements on train induced noises at the platforms of elevated subway stations and bridges were presented.

Keywords railway, elevated structure, bridge, station, vibration, noise, environment

1 Introduction

With the rapid development of human society, more and more elevated railways are emerging. They include urban railways, inter-city railways and high-speed railways. The elevated railways have characteristics such as large transportation capacity, high speed, safety, being on schedule, lower cost compared to underground subway lines, and are free of interference with common ground traffic, and thus become an efficient transit medium. The elevated railway structures in urban regions mainly include elevated bridges and elevated stations [1].

At the same time, the railway traffic induced vibrations and noises have been given more attention. Many results have been published at home and abroad [2–17]. In China, some multifunctional railway stations are composed of underground works, elevated bridges and elevated large-span station halls, such as the Shanghai South Station and the Beijing South Station which are already in operation, the Guangzhou New Railway Station and the Wuhan High-speed Railway Station which are under construction, and some others in design [18]. These stations are very convenient for the transfer of passengers between different transit media because of the integration of the subway station, the urban railway station, the common railway station and the high-speed railway station. They also have novel appearance and high efficiency. While running, the train induces vibrations and noises of elevated railway structures, and their influences on environment, have been complained by the passengers in station and vehicles and the people living near the elevated lines. This problem has been of concern and is under study [1,7–9,17–19].

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2 New railway stations in China

The Beijing South Railway Station is the largest railway station in Asia, with a total area of 94 hectares and total budget of 12.5 billion RMB. The construction area of the station is more than 220000 square meters, which may contain 10500 passengers in the waiting hall. There are 24 tracks and 13 platforms in the station, including 5 tracks and 3 platforms for conventional trains, 12 tracks and 6 platforms for high-speed trains, and 7 tracks and 4 platforms for inter-city trains.

Figure 1 shows the outline and main structure of the Beijing South Railway Station, which is a multifunctional railway station with the unified high-speed railway, common railway, subway lines, urban railway, buses and taxis. The station has five floors: the elevated floor for taxis and cars, the ground floor for buses and passengers' entrance, the minus 1 floor for vehicle parking and traffic

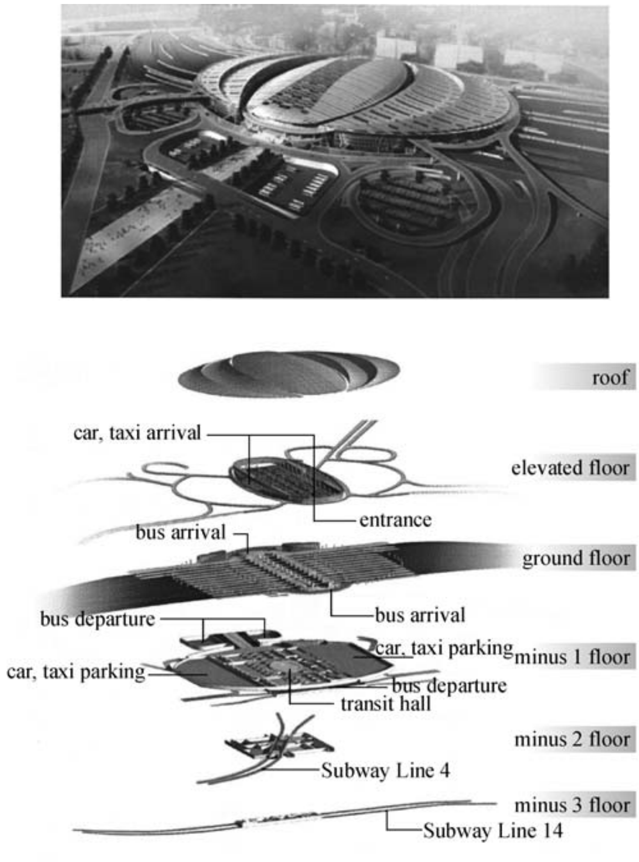
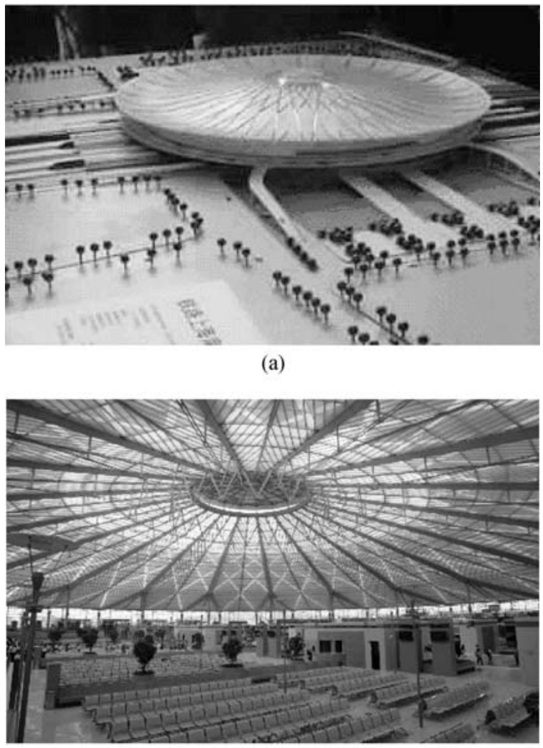


Fig. 1 Beijing South Railway Station


(a)

(b)

Fig. 2 Shanghai South Railway Station. (a) Outline; (b) main structure

exchange and passengers' exit, and with the connections to the urban railway, the minus 2 floor for the Subway Line 4, and the minus 3 floor for the Subway Line 14. The highest roof of the hall is 40 m above the ground.

The Beijing South Railway Station will be the terminal of high-speed railways, inter-city railways and urban railways. The Beijing-Tianjin inter-city railway, with its total length of 115 km and the speed of 350 km/h, has been in operation before the Beijing 2008 Olympic Games. The Beijing-Shanghai high-speed railway, with the total length of 1300 km and the speed of 350 km/h, will be finished by the end of 2010.

The Shanghai South Railway Station is the first round station in the world. The station was completed in 2006, with a total area of 60 hectares, and the construction area of more than 50000 square meters. The main station hall is a huge integrated circular steel structure, with a round roof that is 47 m in height and 200 m in diameter.

Figure 2 shows the outline and the main structure of the Shanghai South Railway Station, which is also a multi-functional railway station combining common railways, subway lines, urban railways, buses and taxis as a whole. The station has three levels: the elevated upper floor with a round departure hall allowing 10000 passengers, an 800 m circular departure passageway and the corresponding check gates; the bottom underground floor with passenger exit tunnels, exchange hall, platforms for the Subways Line 1 and Line 3, reserved light-rail Line 1, and some long-distance buses and tourism lines; the middle floor with 13 tracks and 6 platforms, and passage ways to the southern and northern squares for parking cars and underground shops at the ground level but elevated from underground.

The New Guangzhou Railway Station is one of the four important passenger stations in China Railway Stations. There are 28 tracks on the platform floor of the station, including 4 non-stop ones with the speed of 200 km/h. The main part of the station is an elevated spatial frame structure. There are three floors in the station: the 1st floor is the entrance/exit floor with 12 m in height; the 2nd floor is the platform floor with 9 m in height; and the 3rd floor is the waiting hall floor with 27 m in height, as shown in Fig. 3.

These huge comprehensive stations, owing to their structural characteristics of having a large span, high and heavy roofs, multi-layer elevated bridge-frame combined structures and closed waiting halls, are prone to vibrations and noises induced by moving, braking and starting trains, running machineries and passengers, and sometimes by the buses and cars which run through the elevated station roads.

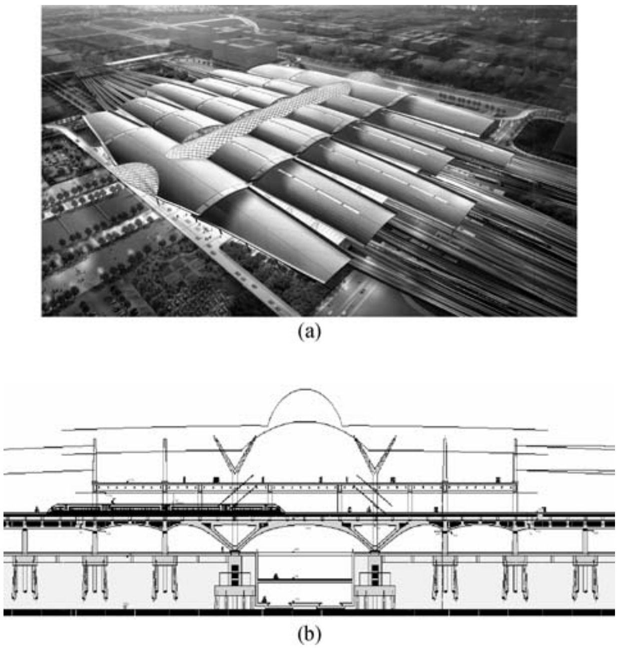


Fig. 3 New Guangzhou Railway Station. (a) Outline; (b) main structure

Generally, the elevated railway station structures can be divided into three types: spatial frame system, bridge system and frame-bridge combined system.

Frame system This system is made up of spatial frame structures and continuous girders supported by the frame (see Fig. 4(a)). In this system, the spatial frame structure works as both building structure and bridge piers, by which the girders of the bridge are supported. This system has the advantages of good integrality, high rigidity and uniform mass distribution. The disadvantages of this system include: it is easy for its columns to collapse unevenly under irregular loads; it is easy to induce structural vibrations by running trains, and it is difficult to design because two types of codes are required.

Bridge system The bridge structure is composed of girders, piers and foundations, and the platforms are built on the bridge, see Fig. 4(b). For this system, the structural performance is similar to that of a common bridge, but higher stiffness and better stability are required. Since the mass center is mainly concentrated at the top of the structure, its earthquake-resistant ability is weak and it is also easy to induce structural vibrations by running trains.

Frame-bridge combined system This system consists of two independent parts: the frame and the bridge. The frame is for the station building, and the bridge is for the railway track, see Fig. 4(c). For this system, the vibrations induced by traffic are weaker than those of the other two types of elevated station structures since the traffic loads are supported only by the bridges.

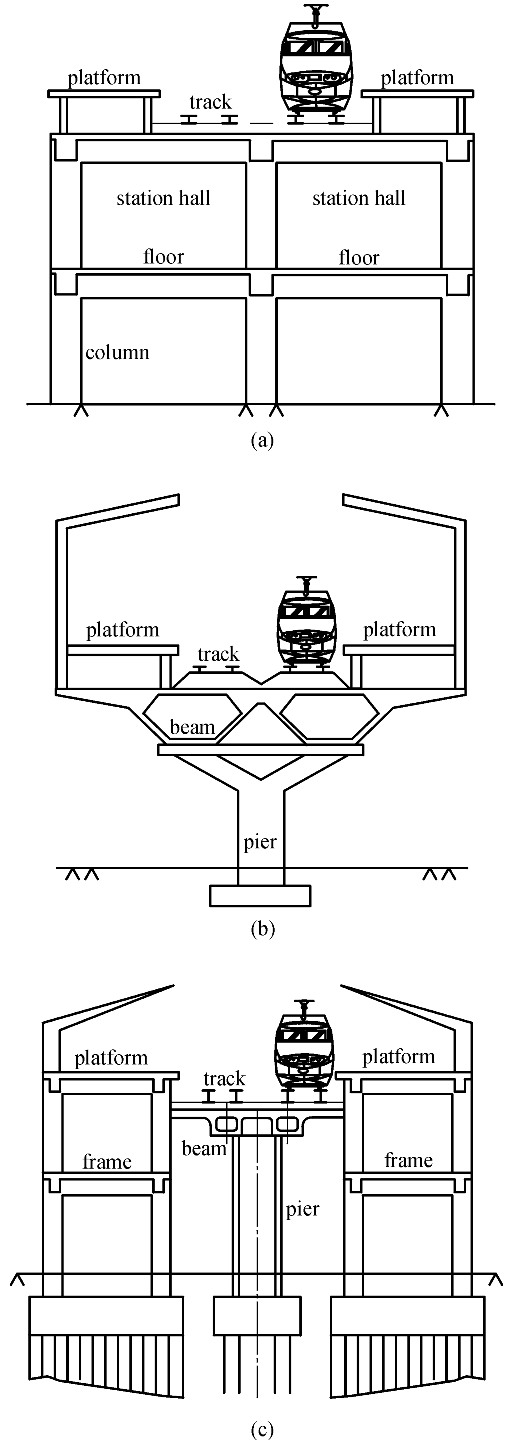


Fig. 4 Structure types of elevated railway stations. (a) Frame system; (b) bridge; (c) frame– bridge combined system

3 Vibration of elevated railway bridges and stations

The vibrations of elevated railway structures, including elevated bridges, stations and multifunctional stations, are induced by the following factors:

Running trains on elevated structures The dynamic interaction of train vehicles and structures is one of the most important factors that induce the vibration of elevated bridges and stations, including: 1) the loading effect of train vehicles at certain speed, namely the vertical and lateral forces formed by a series of gravity loads, which is related to the composition of train, the wheel load arrangement and train speed; 2) the stochastic and periodic factors such as the geometric and dynamic irregularities of track, the hunting movement of the bogies and wheels, and the faults of rails and wheels, which form the self-excitations of the system; 3) the dynamic interactions of vehicles and bridges and the corresponding resonant vibrations, see Fig. 5, including the bridge resonance induced by the periodic action of moving load series of the weights, centrifugal forces of vehicles, by the loading rate of moving load series of vehicles, and the periodic loading of train vehicles excited by rail irregularities and hunting movements, and the vehicle resonance induced by periodic action of regular arrangement of bridge spans and their deflections.

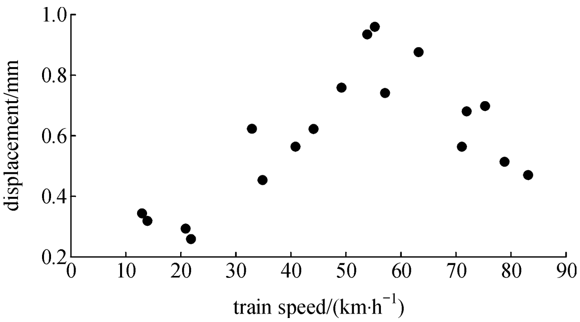


Fig. 5 Bridge deflection vs train speed

Problems about passengers There are several vibration problems to be considered for the passengers on the elevated railway structures: 1) moving at the platforms may induce the structural vibrations of elevated station structures, especially for the large roofs of huge station halls supported by high truss members; 2) passengers in the waiting hall and at the platform may feel discomfort because of the vibrations induced by moving trains or other machineries/equipments; 3) the riding comfort of passengers in vehicles may be affected by the vibration of vehicles when the train moves on elevated bridges.

Braking and tracting of trains Vibrations may be induced by braking force and traction force when a train starts or stops at elevated bridges and station structures. For elevated railway station structures, especially for those with high steel member supported roofs, the vibration induced by braking and tracting may intensify, since the forces behave as a sudden load with an abrupt change in magnitude and may induce a strong impact on the structure, see Fig. 6.

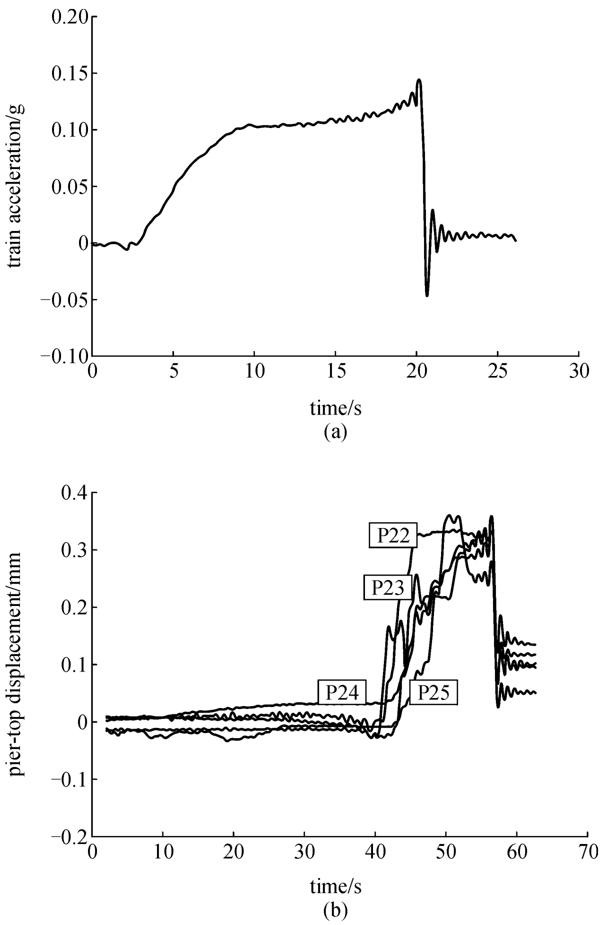


Fig. 6 Braking actions of trains at elevated bridges. (a) Train acceleration; (b) pier-top displacement

Traction motors and other equipments Traction motors and other equipments, such as air ventilation on locomotives and cars and condition machines in the station rooms, may induce the vibrations of platform and waiting hall floors. The vibrations may affect the comfort of passengers, especially for those sensitive to vibrations. The frequencies of these machineries range from 20 Hz to several hundreds Hz.

The vibrations induced by the above factors and their combinations should be carefully studied, estimated in the design stage of elevated bridges and stations, and necessary measures should be taken to prevent and reduce the vibrations.

In the design of the New Guangzhou Railway Station, it was believed that the passing train may cause the vibration of the station structure and affect the comfort of the people in the waiting room, therefore the accelerations at certain points of the waiting hall floor are analyzed, and the comfort for the passengers in the waiting halls are evaluated. The accelerations of the 16 points on the elevated floor of the station platform, which are all at the position of column tops, 21.5 m to 25.25 m from the track central line. The maximum accleration of these places are shown in Fig. 7.

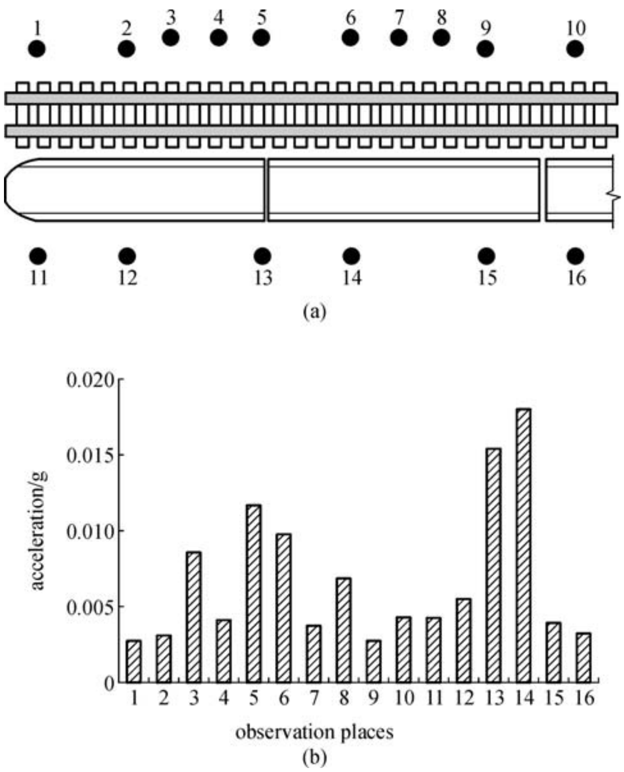


Fig. 7 Observation points at waiting room floor and calculated accelerations. (a) Observation points; (b) maximum acceleration at different observation points

The comfort of the people inside a building under vibration is a complicated issue. Different persons have different sensitivities and endurances to vibration caused by different dynamic loads under different environments. Thus, there are several comfort criteria, such as ISO6897-1984, ISO2631-2, BS6611, the Technical Guidelines for Steel High-rise Buildings in China, the Guideline of Japan Architecture Association. The ATC (Applied Technology Council, USA) [20] recommends in its Design Guidelines– Minimizing Floor Vibrations that the maximum vertical acceleration of building floor should be used as a control parameter, and the limit values for operation rooms, residences/offices, shopping centers and pedestrian bridges are 0.0025 g, 0.005 g, 0.015 g and 0.05 g, respectively within the frequency range of 4 Hz to 8 Hz. There is no direct reference for the vibration standard for the waiting room in the railway station. Since the waiting room and platforms of stations are noisy public cases, the limit may be adopted between those of shopping centers and pedestrian bridges, namely 0.015– 0.05 g, by referencing the ATC's suggestion. The maximum floor acceleration of the Guangzhou Railway Station is 0.0185 g, about 123% for shopping centers and 37% for pedestrian bridges.

4 Noise pollution of elevated railway structures on environment

4.1 Noise sources of elevated railway structures

The noise produced in elevated railway bridges and station structures can be traced to the following factors (see Fig. 8): 1) the wheel-rail noise from the friction and impact between wheel and rail when train runs at high speed; 2) the catenary system noise from the high-speed slipping friction between pantograph and electric wire, or between collector slipper and the third power supply rail; 3) the noise from the motors and other machinery devices; 4) the aerodynamic noise from the high-speed friction between vehicle body and air; 5) The noise from the vibrations of the structure and its accessories induced by running train vehicles.

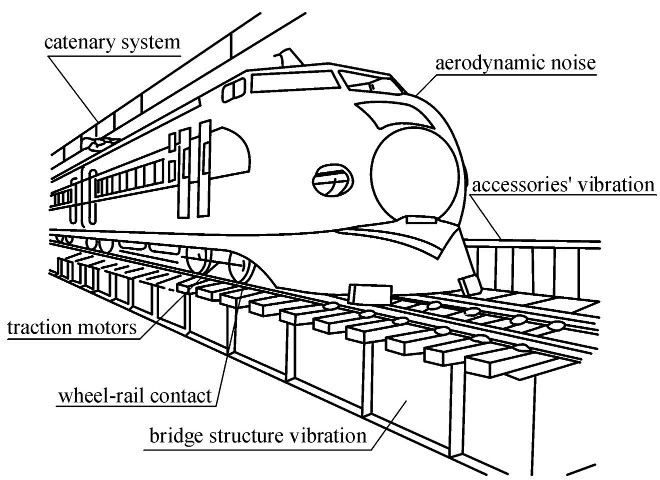


Fig. 8 Noise resources in elevated railway structures

The noise generated by elevated bridges is composed of several noise resources. The integrated noise level at any receiver point can be expressed as

$$L_t = 10\lg\left(10^{L_R/10} + 10^{L_S/10} + 10^{L_P/10} + 10^{L_A/10}\right), \quad (1)$$

where L_R, L_S, L_P and L_A are the noise levels of wheel-rail contact noise, structural noise, catenary noise and aerodynamic noise, respectively, as shown in Fig. 9.

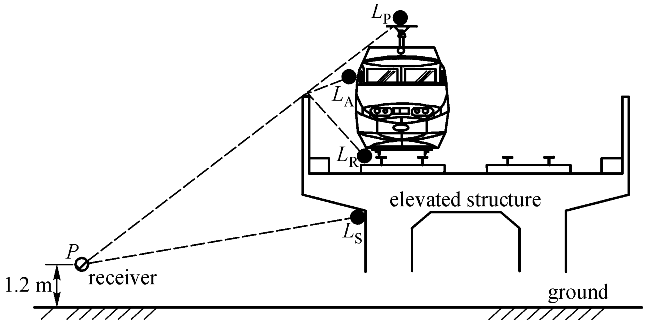


Fig. 9 Noise composition and distribution of elevated bridges

The integrated noise level field distribution of an elevated railway bridge is illustrated in Fig. 10. One can find that the influence distance of the noise and the noise intensities around the elevated bridge are large.

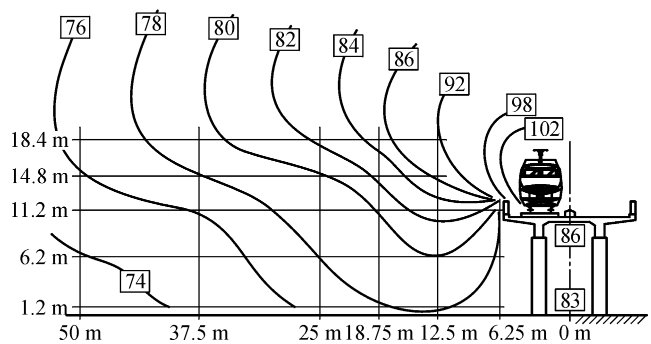


Fig. 10 Noise field distribution of elevated railway bridges

There is also a noise problem to be considered about the passengers for the elevated railway structures, especially in the closed space of the waiting hall in comprehensive stations where considerable noises are induced by moving trains or by other machinery equipments, which mainly makes the passengers in the waiting hall and at the platform feel discomfort because of the noises. Therefore, acoustic design should be carefully performed for elevated railway stations.

4.2 Structural noise of elevated railway structures

The structural vibration-induced noise has low frequency with long wavelengths, normally less than 100 Hz, which is very difficult to isolate by sound barriers or other measures. The materials and types of the structure may influence the noise of the elevated bridge. Generally, concrete bridges generate lower noise than steel bridges. In Japan, some measurements have been taken for twelve types of concrete bridges, the results are shown in Fig. 11, in which A represents an RC frame with a suspended span, B is an RC frame without suspended span, C is an RC rigid frame with a hollow slab, D is an RC hollow plate beam, F is 4-piece RC T-beams, G is 6-piece RC T-beams, H is a composite beam, I is 4-piece PC I-beam, J is 6-piece PC I-beam, K is a box beam, and L is a PC U-shaped beam.

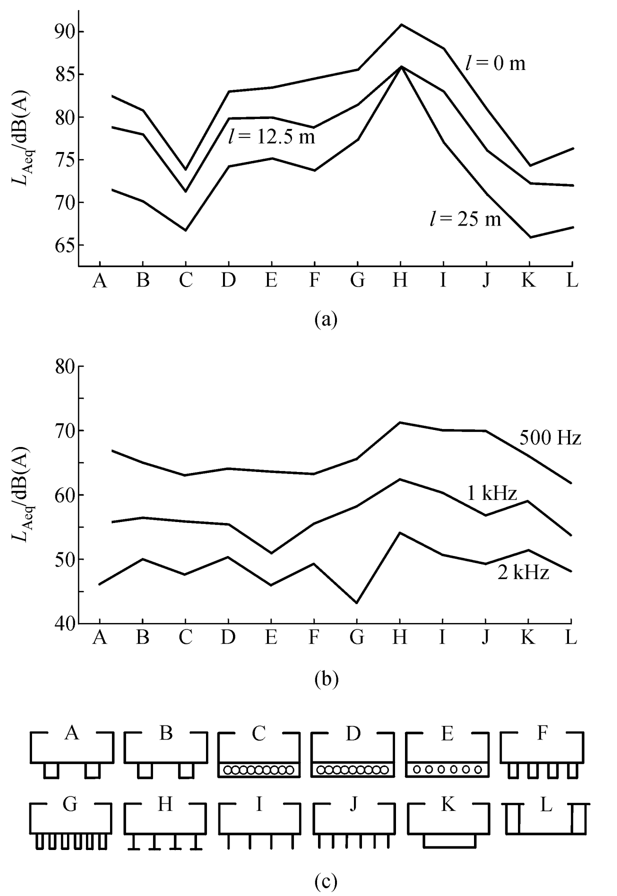


Fig. 11 Comparison of noise at different distances from ground and frequencies in twelve types of bridge girders. (a) Different distances from ground; (b) different frequencies; (c) twelve types of concrete bridge

Elevated railway bridges and station structures are generally composed of several individual substructures such as bars, beams, plates, trusses, etc. To predict the sound power radiation and the distribution of vibration energy of these complex structures, the method of Statistical Energy Analysis (SEA) was used. SEA has been used for the estimation of the distribution of vibration energy throughout the structure and the total loss factors, and for the study of sound transmission in room acoustics.

In the SEA analysis, the structure is divided into several uncoupled members. Each is considered as an independent source of noise. Supposing structural members are composed of different materials, the total radiated sound power can be written as

$$\Pi_{\rm rad} = \rho_0 c\sigma_i S_i (v_i^{-2}) \left[1 + \sum_{j=1, j\neq i}^{N} \frac{E_j}{E_i}\frac{\sigma_j}{\sigma_i}\frac{d_i}{d_j}\right], \quad (2)$$

where $(v^{-2}{}_i)$ is the mean square velocity of the ith member with respect to time and space, d_i is the average thickness of the ith member, S_i is the area of the ith member, σ_i is the radiation efficiency of the structure into air media, c is the wave speed in media, ρ_0 is the density of media material. E_j/E_i is the ratio of the energy stored in the jth member to that in the excited member, which can be determined with the modal densities of the ith and the jth members, the internal loss factor of the ith member and the coupling loss factor from the ith member to the jth one.

4.3 Noise measurement of elevated railway structures

To better understand the noise distribution of elevated railway structures, the investigations were made on some elevated subway bridges and stations, using acoustimeter Center-320.

According to GB/T 14228-1993, the equivalent noise level of platform noise $L_{\rm Aeq}$ can be expressed as [19]

$$L_{\rm Aeq} = 10\lg\left(\frac{T_1 \times 10^{0.1L_{\rm PA1}} + T_2 \times 10^{0.1L_{\rm PA2}}}{T_1 + T_2}\right), \quad (3)$$

where $L_{\rm PA1}$ is the entrance noise level of train from its entering station to stopping at platform, and T_1 is the related time duration; $L_{\rm PA2}$ is the leaving noise level from the train starts at platform and leaves the station, and T_2 is the related time duration. The average equivalent noise level $L_{\rm Aeq}$ of the platform is the average value of 10 continuously measured ones. When the measured noise level is 10 dB less than the background, the data should be corrected according to Table 1.

Table 1 Corrections of measured noise level

difference between measured and background noise levels	corrections
⩾10	0
6–9	−1
4.5	−2
3	−3
<3	measurement failure

4.3.1 Noise level of elevated station of Subway Line 5

The Beijing Subway Line 5 has a total length of 27.6 km, including 14.7 km underground lines and 12.9 km ground and elevated lines. There are 5 elevated stations, 2 ground stations and 15 underground stations, totally 22 stations.

The equivalent noise levels $L_{\rm Aeq}$ were measured at the entrance end (column E in Fig.13), middle (column M in Fig.13) and leaving end (column L in Fig.13) along the train moving direction in 5 elevated stations of the Beijing Subway Line 5, as shown in Figs.12 and 13.

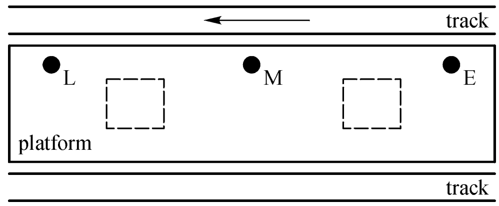


Fig. 12 Measurement locations at platform

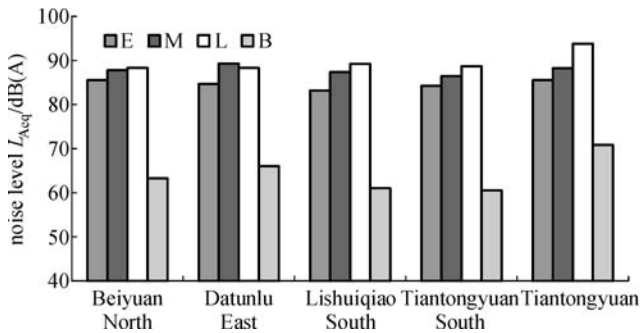


Fig. 13 Measured platform $L_{\rm Aeq}$ at elevated stations

It can be seen that in all the six stations, the equivalent noise levels $L_{\rm Aeq}$ are as high as 88–92 dB (A), which are 23–28 dB (A) higher than the background noises (column B in Fig. 13). $L_{\rm Aeq}$ at leaving ends are higher than at the middle, and those at the middle higher than at the entrance ends. The maximum difference between them reached to 8.2 dB (A) at the Tiantongyuan Station.

4.3.2 Noise comparison of different types of stations

Measurements were carried out on the noise levels in all 22 stations of the Beijing Subway Line 5. The average equivalent noise levels $L_{\rm Aeq}$ measured at the 5 elevated stations, 2 ground stations and 15 underground stations are illustrated in Fig.14.

The comparison of the three types of subway stations shows that the average equivalent noise levels of underground stations are higher than those of the ground ones by 1.8–4.0 dB (A) and the elevated ones by 2.1–6.2 dB (A). This means that the train running in underground stations with closed environment induces higher noises than it does when it runs in ground and elevated stations with open environments.

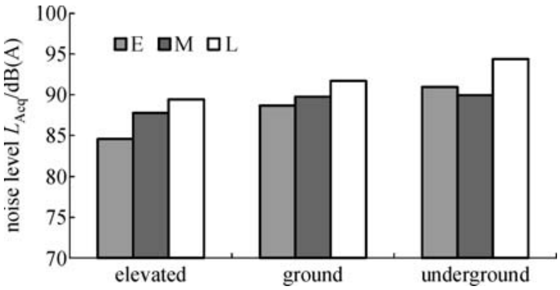


Fig. 14 Noise comparison of different types of stations

4.3.3 Noise distribution of elevated stations of Airport Line

A field measurement was carried out on the noise levels close to an elevated bridge in the Beijing Subway Airport Line. The Beijing Airport Line adopts the linear induction motor system. As shown in Fig.15, the noise levels were measured at the places under the beam, and 5 m, 10 m, 20 m, 30 m and 40 m to the central line of the bridge. The distribution of equivalent noise levels L_{Aeq} close to the bridge is shown in Fig. 16.

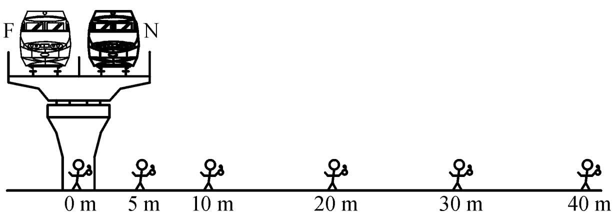


Fig. 15 Noise measurement of elevated bridge in Airport Line

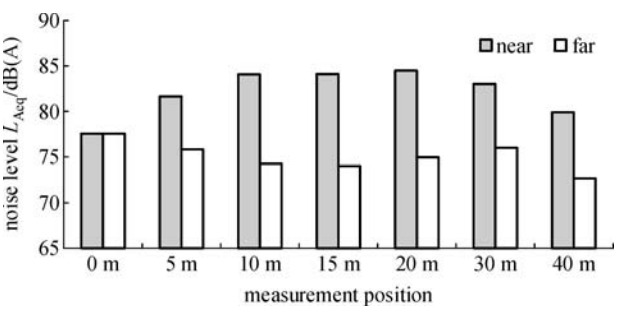


Fig. 16 Distribution of noise close to elevated bridge

It can be seen that the maximum noise levels are 84–84.6 dB (A) appeared at the places 10–30 m from the central line of the bridge, when the train runs on the near side track (N) of the bridge. When the train runs on the far side (F) of the bridge, the measured noise levels are 5.8–10.2 dB (A) lower than those of the train on the near side track.

5 Conclusion remarks

Because of the limit of the length on this paper, there remain some problems to be further studied:

1) **Sources of vibration and noise** the generation mechanism of vibrations and noises of the elevated structures induced by different types of trains which run at different speeds, start or brake in station, moving passengers, running vehicle traction motors and station equipments, and the combination of these loads; the influence of structural types, forms, clearances, heights, spans, stiffness and areas on vibration and noise propagations and distributions; the resonance effect between bridge structure, station structure and loads, and their countermeasures.

2) **Vibration and noise influence on the environment and passengers** the distribution of vibration and noise in inner vehicle, inner-station hall and surrounding elevated bridges, and their influences on environments and passengers.

3) **Vibration and noise mitigation treatments and isolation measures** the structural forms of elevated bridges and stations with low vibrations and noises; the practicable and effective vibration and noise reduction measures; the vibration reduction tracks and other equipments; the noise reduction and isolation measures.

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