



## Article Research on the Dynamic Response of the Multi-Line Elevated Station with "Integral Station-Bridge System"

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Abstract: Elevated stations serve as critical hubs in urban rail transit engineering. The structure of multi-line "building-bridge integrated" elevated stations is unique, with intricate force transfer paths and challenges to clarify dynamic coupling from train vibrations, necessitating the study of such stations' train-induced dynamic responses. This paper presents a case study of a typical "buildingbridge integrated" elevated station, utilizing the self-developed finite element software GSAP-V2024 to establish a simulation model of a coupled train-track-station system. It analyzed the station's dynamic response under various single-track operating conditions and the pattern of the vibration response as the speed changes. Additionally, the study examined lateral vibration response changes in the station under double, quadruple, and sextuple train operations at the same speed. Findings reveal that the station's vertical responses generally increase with speed, significantly outpacing lateral responses. Under single-track operations, dynamic responses vary across different types of track-bearing floors and frame structures with different spans. With an increase in the number of operating train lines, the station's vertical response grows, with lateral responses being neutralized in the mid-span of the triple-span frame structure and amplified at the edges. These results provide a reference for the structural design of multi-line "building-bridge integrated" elevated stations.

Keywords: building-bridge integration; train-induced vibration; multi-line railway; dynamic response; elevated station

## 1. Introduction

As urban areas expand, challenges like rising population density, growing transportation demand, and worsening environmental pollution escalate. The urban rail transit, a pivotal solution, facilitates connectivity across city clusters. Elevated stations, vital in these projects, significantly contribute to passenger distribution and transport connectivity, and accelerate development along railway lines [1], garnering more focus from the construction sector.

Elevated stations are classified into three principal types according to the connection of track beams to station buildings: "building-bridge integrated", "building-bridge separated", and "building-bridge combined" structures. In the building-bridge integrated design, tracks are laid directly on the track-bearing floor, utilizing a unified frame structure. This design ensures a simple grid of frame columns, reduced overall height, and enhanced structural rigidity. The building-bridge separated design features independent bridge structures from station buildings, offering a straightforward structural system with clear force transfer paths. The building-bridge integrated elevated station combines building and bridge structures, leading to notable unevenness in structural stiffness and mass distribution, both horizontally and vertically. This integration presents challenges like intricate load transfer paths, clarifying dynamic coupling from train vibrations, and a lack of unified design standards during the design phase. Many scholars have explored these issues, with extensive on-site experiments conducted on elevated stations. Cai et al. [2] investigated the vibration characteristics of elevated stations, examining vibrations in waiting halls and platforms across time and frequency domains. They identified differences in vibration



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responses due to trains arriving, leaving, and passing through. Yu et al. [3] examined the effects of high-speed train loads on waiting room and business floors' vibrations, assessing vibration serviceability with data from Zhengzhou East Railway Station. Liu, Yang, et al. [4,5] conducted tests and analyses on environmental vibrations in various areas of elevated stations, including platforms and waiting halls, to explore the propagation of train-induced vibrations. Ba et al. [6] performed field tests to evaluate background and structural vibrations from varying speeds, measuring effective vibration acceleration at different points. Furthermore, high-speed trains impact nearby buildings with vibrations and noise [7–9]. Xia et al. [10,11] explored the mechanisms behind train-induced vibrations and noise at elevated stations, examining the effects of train type, speed, and proximity on nearby buildings. Sanayei M, Hesami S et al. [12,13] corroborated finite element models with field data, studying the impact of train speed, soil properties, and structural traits on building vibrations caused by trains. Li and his team performed empirical research on vibrations and noise at large high-speed railway stations due to passing trains, exploring structural vibration patterns and noise radiation during train operations [14].

Other researchers have proposed various numerical models for simulation calculations. Deng et al. [15] suggested taking the load time history from the train-bridge sub-model dynamic calculations as external excitation acting on the bridge-station sub-model. They conducted time history analysis to compute the dynamic response caused by trains passing through the elevated station and evaluated the station's vibration serviceability. Xu, Xie, Yang, Cui, et al. established a train-station vibration analysis system to explore station dynamics and train-induced vibration patterns, focusing on station structure comfort [16–19]. Salih Alan and colleagues researched vibration control for train-induced vibrations at an Ankara station. They simulated the station-foundation interaction with springs and dampers in a finite element model, aligning with Turkish environmental noise laws [20]. Zhang et al. [21] used rigid body dynamics for a train subsystem model and the mode superposition method for a structural model. They explored the analysis method for the train-station structure coupling system under braking force. Zhang et al. devised a numerical model for analyzing vibrations in large-scale integrated building-bridge structures (IBBS), focusing on high-speed railway stations and evaluating vibration mitigation effectiveness [22]. Yang et al. introduced a two-step time-frequency prediction method for superstructures to predict and analyze train-induced vibrations in buildings above subway tunnels [23].

Numerous researchers have explored the vibration characteristics of station structures during train operations, including aspects of safety and comfort. Additionally, they have documented the propagation and attenuation of train-induced vibrations [24–29]. Yet, the dynamic response of multi-line "building-bridge integrated" elevated stations remains less studied. To tackle these challenges, this study examines a typical multi-line "building-bridge integrated" elevated station structures as an integrated unit, formulating spatially coupled vibration equations for this system. These equations are solved through time-domain analysis, leading to the development of a finite element model for the multi-line elevated station. The research delves into the dynamic characteristics of such stations and the propagation of train-induced vibrations, providing design insights for multi-line "building-bridge integrated" elevated station.

#### 2. The Multi-Line Elevated Railway Station

Figure 1 displays the elevated station's structure, designed for 100 km/h with 15 tracks. The "U" in Figure 1 represents the "upward direction" and "D" represents the "downward direction". Its structural system combines steel-reinforced concrete columns, bidirectional prestressed concrete beams, and cast-in-place concrete slabs into a spatial frame. The station comprises three levels: a 9.09-m-high platform floor, a 6.90-m-high track-bearing floor, and a 0.70-m-high hall floor. It is uniquely segmented into three parts: perpendicular to the tracks, with a one-span, three-span, and two-span frame structure, respectively. Parallel to the tracks, each section features a three-span structure, and each span is 21 m long. In Figure 1, '#' represents the track. Tracks 3#, 4#, 11#, and 12# are

supported by bridge structures, isolated from the main frame by seismic joints, making them independent. Thus, this study focuses on the vibrations from trains on the elevated station's tracks, not including bridges.



**Figure 1.** Schematic diagram of station structure (unit: mm): (**a**) lateral view of station; (**b**) elevation view of station.

#### 3. Train-Track-Station Spatially Coupled Model

This paper utilizes GSAP, a dynamic simulation analysis finite element software developed by the author, to accurately model the track–station structure. The large scale of the station structure, coupled with its numerous degrees of freedom (DOFs), makes solving for such a multitude of DOFs quite challenging. To address this challenge and enhance computational efficiency, the paper adopts the principle of total potential energy with stationary value in elastic system dynamics and the "Set in right position" rule for formulating matrices as proposed by Zeng of Central South University [30,31]. It treats the train, track, and station structures as an integrated system, establishes a coupled vibration equation for the train–track–station, and employs time-domain analysis and computer numerical simulation for solution.

#### 3.1. Train Spatial Vibration Model

3.1.1. Assumptions of the Train Model

To enhance computational efficiency while ensuring the accuracy of the train spatial model, this paper simplifies the train model based on its construction features, making the following assumptions [32]:

(1) The train body, bogies, and wheelsets are all assumed to be rigid bodies, considered only to undergo minor vibrations;

(2) The train travels at a constant speed on the track, with the longitudinal motion of the train not considered;

(3) The creep force of the wheel rail and the springs in the train model are linear, and the damping of the train model is viscous.

(4) The vertical displacement of the wheelset and track on the station remains constant.

#### 3.1.2. Establishment of the Train Model

Based on the above assumptions, the train consists of one body, two bogies, and four wheelsets. The vehicle body and bogie exhibit five DOFs—lateral, vertical, roll, yaw, and pitch—while the wheelset's motion is described by two DOFs, namely in the lateral and roll. Figure 2 illustrates the specific vehicle vibration analysis model, and Table 1 details the DOFs of the vehicle.



Figure 2. The model of the train: (a) side view; (b) elevation view; (c) plan view.

Table 1. Definition of DOF Variables for each vehicle.

Components	Lateral	Vertical	Yaw	Pitch	Roll
Body	Y <sub>c</sub>	Z <sub>c</sub>	$\psi_c$	$\phi_c$	$\theta_c$
Front bogie	$Y_{z_1}$	$Z_{z_1}$	$\psi_{z_1}$	$\phi_{z_1}$	$\theta_{z_1}$
Rear bogie	$Y_{z_2}$	$Z_{z_2}$	$\psi_{z_2}$	$\phi_{z_2}$	$\theta_{z_2}$
1st wheelset	$Y_{s_1}$	/	$\psi_{s_1}$	/	/
2nd wheelset	$Y_{s_2}$	/	$\psi_{s_2}$	/	/
3rd wheelset	$Y_{s_3}$	/	$\psi_{s_3}$	/	/
4th wheelset	$Y_{s_4}$	/	$\psi_{s_4}$	/	/

The other parameters in the Figure 2 are defined as follows:  $M_{Z_1}$ ,  $M_{Z_2}$ ,  $M_C$  represent the mass of the front bogie, rear bogie, and vehicle body.  $J_{\phi_{Z_1}}$ ,  $J_{\phi_{Z_2}}$ ,  $J_{\phi_C}$  denote the roll moments of inertia for the front bogie, rear bogie, and car body, while  $J_{\psi_{Z_1}}$ ,  $J_{\psi_{Z_2}}$ ,  $J_{\psi_C}$ represent the yaw moments of inertia for the same components, respectively.  $J_{\psi_{s_1}}$ ,  $J_{\psi_{s_2}}$ ,  $J_{\psi_{s_3}}$ ,  $J_{\psi_{s_4}}$  are the yaw moments of inertia for the 1st, 2nd, 3rd, and 4th wheelsets, respectively.  $k_1^v$ ,  $c_1^v$ ,  $k_1^h$ ,  $c_1^h$ ,  $k_1^l$ ,  $c_1^l$  correspond to the vertical, horizontal, and longitudinal stiffness and damping of the primary suspension.  $k_2^v$ ,  $c_2^v$ ,  $k_2^h$ ,  $c_2^h$ ,  $k_2^l$ ,  $c_2^l$  signify the same parameters for the secondary suspension.

The 23 displacement parameters of the train model are as shown in Equation (1).

$$\{\delta\}_{v}^{e} = \{Y_{s_{1}} Y_{s_{2}} Y_{s_{3}} Y_{s_{4}} \psi_{s_{1}} \psi_{s_{2}} \psi_{s_{3}} \psi_{s_{4}} Y_{z_{1}} Y_{z_{2}} Z_{z_{1}} Z_{z_{2}} \psi_{z_{1}} \psi_{z_{2}} \phi_{z_{1}} \phi_{z_{2}} \theta_{z_{1}} \theta_{z_{2}} Y_{c} Z_{c} \psi_{c} \phi_{c} \theta_{c}\}^{\mathrm{T}}$$
(1)

The position of the train on the track constantly changes. Initially, the total vibration potential energy of a single vehicle section must be calculated. By applying the principle of total potential energy with stationary value in elastic system dynamics and the "Set in right position" rule for formulating matrices, the  $[M_v]$  (mass),  $[K_v]$  (Stiffness), and  $[C_v]$  (Damping) matrices essential for the train simulation model in this paper can be generated:

$$[M_v]\left\{\ddot{\delta}_v\right\} + [C_v]\left\{\dot{\delta}_v\right\} + [K_v]\left\{\delta_v\right\} = \{P_v\}$$
<sup>(2)</sup>

where  $\{\delta_v\}$ ,  $\{\delta_v\}$ ,  $\{\delta_v\}$ , respectively, represent the arrays of acceleration, velocity, and displacement parameters.

#### 3.2. Track-Station Spatial Vibration Model

The finite element analysis model of this paper focuses on the track–station structure's main framework, omitting the canopy. It utilizes two-node spatial beam elements for beams and columns, and four-node shell elements for floor slabs. The core modeling strategy entails generating mass and stiffness matrices for each element from material parameters in a local coordinate system. Implementing the "Set in right position" rule for formulating matrices allows for the integration of all element matrices into comprehensive mass and stiffness matrices for the track–station model.

#### 3.2.1. Establishment of Mass and Stiffness Matrices

### 1. Beam element;

A spatial beam element features two end nodes, i and j. Each node encompasses two translational degrees and one rotational degree of freedom (DOFs) within the local coordinate system, summing up to six DOFs per beam element. The local coordinate system originates at node i, with the axis from node i to node j constituting the x-axis. Introducing a point k, the plane spanned by i, j, and k constitutes the X-Y plane, with the Z-axis orientation determined by the right-hand rule. Thus, the mass and stiffness matrices of a spatial beam element in this local coordinate system are as follows:





where *l* is the length of the beam element; A is the cross-sectional area of the beam element;  $\rho$ is the density of the beam element material;  $I_{\rho}$ ,  $I_{Y}$ ,  $I_{z}$  are the moments of inertia of the beam element's cross-section about the x, y, z axes, respectively;  $r_y$ ,  $r_z$  are the radius of the gyration of the beam element's cross-section about the y, z axes, respectively; and  $A_y$  and  $A_z$  are the shear areas of the beam element along the local coordinate system's y, z axes, respectively.

#### 2 Shell element;

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A shell element consists of four nodes, corresponding to the four corners of a rectangle, with each node having two translational degrees of freedom, totaling eight degrees of freedom per shell element. Equations (6) and (7) display the mass and stiffness matrices of the shell element, where *a* and *b* represent half the length of the sides of the plate element,  $\rho$  is the material density, and *t* is the thickness of the plate element.

$$M] = \frac{ab\rho t}{9} \begin{bmatrix} 4 & 0 & 2 & 0 & 1 & 0 & 2 & 0 \\ 0 & 4 & 0 & 2 & 0 & 1 & 0 & 2 \\ 2 & 0 & 4 & 0 & 2 & 0 & 1 & 0 \\ 0 & 2 & 0 & 4 & 0 & 2 & 0 & 1 \\ 1 & 0 & 2 & 0 & 4 & 0 & 2 & 0 \\ 0 & 1 & 0 & 2 & 0 & 4 & 0 & 2 \\ 2 & 0 & 1 & 0 & 2 & 0 & 4 & 0 \\ 0 & 2 & 0 & 1 & 0 & 2 & 0 & 4 \end{bmatrix}$$
(6)
$$[K] = \begin{bmatrix} k_{11} & k_{12} & k_{13} & k_{14} \\ k_{21} & k_{22} & k_{23} & k_{24} \\ k_{31} & k_{32} & k_{33} & k_{34} \\ k_{41} & k_{42} & k_{43} & k_{44} \end{bmatrix}$$
(7)

(4)

The expression for the sub-stiffness matrix within the stiffness matrix in Equation (7) is shown in Equation (8).

$$[k_{ij}] = \iint t[B_i]^T[D][B_j]dxdy \tag{8}$$

#### 3.2.2. Establishment of the Damping Matrix

Calculating the damping matrix for a structure is notably more challenging than determining its stiffness and mass matrices. Due to its simplicity and convenience, Rayleigh damping is widely adopted in structural dynamic analysis. Consequently, it is commonly applied in engineering projects for deriving the damping matrix. The formula for Rayleigh damping used in this study is detailed in Equation (9).

$$[C] = \alpha[M] + \beta[K] \tag{9}$$

In Equation (9), [M] and [K] represent the structure's mass matrix and stiffness matrix, respectively.  $\alpha$  and  $\beta$  are proportional coefficients, which are constants. Once the finite element model of the bridge is constructed,  $\alpha$  and  $\beta$  can be obtained through modal analysis, as illustrated in Equations (10) and (11).

$$\alpha = \frac{2\omega_1\omega_2}{\omega_1^2 - \omega_2^2} (\omega_1\xi_2 - \omega_2\xi_1)$$
(10)

$$\beta = \frac{2(\omega_1\xi_1 - \omega_2\xi_2)}{\omega_1^2 - \omega_2^2}$$
(11)

 $\omega_1$  and  $\omega_2$  represent the first and second natural frequency of the station finite element model, respectively, while  $\xi_1$  and  $\xi_2$  correspond to the first and second modal damping of the finite element model. Therefore, once the overall stiffness and mass matrices of the bridge–station analysis model are established, the overall damping matrix can be obtained using the aforementioned method.

#### 3.2.3. Finite Element Model of Station

Figure 3 illustrates the finite element model of the station, featuring 2574 nodes, 2533 beam elements, and 1615 shell elements, all constructed from linear elastic materials. The elasticity modulus and Poisson's ratio adhere to specified standards, with the concrete structure's damping ratio established at 2%. Table 2 outlines the components' material strength classes.



Figure 3. Finite element model of multi-line "building-bridge integrated" elevated station.

Table 2. Material strength classes for station components	s.
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Components	Strength Class
Platform level beams, columns, and floor	C50
Track-bearing layer longitudinal beams, transverse beams	C60
Track-bearing layer columns, floor	C50
Concourse level beams, concrete columns, and floor	C50
Inner steel frame of hall level columns	Q235

#### 3.3. Establishment of the Train-Track-Station System Coupled Vibration Equation

At any given time t, deriving the coupled vibration equation for the train-track-station system requires calculating the total potential energies of both the track-station and the train. The sum of these energies forms the system's total potential energy. The train-track-station system is viewed as an integrated unit, with self-excitation due to track irregularities and external excitation from vehicular loads. Utilizing Qingyuan Zeng's previously mentioned theory allows for the formulation of the system's vibration equation at time t:

$$[K]\{\delta\} + [C]\{\dot{\delta}\} + [M]\{\ddot{\delta}\} = \{P\}$$
(12)

where [K], [C], [M] represent the stiffness, mass, and damping matrices of the train–track– station system at time t, respectively;  $\{\delta\}$ ,  $\{\dot{\delta}\}$ ,  $\{\ddot{\delta}\}$  correspond to the displacement, velocity, and acceleration arrays for the system at time t; and  $\{P\}$  is the load array acting on the system at time t, consisting of wheel-rail contact forces due to track irregularities and the self-weight of the vehicle.

In Equation (12), the right-side load array includes only the train's gravitational forces. To solve for the dynamic response of the train–track–station system during operation, excitations from track irregularities and deformations must replace the vibration parameters on the left side of Equation (12). Accordingly, the displacement parameter  $\{\delta\}$  in Equation (12) is divided into *k* known and *n* unknown parameters, leading to  $\{\delta\}$ 's expression as follows:

$$\{\delta\} = \{\delta_k \, \delta_n\}^{\mathrm{T}} \tag{13}$$

Equation (12) can be derived as:

$$\begin{bmatrix} K_{kk} & K_{nk} \\ K_{kn} & K_{nn} \end{bmatrix} \begin{cases} \delta_k \\ \delta_n \end{cases} + \begin{bmatrix} C_{kk} & C_{nk} \\ C_{kn} & C_{nn} \end{bmatrix} \begin{cases} \dot{\delta}_k \\ \dot{\delta}_n \end{cases} + \begin{bmatrix} M_{kk} & M_{nk} \\ M_{kn} & M_{nn} \end{bmatrix} \begin{cases} \ddot{\delta}_k \\ \ddot{\delta}_n \end{cases} = \begin{cases} 0 \\ P \end{cases}$$
(14)

Expanding Equation (14), we obtain:

$$[K_{nn}]\{\delta_n\} + [C_{nn}]\{\dot{\delta}_n\} + [M_{nn}]\{\ddot{\delta}_n\} = \{P\} - [K_{nk}]\{\delta_k\} - [C_{nk}]\{\dot{\delta}_k\} - [M_{nk}]\{\ddot{\delta}_k\}$$
(15)

$$[K_{kk}]\{\delta_k\} + [C_{kk}]\{\dot{\delta}_k\} + [M_{kk}]\{\ddot{\delta}_k\} + [M_{kn}]\{\ddot{\delta}_n\} + [C_{kn}]\{\dot{\delta}_n\} + [K_{kn}]\{\delta_n\} = 0$$
(16)

Equation (16) is a linearly dependent matrix equation and must be eliminated. Since all terms on the right side of Equation (15) are known, it constitutes a solvable vibration matrix equation for the train–track–station system with a free term. Therefore, the dynamic response of the train–track–station coupling system can be determined based on this.

#### 3.4. Solution of the Train–Track–Station System Coupled Vibration Equation

For linear structures, mode superposition methods, such as Duhamel integration and Fourier transform, are commonly used for dynamic calculation and analysis. These methods offer simplicity in calculation, and provide an intuitive understanding of the contribution of each vibration mode to structural vibration.

This study addresses the train-track-station system, a complex time-varying entity. Changes in spring and damping properties mean the system's vibration equation coefficients constantly shift, making mode superposition methods impractical. Instead, a step-by-step integration method within the time domain emerges as a viable analytical approach for the motion equations. This method divides the system's vibration duration under external loads into numerous intervals, keeping parameters static within each. The system's dynamic response at the beginning of a time interval is used as the initial condition for vibration, allowing the system's response at the end of that interval to be determined and used as the initial condition for the next interval. By repeating this calculation process,

the vibration response for all time intervals can be determined. This paper employs the step-by-step integration method for solution.

#### 3.5. Verification of the Spatial Model

This study's finite element simulation model and computational approaches align with those described in Reference [33]. That research examines the influence parameters of the dynamic response of the elevated station with the "integral station-bridge system". Designed for 120 km/h speeds, the station utilizes a complete cast-in-place spatial frame structure. Structurally, it includes a hall level, track-bearing level, and platform level, organized from the bottom upwards. The overall dimensions are 21.62 m in height, 120 m in length, and 31.80 m in width, with three transverse rows of columns spaced 10.5 m apart. Longitudinally, it comprises 10 spans of 12 m each, devoid of expansion joints. Figure 4 displays the station's finite element model.



Figure 4. Finite element model of station.

Numerous studies indicate that the vibration response of station structures is primarily influenced by the vertical loads from trains, with the station's vibration predominantly characterized by vertical responses [2,6,33]. To validate the model's credibility and the computational results' reliability, this study focused on the hall and platform levels for vertical response measurements, comparing the observed data with numerical simulations. An unloaded six-car train passing at 110 km/h in a downward direction served as the on-site condition for measurement. The schematic diagram of the lateral arrangement of measuring points is shown in Figure 5. Points A1 and A2 were designated at the hall level, with points B1 and B2 at the platform level. Figure 6 illustrates the vertical acceleration time–history curves at these points, while Table 3 compares the measured and simulated acceleration peak values. The close match in peak values, being of the same magnitude order, confirms the model's spatially coupled vibration calculation accuracy.



Figure 5. Schematic diagram of lateral arrangement of measuring points.



**Figure 6.** Vertical acceleration time–history curve of each measuring point: (**a**) measured time–history curve; (**b**) calculated time–history curve.

Table 3.	Comparison	of peal	k acce	leration.
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Position	Point	Peak Acceleration (mm/s <sup>2</sup> )		
10511011		Measured Value	Calculated Value	
1.111.1	A1	42.46	32.98	
hall level	A2	50.96	38.37	
platform level	B1	123.86	152.57	
	B2	107.75	101.50	

# **4.** Calculation and Analysis of Vibration in the Train–Track–Station Spatially Coupled System *4.1. The Natural Vibration Characteristics of Station*

The station's natural frequency and mode shapes provide an intuitive representation of its structural stiffness. Utilizing the finite element analysis model developed earlier, the study examined the station structure's natural vibration characteristics, detailed in Table 4.



Table 4. The natural vibration characteristics of elevated station.

#### 4.2. Dynamic Response Results and Analysis of the Station under Different Single-Track Conditions

Based on the finite element model established earlier, a coupled vibration analysis of the train-track-station system is conducted. The train model uses the China Railway High-speed 3 (CRH3). It consists of 16 cars, including 8 motor cars and 8 trailer cars. The German low-disturbance spectrum is used to simulate additional track irregularities during train operation. The analysis in this section focuses on single-track train conditions. Out of the station's 11 tracks, 7 with unique operating conditions were selected due to the similarities in the conditions among some tracks. The seven single-track train conditions correspond to tracks 1#, 2#, 5#, 6#, 7#, 13#, and 14# in Figure 1a. The specific train formation and operational conditions are shown in Table 5 below. The structural dynamic response is calculated for a single-track fully loaded train passing through the station in the down direction at speeds of 60~100 km/h.

Table 5. The train formations and operational conditions.

Train Model	<b>Train Formation</b>	Speed (km/h)	Working Condition
CRH3	$(M^{1} + T^{1} + T + M) \times 4$	60, 70, 80, 90, 100	Single-track train (1#, 2#, 5#, 6#, 7#, 13#, 14#)

<sup>1</sup> The M is motor car, and the T is trailer car.

To illustrate the variation in structural responses under different single-track train conditions and speeds, Figure 7 presents curves of lateral and vertical movements and accelerations for seven distinct single-track scenarios, for both the track-bearing and platform floors. All structural vibration displacement values are measured relative to the initial equilibrium position.

Figure 7 reveals that for a single-track CRH3 train traveling at speeds of 60~100 km/h, both the track-bearing and platform floors experience greater vertical than lateral displacements and accelerations at all speeds. Lateral movements and accelerations exhibit minimal changes as the speed increases. Overall, vertical displacements and accelerations at the track-bearing floor increase with speed. At the platform floor, vertical displacement increases with speed, while vertical acceleration first decreases then increases.

A single-track bearing floor contains one track, while a double-track bearing floor contains two tracks. As depicted in Figure 1, tracks 1#, 2#, 5#, and 13# reside on a single-track floor, with tracks 6#, 7#, and 14# situated on a double-track floor. At identical speeds, the platform floor's lateral and vertical movements and accelerations—collectively termed as lateral and vertical responses—are more pronounced when a train traverses track 5# than on tracks 6# and 7#. Similarly, at equal speeds, track 13# elicits greater lateral and vertical responses on the platform floor than track 14#. Moreover, at the same velocity, a single-track train induces notably lower lateral and vertical responses on a double-track bearing floor.



**Figure 7.** Maximum dynamic response of track-bearing floors and platform floors at the speed of 60~100 km/h under seven types of single-track train conditions: (**a**) lateral displacements of the track-bearing floors; (**b**) vertical displacements of the track-bearing floors; (**c**) lateral acceleration of the track-bearing floors; (**d**) vertical acceleration of the track-bearing floors; (**e**) lateral displacements of the platform floors; (**f**) vertical displacements of the platform floors; (**g**) lateral acceleration of the platform floors; (**h**) vertical acceleration of the platform floors.

Considering the span of frame structures, tracks 1# and 2# are on single-span frames, 5#, 6#, and 7# are on triple-span frames, and 13# and 14# are on double-span frames. In a general trend, the platform floor's lateral and vertical responses from trains on the double-span 13# track are less than on the single-span 1# and 2# tracks but greater than on the triple-span 5# track.

#### 4.3. The Impact of Multi-Track Train Operations on Station Dynamic Response

To assess the station's structural dynamic response to varying numbers of simultaneously operating trains, this study concurrently passed double, quadruple, and sextuple CRH3 trains through the station at 100 km/h. The train count was symmetrically increased from the central triple-span frame structure, as shown in Table 6, which details specific train formations and operational conditions. The vibration response collection points started at the intersection of cross-track and along-track central axes at the edge of the track-bearing floor, near track 1#. These points extended along the cross-track direction. For the track-bearing floor, collection points were positioned at the center. For the platform floor, collection points were located at both side edges and the center, as illustrated in Figure 8.

**Table 6.** The train formations and operational conditions.

Train Model	<b>Train Formation</b>	Speed (km/h)	Working Condition
CRH3	$(M^{1} + T^{1} + T + M) \times 4$	100	Double trains (7#, 8#)
CRH3	$(M^{1} + T^{1} + T + M) \times 4$	100	Quadruple trains (6#, 7#, 8#, 9#)
CRH3	$(M^{1} + T^{1} + T + M) \times 4$	100	Sextuple trains (5#, 6#, 7#, 8#, 9#, 10#)

<sup>1</sup> The M is motor car, and the T is trailer car.



Figure 8. Schematic diagram of lateral arrangement of vibration measuring points.

To demonstrate the impact of the number of operating trains on the vibration response of the track-bearing and platform floors, as well as the response distribution across the cross-track direction, the calculated lateral and vertical dynamic responses are plotted as curves, as shown in Figures 9 and 10.



**Figure 9.** Maximum dynamic response at the mid-span of station track-bearing floors under different number of operating train lines: (a) lateral displacements of the track-bearing floors; (b) vertical displacements of the track-bearing floors; (c) lateral acceleration of the track-bearing floors; (d) vertical acceleration of the track-bearing floors.

Figure 9 shows that with two trains, the lateral displacement in the track-bearing floor decreases from the mid-span towards the edges. With four and six trains, the lateral displacement at the frame edges exceeds that at mid-span. This occurs because, with more trains, the symmetric dynamic loads are partially offset at the structure's center. At the same time, the track-bearing floor edges experience vibration amplification due to superposition. Moreover, when multiple trains are in operation, the lateral acceleration in the track-bearing layer is lower at mid-span compared to the boundaries. Overall, the trend shows that as the number of trains increases, both the vertical displacement and acceleration in the track-bearing floor rise, with vertical responses markedly surpassing lateral ones.

Figure 10 reveals that with an increase in the number of operating trains, the lateral displacement and acceleration at the platform floor of the frame structure follow a similar pattern, displaying troughs at the center and amplified vibration responses near the edges. Overall, as the number of operating trains increases, there is a trend of increasing vertical displacement and acceleration at the platform floor, with vertical responses being significantly greater than lateral responses.



**Figure 10.** Maximum dynamic response at the mid-span of station platform floors under different number of operating train lines: (**a**) lateral displacements of the platform floors; (**b**) vertical displacements of the platform floors; (**c**) lateral acceleration of the platform floors; (**d**) vertical acceleration of the platform floors.

#### 5. Conclusions

This paper examines a typical multi-line "building-bridge integration" elevated station. It establishes a spatially coupled vibration equation and a finite element analysis model for the train–track–station system. These are based on the principle of total potential energy with stationary value in elastic system dynamics and the "Set in right position" rule for formulating matrices. The study analyzes the dynamic response characteristics of multi-line elevated station structures and how these responses vary with different numbers of operational train tracks. It yields the following conclusions:

- (1) When a single train passes through the station, the track-bearing and platform floors show only slight increases in lateral displacement and acceleration with speed, which are smaller than the vertical movements and accelerations at the same speed. Generally, the vertical displacement and acceleration of the track-bearing floor, as well as the vertical displacement of the platform floor, increase with speed. Notably, the platform floor's vertical acceleration first decreases and then increases as the speed rises.
- (2) The track-bearing layer is classified into a single-track bearing floor and double-track bearing floor, depending on the number of tracks. When moving at the same speed, a single train on a single-track bearing floor induces a stronger dynamic response in both the track-bearing and platform floors than it does on a double-track floor.

- (3) Station structures can be classified into single-span, double-span, and triple-span frame types. With train speed as the sole variable, the dynamic response of the platform floor generated by a single train on the single-track bearing floor of multispan frame structures decreases sequentially as the number of spans increases.
- (4) This study uses the methodology described in the references for developing spatially coupled models and solving vibration equations. Minor differences between the peak acceleration values measured on-site at the platform and hall levels, compared to their theoretical counterparts, confirm the spatial model's reliability and the computational data's accuracy. This demonstrates the method's effectiveness in closely approximating the vibration response characteristics of real structures.
- (5) As the number of operating train lines increases, the track-bearing and platform floor layers exhibit a compensation of lateral dynamic responses at the center of the three-span structure, while an amplification of vibration due to superposition occurs at the frame edges. Both the track-bearing and platform floors show that vertical responses exceed lateral responses, with an increasing trend as the number of operational train tracks rises.

This study explored the structural dynamic response of multi-line "building-bridge integration" elevated stations. An increase in the number of train lines necessitates larger station structures, making the propagation of dynamic responses more complex. This research provides design references for future large-scale "building-bridge integration" elevated stations and data for future station design standards. In this paper, larger responses were observed in the double-track bearing floors and at the edges of multi-span structures within the station structure, identifying them as critical areas needing attention in future station designs. Moreover, this study focused only on the vibration responses of the platform and track-bearing floors of station structures, without examining waiting hall responses. Future research should extend to include the investigation of train-induced responses in waiting halls.

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