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Damage Model of Bridge Bearing and Its Influence on Train-Track-Bridge Dynamic System

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1. Introduction

Bridge bearing plays an important role in bridge systems by transferring loads between bridge beam and pier, whose health status directly and greatly affects the operation performance of bridge systems. In Chinese high-speed railways, bridge occupies a large proportion, leading to a great number of bearings. Influenced by the reciprocal actions of wheel loads and the change of the environment, the characteristics of bearings may change, and even damage (such as aging of rubber, cracks, and so on) appears in the bearings. If the bearing damage appears in a bridge system, the connection between the bridge superstructure and substructure changes. When high-speed train runs past bridge equipped with damaged bearings, dynamic performances of the train-track-bridge interaction system may be aggravated, and the running safety and riding comfort of high-speed trains may also be threatened in serious cases.

Many scholars worldwide have focused on the performance of bridge bearings, and many beneficial suggestions have been proposed. Some studies focus on the mechanical behavior of bearings. For instance, Gilstad investigated the stability of the bearing structures with the increase of lateral forces acting on bridges [1]. Considering the nonlinear characteristic, Hamzeh et al. established a 2D finite element model of the rubbing bearing. Adopting this model, the influence factors of bearing stresses and strains were analyzed, and the relationship between the lateral deformation and vertical deformation of the bearing was also obtained [2]. Moreover, many existing works investigate the influences of bearings without damage on the vibrations of bridge systems. Olmos and Roesset investigated the effects of the rubber bearings on the seismic responses of bridges [3]. Taking the bearing's nonlinear behavior into consideration, Mutobe and Cooper analyzed the nonlinear vibrations of a large bridge with isolation bearings [4]. Filipov et al. calculated the dynamics performance of bridges with nonlinear bearing models subjected to seismic actions [5]. Most of the existing researches focus on the bearings without damage, and only a few studies do works with damaged bearings. Kim et al. modeled the damaged bearing as a friction element, and the damage in different degrees was considered as different friction factors [6]. Employing this bearing element, the influences of damaged bearings on the seismic performance of a bridge were analyzed. After that, the rubber aging and sliding surface abrasion of the bearings were investigated by Itoh et al. [7] and Ala et al. [8] respectively. In 2016, Chen et al. proposed a novel method to recognize bridge bearing damage based on the Neural Network theory [9]. However, it is no doubt that the damaged bearings affect the dynamic responses of the train-track-bridge system, few studies have paid attention to this research field.

This work presents an investigation on the influence of bearing damage on the dynamic behavior of the high-speed train-track-bridge coupled system. Firstly, description of bridge bearing damage is explained in the Section 2, and then a detailed high-speed train-track-bridge dynamic model is established based on the train-track-bridge dynamic interaction theory in Section 3. Considering single-point-damage and multi-point-damage of bridge bearings, the influences of bearing damages on the dynamic responses of the train-track-bridge system are investigated in the next section. Finally some important conclusions are reached according to the obtained results.

2. Mathematical description of bridge bearing damage

2.1. Typical bridge bearing damage

Many bearing damage types exist in engineering, and different damage types appear in different kinds of bearings. By now, several kinds of bearings are widely adopted in bridge engineering, mainly including the spherical steel bearing, the basin rubber bearing, and the laminated rubber bearing (Table 1). The common damage for each kind of bearing is given in Table 1 [9], and some typical bearing damage is shown in Fig. 1.

As concluded from the existing works, the bearing damages can be classified into the following two aspects:

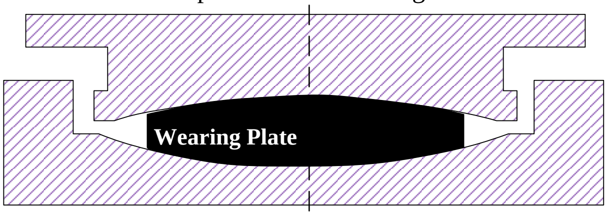
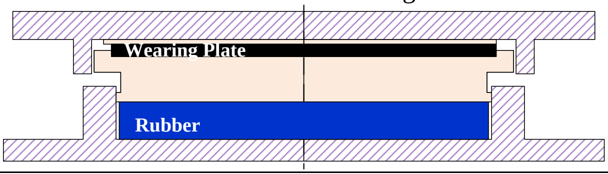
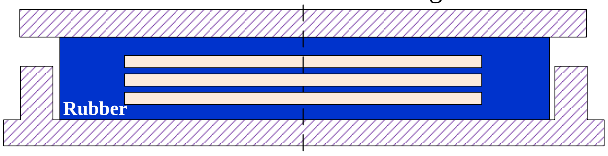
1. Degradation of material properties, such as rubber aging. If the material characteristic changes, the elasticity modulus and the shear modulus also change simultaneously. China Academy of Railway Sciences (CARS) investigated many railway bridge bearings serving for almost 20 years, and concluded that the elasticity modulus and the shear modulus of the rubber bearings have changed by 20% and 27%, respectively [9]. These changes directly affect the vertical and horizontal stiffness of the bearing systems.

2. Degradation of structures, such as plastic deformation and abrasion of steel part. These structure degradations make the change of the contact relationships between the two contacted parts, which directly change the contact forces synchronously. The contact forces are greatly influenced by relative velocities between super-

structures and substructures [6, 10].

Table 1

Common bearing damages

Bearing	Typical damage
Spherical steel bearing 	Abrasion of steel part Steel corrosion Cracks in steel part Plastic deformation of steel part Unsoldering Failure of anchoring part and fixed part
Basin rubber bearing 	Rubber aging Crack in rubber part Unsoldering Abrasion of PTFE (Poly tetra fluoro ethylene) plate and steel
Laminated rubber bearing 	Rubber aging Crack in rubber part Bulge Oversize shear deformation Void between rubber part and support part

a

b

c

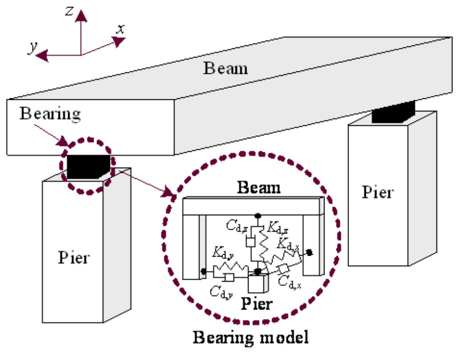
d

Fig. 1 Typical bearing damages: a - abrasion of friction surfaces; b - unsoldering; c - oversize shear deformation; d - rubber aging and crack

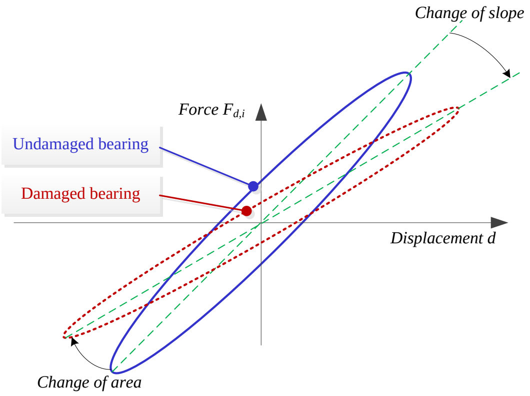
2.2. Mathematical model of bearing damage

Based on the above explanations, the damage model of bridge bearing is displayed in Fig. 2, where d is the relative displacement between superstructure and sub-structure. In the damage model, the change of stiffness directly affects the slope of the center line of the hysteresis loop, and the change of damping mainly affects the area and sharp of the hysteresis loop. It should be noted that, rubber bearing (basin rubber bearing and laminated rubber bearing) is greatly employed in bridge engineering, and the elasticity and dynamic performance of rubber bearing are mainly provided by rubber block, whose hysteresis loop is ellipse [11]. Hence hysteresis loop of ellipse type is given in Fig. 2.

Moreover, the beam vibrations (in the range of low-frequency) in the orthogonal directions of x, y and z are uncoupled [12], thus from the point of bridge vibration, any bearing damages can also be broken up into the changes of bearing stiffness in three directions of x, y and z.



a



b

Fig. 2 Bearing damage model: a - interaction forces of bearing; b - hysteresis loop of bearing

Hence, the characteristic of damaged bearing is simulated by:

$$F_{d,i} = K_{d,i} d + C_{d,i} \dot{d} \quad (i = x, y, z), \tag{1}$$

where: $K_{d,i}$ is the stiffness of damaged bearing in i (i=x, y, z) direction; $C_{d,i}$ is the damping of damaged bearing in i (i=x, y, z) direction, and $F_{d,i}$ is the interaction force between superstructure and substructure.

As known from the reference [13], the damping in Eq. (1) can be expressed by:

$$C_{d,i} = \frac{A}{\pi \omega d_m^2}, \tag{2}$$

where: A is the area of the hysteresis loop, ω is the frequency of excitation; d_m is the amplitude of displacement.

Eq. (1) can be further expressed by:

$$F_{d,i} = K_{d,i} d + \frac{A}{\pi \omega d_m^2} \dot{d} \quad (i = x, y, z). \tag{3}$$

To simplify Eq. (3), the model in Fig. 3 is adopted. In the figure, d_0 is the x-coordinate of the major axis of the ellipse, d_m is the amplitude (in x-direction) of displacement, and α is the slope angle of the center line of the ellipse.

According to Fig. 3, the length of major axis of the ellipse is:

$$OP = \frac{d_0}{\cos \alpha}. \tag{4}$$

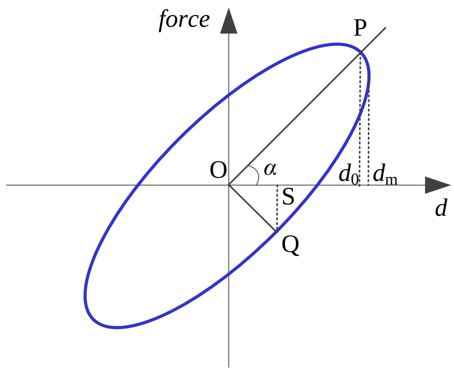


Fig. 3 Geometrical relationship in the hysteresis loop

Thus, the length of minor axis of the ellipse is:

$$OQ = \frac{A}{\pi \cdot OP} = \frac{A \cos \alpha}{\pi d_0}. \tag{5}$$

Further,

$$\begin{cases} OS = OQ sin\alpha = \dfrac{A cos\alpha sin\alpha}{\pi d_0} \\ SQ = OQ cos\alpha = \dfrac{A cos^2\alpha}{\pi d_0} \end{cases}. \tag{6}$$

It should be noted that the point (OS, -SQ) is on the ellipse whose function is expressed in Eq. (3). Then, the following relationship is tenable:

$$\frac{A cos^2\alpha}{\pi d_0} + K_{d,i} \frac{A cos\alpha sin\alpha}{\pi d_0} + \frac{A^2}{\pi^2 \omega d_0 d_m^2} cos2\alpha = 0, \tag{7}$$

$$cos^2\alpha + K_{d,i} cos\alpha sin\alpha + \frac{A}{\pi \omega d_m^2}(cos^2\alpha - sin^2\alpha) = 0. \tag{8}$$

Hence,

$$A = \frac{\pi \omega d_m^2 cos\alpha (cos\alpha + K_{d,i} sin\alpha)}{sin^2\alpha - cos^2\alpha}. \tag{9}$$

Then, Eq. (3) is re-written as:

$$F_{d,i} = K_{d,i} d + \frac{cos\alpha (cos\alpha + K_{d,i} sin\alpha)}{sin^2\alpha - cos^2\alpha} \dot{d} \quad (i = x, y, z). \tag{10}$$

To clearly describe the damage rate of the bearing, a parameter μ named 'damage rate' is defined, as seen in the following equation.

$$K_{d,i} = (1 - \mu) K_{0,i} \quad (i = x, y, z), \tag{11}$$

where: $K_{d,i}$ is the stiffness of damage bearing in i (i=x, y, z)

direction; $K_{0,i}$ is the original stiffness of bearing without damage; μ is the defined damage rate, which is set to 0%, 20%, 40%, 60%, 80% in this work according to the study [6].

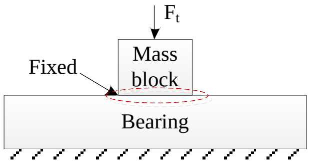
Finally, the mathematical description of bridge bearing damage is given as:

$$F_{d,i} = (1-\mu)K_{0,i}d + \frac{cos\alpha[cos\alpha + (1-\mu)K_{0,i}sin\alpha]}{sin^2\alpha - cos^2\alpha}\dot{d}$$
$$(i = x, y, z), \tag{12}$$

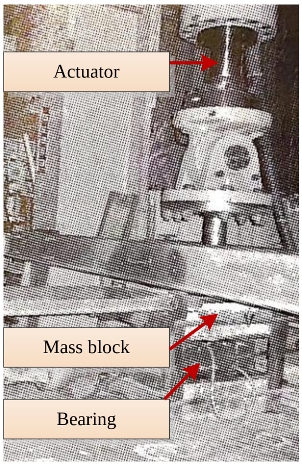
$$F_{d,i} = \underbrace{(1-\mu)K_{0,i}d}_{stiffness\ item} + \underbrace{\frac{1+(1-\mu)K_{0,i}tan\alpha}{tan^2\alpha - 1}\dot{d}}_{damping\ item}$$
$$(i = x, y, z). \tag{13}$$

2.3. Validation of proposed model

Aiming at a damaged laminated rubber bearing with rubber bulge, Zhuang [11] conducted a laboratory test, as shown in Fig. 4. In this test, excitation F_t is an impact force, whose value is 10 kN. The mass of mass block is 100 kg, and the elasticity modulus of the tested bearing is 584 MPa. Adopting this test, the vibration of mass block subject impact force is obtained, from which the dynamic performance of the damaged bearing is also investigated.



a



b

Fig. 4 Test conducted by Zhuang [11]: a - design of the test; b - photo of the test

Adopting the tested results, the validation of this proposed damage bearing model is performed, as shown in Fig. 5. It should be stated that only attenuation rate of the displacement amplitude and vibration frequency are given in the published work, hence attenuation rate and vibration frequency are also employed in this present study to do the validation.

As seen from the result, the tested and simulated attenuation rates are 0.692 and 0.631, and the error is 8.8%. Moreover, the tested and simulated vibration frequencies are 41.2 Hz and 38.9 Hz, whose error is 5.6%. The above comparisons indicate that the proposed bearing damage model is effective to reveal damage behavior of rubber bearing.

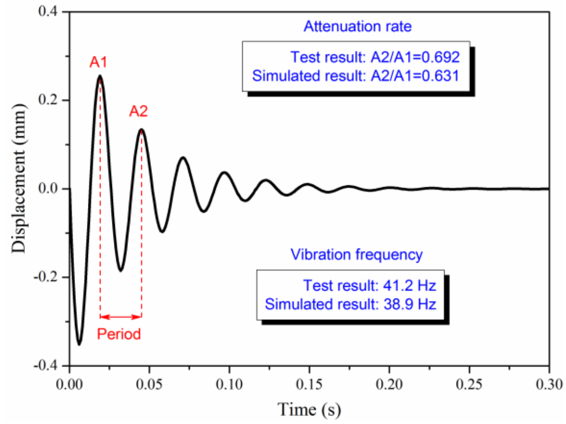


Fig. 5 Validation of proposed damage bearing model

3. Difference between established bearing damage model with traditional linear model

In most existing studies, the damaged bearing is usually modeled as linear spring without the nonlinear part. To illustrate the difference between proposed bearing damage model with traditional linear damage model, a calculation is conducted in this part.

The mathematical expressions of proposed damaged bearing model and traditional linear damaged model are given as:

$$\begin{cases} F_{d,i} = (1-\mu)K_{0,i}d + \dfrac{1+(1-\mu)K_{0,i}tan\alpha}{tan^2\alpha - 1}\dot{d} \ (i = x, y, z) \\ F_{t,i} = (1-\mu)K_{0,i}d \quad (i = x, y, z) \end{cases}. \tag{14}$$

where: $F_{t,i}$ is bearing force in the traditional linear model, which is proportional to stiffness of bearing,

As clearly seen from Eq. (14), compared to traditional model, the proposed damaged bearing model contains damping item. With the increase of d, the comparison of bearing force can be seen in Fig. 6. Damping effect can be clearly seen from the result.

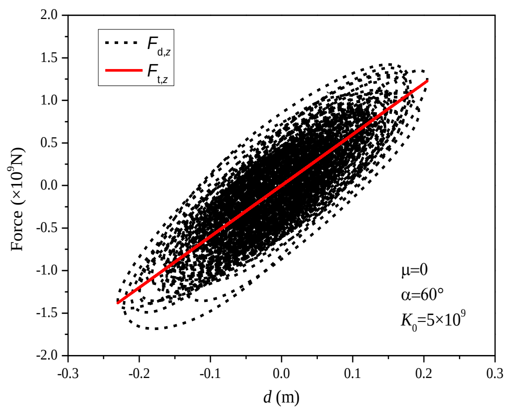


Fig. 6 Comparison of bearing force with change of d

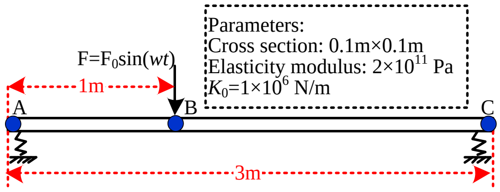


Fig. 7 Calculation model

In the calculation, the mechanical model in Fig. 7 is adopted. The dynamic behaviors of point B are obtained, as well as two supporting forces (F_A and F_C) on point A and point C. In the calculation, the amplitude of the applied excitation F_0 is 1×10^4 N and the circular frequency w is set to 0.2 rad/s. Other key parameters can be seen in Fig. 7.

Figs. 8-9 give the comparison of the results obtained by the proposed model and traditional linear model both in time-domain and in frequency-domain. As seen from the comparisons, the results are obviously different in time-domain and in frequency-domain, especially in frequency-domain.

Moreover, Fig. 10 illustrates the comparisons with different damage rate μ. As seen from the figure, the results obtained by the new model are a little smaller than those obtained by traditional model. This is caused by the effect of additional damping.

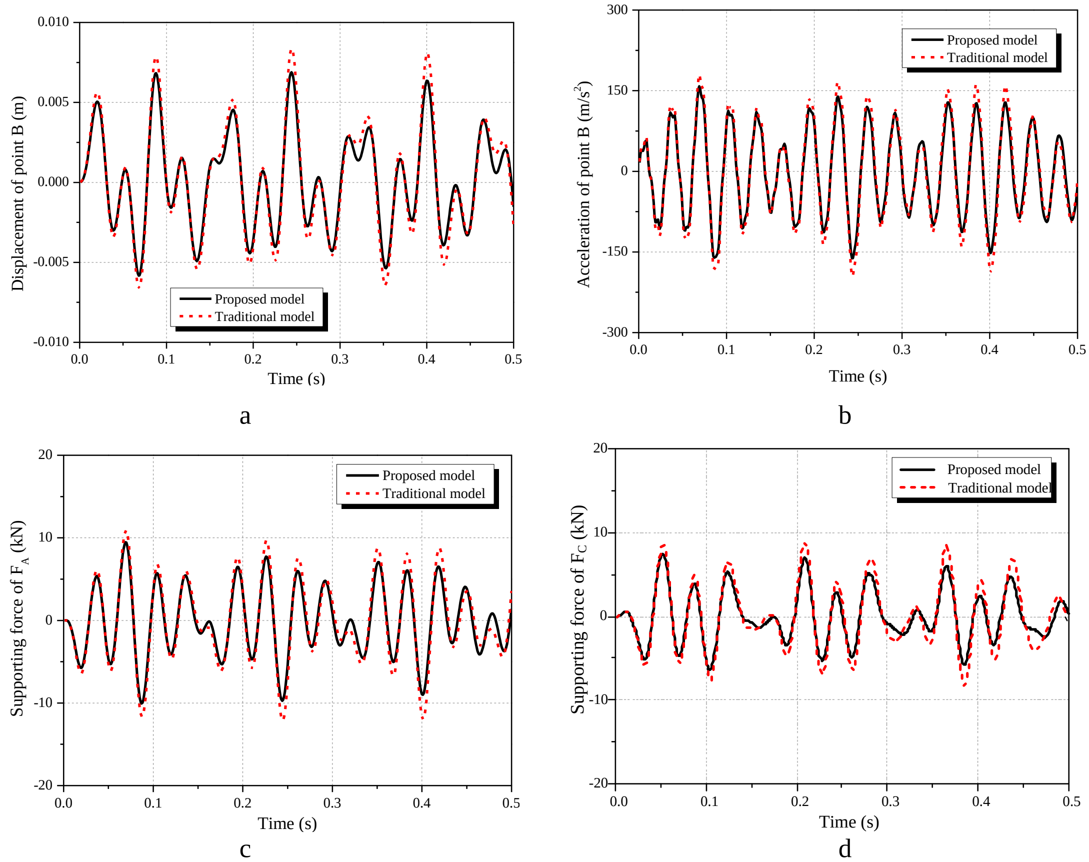


Fig. 8 Comparison of the results in time-domain: a - displacement of point B; b - acceleration of point B; c - force of F_A; d - force of F_C

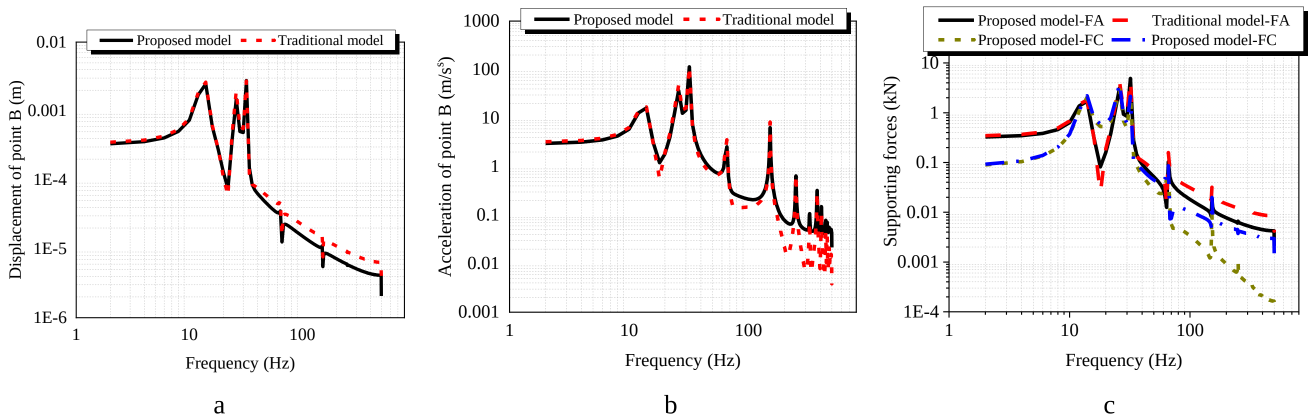


Fig. 9 Comparison of the results in frequency-domain: a - displacement of point B; b - acceleration of point B; c - supporting forces

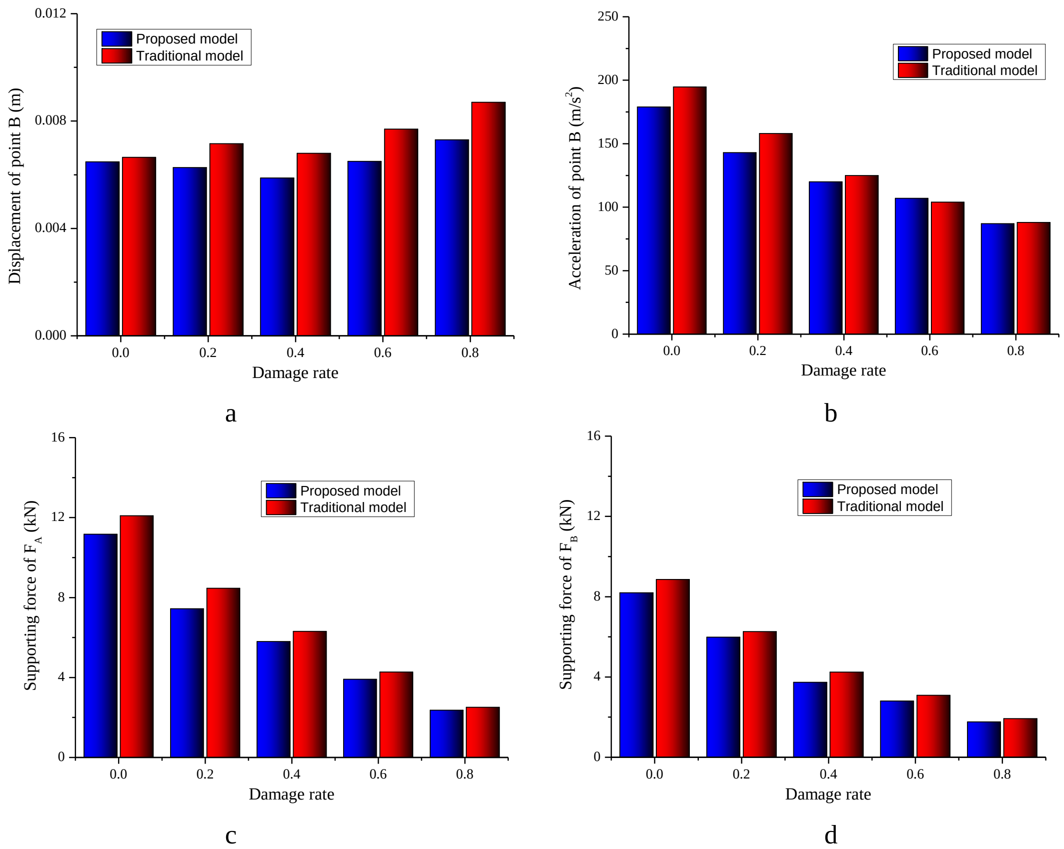


Fig. 10 Comparison with different damage rate: a - displacement of point B; b - acceleration of point B; c - force of FA; d - force of FC

4. Dynamic model of high-speed train-track-bridge system considering bridge bearing damage

Bridge bearing damage is clearly defined in the above section, and the dynamic model of high-speed train-track-bridge system considering bridge bearing damage is established, in which bearings are regarded as connection springs between bridge beams and piers.

The established coupled model consists of a train submodel, a track submodel and a bridge submodel [14-17], as shown in Fig. 11.

The high-speed train dynamic model is formed by several high-speed vehicle submodels according to the practical engineering marshing. The modelling principle of each vehicle is listed below:

- All the vehicles are arranged on rails in a row with constant distance, and run at the same speed.
- Each vehicle system is regarded as several rigid bodies, including one carbody, two frames, and four wheel-sets. The carbody and the frames are connected by secondary suspension, and the frames and the wheel-sets are jointed by the primary suspension.
- Non-linear performance of suspension system is considered, rather than traditional linear spring-damping model.
- Five degrees of freedom of each rigid body are considered, i.e. the bounce motion, the sway motion, the roll motion, the yaw motion and the pitch motion. Hence each vehicle submodel contains 5 DOFs/body ×7 bodies=35 DOFs.
- The submodel is established based on multi-body dynamics, and the detailed modelling procedure and dynamic equations can be referred to published work [14].

In practical engineering of high-speed railway, ballastless slab track structure contains several important parts, i.e. rail, fastener, concrete slab, CA mortar, and concrete base. The track is modeled based on finite element method, and the modeling principle is listed below:

- Rail is modeled by beam element considering the practical cross-section, and the length of each rail element is set to 0.1 m.
- Fastener is modeled by linear spring-damping element connecting corresponding locations on rail and concrete slab.
- Concrete slab is simulated by solid element due to its regular shape, as well as the CA mortar layer.
- Concrete base is fixed with bridge beam by shear studs, hence this part is considered in the density of bridge beam.

Adopting the above modeling principle, the finite element model of the track system can be established.

The bridge structure, including beam, pier and bearing, is also established based on finite element method. In this work, the beam and pier are simulated by beam element while the bearing is simulated by non-linear spring-damping element according to Eq. (13). hence

As for the wheel-rail interaction relationship, two kinds of wheel-rail forces are involved, namely the wheel-rail normal contact force and wheel-rail creep force. The wheel-rail normal force is calculated based on the non-linear Hertizian contact theory, while the wheel-rail creep force is simulated employing Kalker creep theory. The detailed equations of wheel-rail dynamic interaction can be seen in work [13,14].

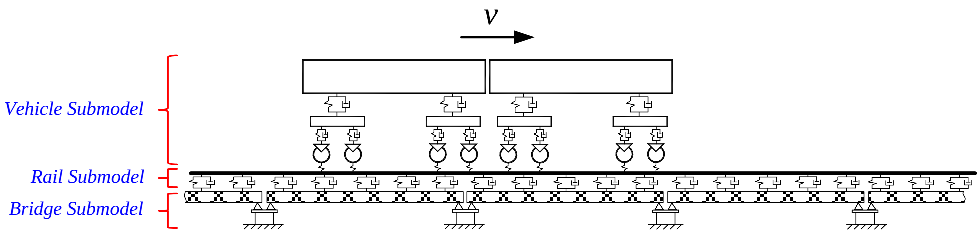


Fig. 11 Dynamic model of high-speed train-track-bridge system

5. Influence of bearing damage on dynamic behavior of high-speed train-track-bridge system

Dynamic model of high-speed train-track-bridge coupled system is established, adopting which the influence of damaged bearing on the dynamic behavior of the system is investigated below.

5.1. Parameters adopted in calculation

The key parameters of the running high-speed train are given in Table 2. The cross sections of the bridge can be seen in Fig. 12, and the arrangement of the bearings is shown in Fig. 13.

Table 2

Parameters of the high-speed train

Item	Value	Unit
Operation speed	350	km/h
Distance between bogie centres	17.375	m
Bogie wheelbase	2.5	m
Wheel rolling circle diameter	0.92	m
Carbody mass	38.884	t
Bogie frame mass	2200	kg
Wheelset mass	1517	kg
Inertia moment of carbody about X/Y/Z axis	125.9/1905.3/1797.9	$t\cdot m^2$
Inertia moment of bogie frame about X/Y/Z axis	1236/1233/2336	$kg\cdot m^2$
Inertia moment of wheelset about X/Y/Z axis	693/118/693	$kg\cdot m^2$
Primary suspension stiffness in X/Y/Z axis (per axle box)	919.8/919.8/886.5	kN/m
Secondary suspension stiffness in X/Y/Z axis (per side of bogie)	135/135/225	kN/m

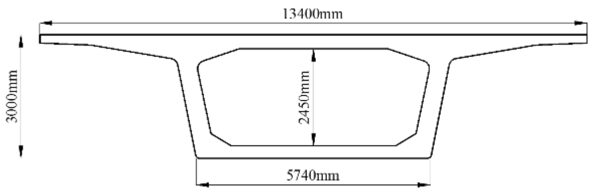


Fig. 12 Cross sections of the beam

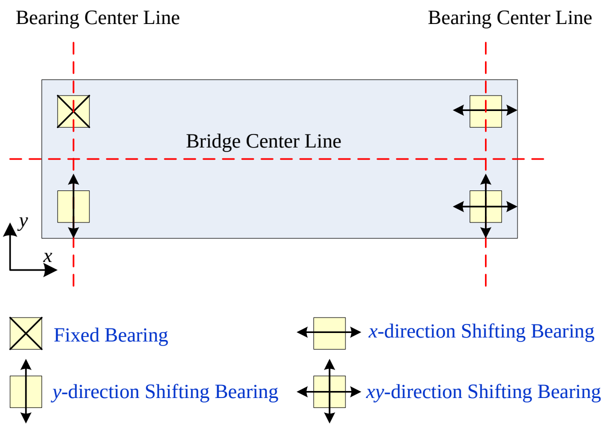


Fig. 13 Arrangement of the bearings

As seen in Fig.13, total 4 bearings are adopted in the bridge, including:

- ➢ A fixed bearing. The DOFs in all directions (x direction, y direction and z direction) of this bearing are restrained.
- ➢ A x-direction shifting bearing. The DOFs in y/z directions of this bearing are restrained.
- ➢ A y-direction shifting bearing. The DOFs in x/z directions of this bearing are restrained.
- ➢ A xy-direction shifting bearing. The DOFs in z direction of this bearing are restrained.

Thus, damage may occur in 8 conditions, and the information of bearing damage condition is numbered to make the explanation in the following calculations more clear, as listed in Table 3.

Table 3

Numbered information of bearing damage condition

Number	Information of bearing damage
#1	Damage in *x* direction of fixed bearing
#2	Damage in *y* direction of fixed bearing
#3	Damage in *z* direction of fixed bearing
#4	Damage in *y* direction of *x*-direction shifting bearing
#5	Damage in *z* direction of *x*-direction shifting bearing
#6	Damage in *x* direction of *y*-direction shifting bearing
#7	Damage in *z* direction of *y*-direction shifting bearing
#8	Damage in *z* direction of xy-direction shifting bearing

As seen from the above Table 3: a) #1 and #6 are damages in *x* direction; b) #2 and #4 are damages in *y* direction; c) #3, #5, #7, and #8 are damages in *z* direction.

In the following calculations, two types of bearing damages are considered, namely single-point-damage (SPD) and multi-point-damage (MPD).

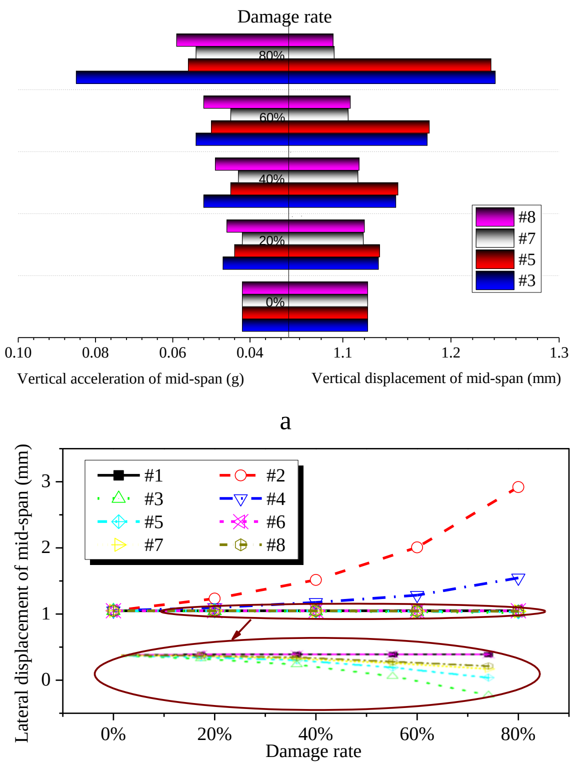
In the calculations with SPD, damage in only one direction of one certain bearing occurs, indicating in each calculation only one bearing damage condition in Table 3 is set. While in the calculations with MPD, 2 or more bearing damage conditions in Table 3 appear simultaneously.

5.2. Influence of single-point-damage on the system

Adopting the dynamic model in Section 3, the influence of SPD on the dynamic system is analyzed by setting damage rate in Eq. (15) to 0%, 20%, 40%, 60%, 80% respectively. The calculated train indicators are listed in Table 4, while bridge vibrations are shown in Fig.14.

As seen from the results, influences of bearing damages on train vibrations are very small, while those on bridge vibrations are great. Bridge vibrations change a lot when damages occur in different bearings.

Vertical displacement of mid-span is not sensitive to damage in horizontal direction (x-direction and y-direction), while that is greatly influenced by damage in vertical direction. With the increase of damage rate of #3 and #5, the vertical displacement increases. While with the increase of damage rate of #7 and #8, the displacement decrease, which is induced by the distance between bridge centerline and track centerline. The change of vertical acceleration of mid-span is similar to that of displacement, which is also not sensitive to horizontal damage. With the increase of damage rate in vertical direction, the acceleration of mid-span increases sharply.



a

b

Fig. 14 Influence of SPD on bridge vibration: a - in vertical; b - in lateral

Table 4

Influence of SPD on running train

Indicator	Damage information	Damage rate				
		0 %	20 %	40 %	60 %	80 %
Derailment factor	#1	0.12894	0.12894	0.12894	0.12894	0.12894
	#2	0.12894	0.12892	0.12876	0.12873	0.12871
	#3	0.12894	0.12871	0.12868	0.1252	0.11468
	#4	0.12894	0.12895	0.12895	0.12895	0.12895
	#5	0.12894	0.1287	0.1287	0.12865	0.12861
	#6	0.12894	0.12894	0.12894	0.12894	0.12894
	#7	0.12894	0.12876	0.12872	0.12868	0.12866
	#8	0.12894	0.12874	0.1287	0.1287	0.12866
Vertical acceleration of car body (g)	#1	0.04373	0.04373	0.04373	0.04373	0.04373
	#2	0.04373	0.04373	0.04372	0.04372	0.04371
	#3	0.04373	0.0437	0.04366	0.0436	0.04347
	#4	0.04373	0.04373	0.04373	0.04373	0.04373
	#5	0.04373	0.0437	0.04366	0.04359	0.04346
	#6	0.04373	0.04373	0.04373	0.04373	0.04373
	#7	0.04373	0.04372	0.04371	0.04369	0.04365
	#8	0.04373	0.04372	0.0437	0.04367	0.43627

Moreover, the bearing damage has a great influence on the lateral displacement of mid-span. The damage in x-direction has almost no influence on bridge lateral vibration. With the increase of damage rate in y-direction, the bridge lateral displacement increases sharply. With the damage in z-direction, the lateral displacement decreases. It should be noted that the influence of damage in fixed bearing is much larger than that in other bearings. Oppositely, lateral acceleration of mid-span is not sensitive to bearing damage, hence this indicator is not displayed in this work.

5.3. Influence of multi-point-damage on the system

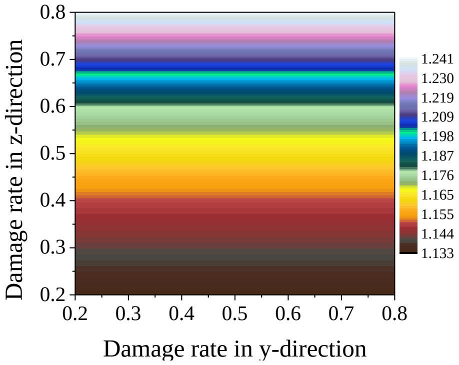
MPD consists of two aspects: MPD in one bearing, and MPD in different bearings. Hence in the following section, this issue is also discussed in two aspects.

As concluded in the above section, the influence of damage in x-direction is small and train vibration is not sensitive to bearing damage. Hence, in the following calculations, the influence of bearing damage in y and z directions on bridge vibration is emphasized.

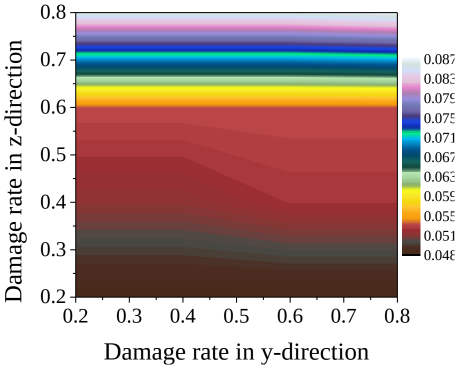
1. MPD in one bearing. Taking the combined damages of #2 and #3 as an example to explain the influence of MPD in one bearing on the bridge vibrations, as seen in Fig. 15.

As seen from Fig. 15, with the damages in y-direction and z-direction in one certain bearing, vertical displacement and acceleration of mid-span increase with the increase of damage rate in z-direction, which is not sensitive to damage rate in *y*-direction. As for lateral displacement of mid-span, the damage in *z*-direction has little influence, while that in *y*-direction greatly affects this indicator.

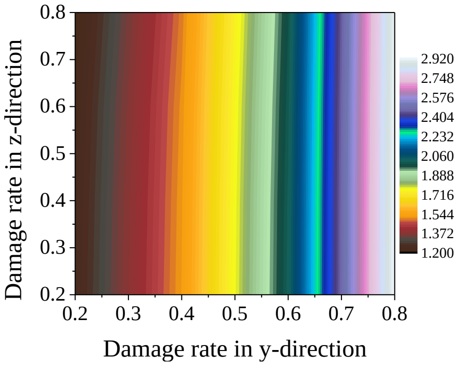
Moreover, the influences of combined damages of #4 and #5 (damage in the *x*-direction shifting bearing) on bridge vibrations have also been investigated, which indicates that the influence of damage in fixed bearing is much larger than that in other bearings.



a



b

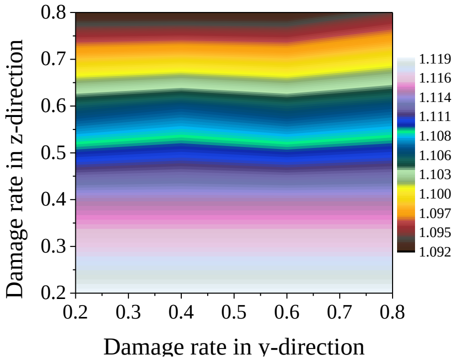


c

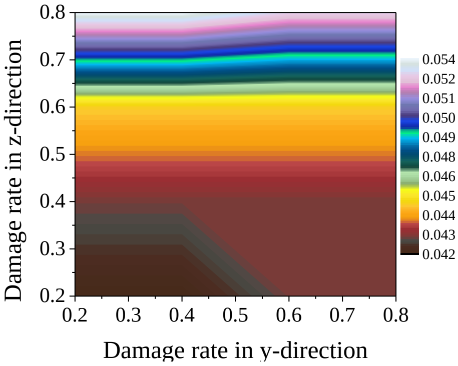
Fig. 15 Influence of MPD in one bearing on bridge vibrations: a - vertical displacement of mid-span; b - vertical acceleration of mid-span; c - lateral displacement of mid-span

2. MPD in different bearings. Taking the combined damages of #2 (damage in the fixed bearing) and #7 (damage in the y-direction shifting bearing) as an example to explain the influence of MPD in one bearing on the bridge vibrations, as seen in Fig. 16.

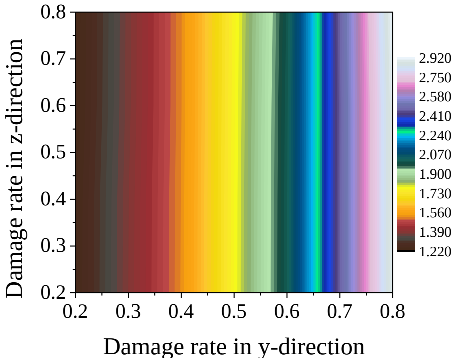
As seen from Fig. 16, bridge vertical displacement is not sensitive to damage in *y*-direction, which changes sharply with the damage in *z*-direction, while the change rate decreases with the increase of damage rate in *z*-direction. It also can be seen that the damage in *z*-direction in fixed bearing has a great influence on bridge vertical displacement than on displacement in other directions. Moreover, vertical acceleration and its change rate increase with the increment of damage in *z*-direction, and the damage in fixed bearing is larger than other bearings. As seen from Fig.16, lateral displacement changes sensitively to the damage in *y*-direction in fixed bearing.



a



b



c

Fig. 16 Influence of MPD in different bearings on bridge vibrations: a - vertical displacement of mid-span; b - vertical acceleration of mid-span; c - lateral displacement of mid-span

6. Conclusion

Focusing on a practical engineering issue, i.e. bridge bearing damage in high-speed railway, this work has presented a framework to investigate the damage model of bridge bearing, and has investigated the influence of bearing damage on the train-track-bridge system. The following conclusions have been drawn:

1. Results obtained by the proposed model and the traditional linear model are different, especially in frequency-domain. Compared to results by traditional linear model, those obtained by the proposed model are smaller due to the additional damping effect.

2. Bridge bearing damage has almost no influence on the train vibrations, while has great effect on bridge vibrations.

3. Among all the damaged bearings in this work, the influence of damage in x-direction has the least influence on the system. The influence of damage in fixed bearing is larger than that in other bearings, indicating that more attentions should be paid to the health monitoring of fixed bearings in railway engineering.

Declaration of Conflicting Interests

The authors declare no conflict of interest in preparing this article.

Data Availability Statement

No data were used to support this study.

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DAMAGE MODEL OF BRIDGE BEARING AND ITS INFLUENCE ON TRAIN-TRACK-BRIDGE DYNAMIC SYSTEM

S u m m a r y

Bridge bearing damage is unavoidable in railway engineering, which directly affect the operation safety of the whole system. A study on the damage model of bridge bearing and its influence on the dynamic responses of the high-speed train-track-bridge system is conducted in this present work. Primarily, mathematical description of bridge bearing damage model is explained in detail, which is then compared with the traditional linear model. Then a 3D train-track-bridge dynamic model considering bearing damage is established based on the train-track-bridge dynamic interaction theory. Adopting the established dynamic model, the influences of single-point-damage and multi-point-damage on the dynamic behaviors of the coupled system are deeply investigated. The obtained results show that the calculated responses by the proposed model and the traditional linear model are different, especially in frequency-domain. Compared to results of traditional linear model, the results obtained by the proposed model are smaller due to the additional damping effect. Bridge bearing damage has almost no influence on train vibrations, however has great impact on bridge vibrations. The damage in z-direction mainly affects the vertical vibrations, while damage in y-direction mainly influences the lateral vibrations. Among all the damaged bearings in this work, the influence of damage in x-direction has the least influence on the system. The damage in the fixed bearing is larger than that in other bearings, indicating that more attentions should be paid to the health monitoring of fixed bearings in railway engineering.

Keywords: high-speed railway; bearing damage; train-track-bridge dynamics; dynamic response; single-point damage; multi-point damage.

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