

DYNAMIC FACTOR OF BRIDGES SUBJECTED TO LINEAR INDUCTION
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Abstract. The linear induction motor (LIM) has been used in urban rail transit systems in China and other parts of the world. However, specialized specifications for design or assessment of bridges in urban rail transit systems have not yet been established. The electromagnetic force of LIM complicates vehicle-bridge interaction. In this paper, a typical bridge on the Guangzhou metro line 4 is evaluated both experimentally and theoretically to determine vehicle-bridge interaction characteristics. The LIM vehicle is represented by a model of secondary suspension with 6 degrees of freedom, and the bridge is modeled using standard beam elements. The coupled motion equation is formulated using the principle of total potential energy with stationary value in an elastic system and solved by using the Newmark- β method. Field dynamical tests were also performed on the bridge. The calculated and experimental vertical displacement time-histories for LIM trains crossing the bridge were obtained and dynamic factors were developed. A formula for determination of the dynamic factor, which can provide an engineering basis for design and evaluation of bridges in urban rail transit system, is proposed.

Keywords: linear induction motor (LIM), elevated bridge, train, interaction, dynamic factor (DF), electromagnetic force.

1. Introduction

Construction of fast rail transit systems is becoming a trend for development and modernization of city infrastructure besides the rapid development of the passenger transportation between cities or states (Butkevičius 2007). Nevertheless, construction of urban rail transit systems is expensive, and research is needed to ensure safe and economical systems. Japan began to develop LIM metro systems in the 1970s and the 1st LIM metro line of Osaka line 7 was built in 1990 (Isobe *et al.* 1999). Canada built the LIM Skytrain system in Vancouver in 1986 (Liebelt 1986). Due to economical construction costs, stability and curve passing capability, LIM technology has now been used in more than 10 lines in 5 countries. Guangzhou metro line 4 is the 1st metro line in China to adopt the LIM metro system. The 1st section from Xinzao to Huangge opened to traffic in 26 November, 2006, and the Huangge to Jinzhou Section began operations on 1 May, 2007 (Wei *et al.* 2007).

The motor (magnet and winding) and rotor (reaction plate) of the LIM are installed on the bogie and track, respectively. An electromagnetic force is generated between the bogie and track. The traction force is provided directly

between the motor and rotor rather than through friction between the wheel and the rail. The LIM metro system is a new urban transportation system incorporating elements of maglev and traditional rail transportation (Matsumaru 1999). Hobbs and Pearce (1974) studied the dynamic characteristics of LIM vehicles in the 1970s. Fatemi *et al.* (1996) from Canada carried out dynamic analyses of a new track for a linear metro system. Parker and Dawson (1979) and Teraoka (1998) studied the development of the LIM system for urban rail transit. In China, Xia *et al.* (2010) developed a three-dimensional dynamic interaction model and established the equations of motion by using the measured track irregularities for a LIM train and elevated bridge system.

Dynamic factor (DF) is one of the most important dynamic responses of bridges under moving load (Reis *et al.* 2008; Reis, Pala 2009). Many studies have shown that DFs depend on various factors, namely the geometry of the bridge, the type of load, the velocity of the vehicles and the roughness of the deck surface for road bridges (Broquet *et al.* 2004; Zhang *et al.* 2001). For rail bridges, vehicle-bridge interaction is complicated (Wu, Yang 2003), and the electromagnetic force of LIM metro system increases the

complexity. Specialized codes for design of this type of vehicle loading in the urban railway transportation system have not yet been established. In order to further study the LIM metro system train-bridge dynamic coupling, a typical bridge on the Guangzhou metro line 4 is evaluated both experimentally and theoretically to determine vehicle-bridge coupled vibration response characteristics. The coupled motion equation is formulated using the principle of total potential energy with stationary value in an elastic system and solved using the Newmark- β method. The calculated and experimental dynamic displacement responses for LIM trains moving cross the bridge are obtained and dynamic factors are developed based on random vibration theory. A formula for determination of the DF of bridges of urban rail transit which can be used for design of new bridges and evaluation of existing bridges is proposed.

2. Electromagnetic force

There are two methods for attaching motors to the vehicle: axle suspension and bogie suspension (Lou 2006). In the axle suspension system, motors (stators) are installed on the two-wheel box, and in the bogie suspension system, motors (stators) are installed on the bogie. Only the bogie suspension system is considered in this paper. The LIM metro system generates electromagnetic force between the stator installed on the train (bogie) and reaction plate on the bridge. The electromagnetic force is divided into longitudinal and vertical force. The longitudinal force is used for propulsion and braking. The vertical electromagnetic force varies with the air gap, and does not depend on the traction force between wheel and track. The value of the vertical electromagnetic force depends on the air gap. The air gap varies with rail irregularity and bridge displacement relative to the train, which changes the electromagnetic force of the moving train. The variable electromagnetic force influences the system dynamic response which can further influence the air gap (Nonaka, Higuchi 1988; Yoshida et al. 2005).

Based on data provided by the LIM manufactories and conic fitting method, the vertical electromagnetic force F can be expressed as (Gu et al. 2008):

$$F = 0.12269z^2 - 3.4311z + 54.006, \quad (1)$$

where F – vertical electromagnetic force, kN; z – air gap, mm.

In this paper, the assumptions used to obtain the electromagnetic force are: the electromagnetic force varies with distance between bogie and bridge, the distance between bogie and bridge is determined by the displacement of the bogie and vertical displacement of bridge and the reaction plate is fixed on the bridge and no relative displacement between rail and reaction plate; motor fixed on the bogie and no relative displacement between bogie and motor occurs. The vertical electromagnetic force per unit length is (Gu et al. 2008):

$$f_{ij}(x) = \frac{F_{ij}(x)}{L} = \frac{(-1.5z_{ij}(x) + 47.917)}{L}, \quad (2)$$

$$z_{ij}(x) = d - \frac{Z_S(x_{ij1}) + Z_S(x_{ij2})}{2}, \quad (3)$$

where $f_{ij}(x)$ – vertical electromagnetic force per unit length; L – the distance between the two wheel sets of a bogie, m; $z_{ij}(x)$ – the air gap of a point on stator; d – design value of air gap; $Z_S(x_{ij1})$ – the height irregularity of the 1st bogie of i^{th} two-wheel assembly of the j^{th} vehicle; $Z_S(x_{ij2})$ – the height irregularity of the 2nd bogie of i^{th} two-wheel assembly of the j^{th} vehicle. If only vertical electromagnetic force is considered, then the electromagnetic force of a bogie length is:

$$F_{ij}^Z = \int_l f_{ij}(x) dx. \quad (4)$$

Not all electromagnetic forces directly affect the vibration of vehicle. When the air gap is unchanged, the vertical electromagnetic forces can be viewed as an inherent property of the vehicle. The constant electromagnetic force has no direct influence on the vehicle. When the electromagnetic force varies with the air gap, the relative variable value is the factor that affects vehicle vibration.

3. LIM train-bridge dynamic model

3.1. LIM vehicle model

The LIM train considered in this paper consists of 4 coupled vehicles. As shown in Fig. 1, the vehicle model consists of a car body, 2 bogies and 2 wheels per bogie. The car body and bogie are modeled as rigid bodies with mass and mass moment of inertia about the transverse horizontal axis through their centers of gravity, respectively. The motion of the i^{th} vehicle may be described by the vertical displacement with respect to its center of gravity. The motions of the front and rear wheels of the i^{th} vehicle can be described by their vertical displacement. Therefore, the total number of DOFs for one vehicle is 6. The joints between car body and bogies, and bogies and wheels can be modeled as spring-dampers.

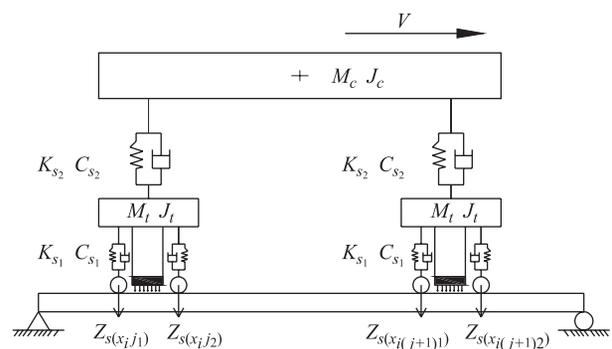


Fig. 1. LIM vehicle-bridge vertical coupling vibration model

In summary, the vehicle modeling assumptions are: (1) the vehicle system is a multi-DOF vibration system, in which the car body, bogies and wheels are considered as rigid bodies, whose axial deformations and distorted deformations are neglected; (2) only vertical dynamic behaviour is considered; (3) the spring-dampers between the car body and bogies are referred to as a “secondary suspension”; and (4) the spring-dampers between the bogie and wheels are referred to as a “primary suspension”.

3.2. Bridge model

The bridge considered in this paper is a small span bridge with double tracks, the lateral stiffness is large, so only vertical vibration is considered. The bridge is modeled using the standard beam element with 2 DOFs at each node, i.e. vertical displacement y_i and rotation θ_i .

4. Equation of motion for LIM train-bridge interaction system

The LIM train-bridge interaction system is shown in Fig. 1. The equation of motion for the LIM train-bridge interaction system can be derived using the principle of total potential energy with a stationary value in elastic system dynamics (Lou 2006). The equation can be expressed in submatrix form as:

$$\begin{bmatrix} M_v & 0 \\ 0 & M_b \end{bmatrix} \begin{Bmatrix} \ddot{X}_v \\ \ddot{X}_b \end{Bmatrix} + \begin{bmatrix} C_v & C_{vb} \\ C_{bv} & C_b \end{bmatrix} \begin{Bmatrix} \dot{X}_v \\ \dot{X}_b \end{Bmatrix} + \begin{bmatrix} K_v & K_{vb} \\ K_{bv} & K_b \end{bmatrix} \begin{Bmatrix} X_v \\ X_b \end{Bmatrix} = \begin{Bmatrix} F_v \\ F_b \end{Bmatrix}, \quad (5)$$

where the subscripts v, b – the vehicle and bridge, respectively; vb, bv – interaction of vehicle and bridge; $M, C, K,$ and F – the mass, stiffness, damping submatrices, and force vectors respectively; $X, \dot{X},$ and \ddot{X} – displacement, velocity, and acceleration subvectors.

5. Engineering background

5.1. Engineering description

Guangzhou metro line 4 is the 1st metro line to use the LIM metro system in China. The total length of more than 56 km includes viaduct bridges of almost 30 km from Xingzao to Nansha. The Xingzao to Huangge section began operations on 26 November, 2006, and Huangge to Nansha Section opened to traffic on 1 May, 2007. Except for several large span bridges, the main bridge type in line 4 includes 20 m, 25 m, 27.5 m, 30 m, 32.5 m, 40 m and 41.9 m simply supported prestressed concrete (PC) box girder bridge. The two reaction plates of the LIM are installed in the middle of each track on the bridge deck. The long welded rails are supported on the monolithic concrete bed. A passenger evacuation platform is installed on the bridge deck between the two tracks. The typical LIM elevated bridge of Guangzhou metro Line 4 is shown in



Typical bridge



Bridge deck

Fig. 2. The LIM elevated bridge of Guangzhou metro line 4

Fig. 2. The width of the bridge is 9.3 m with double-tracks. The typical section heights equal 1.7 m and 2.3 m. The top slab thickness of the 30 m simply supported PC box girder is 250 mm, the bottom slab thickness is 250 mm, and the web thickness is 300 mm.

In this paper, the relative displacement between the track and bridge deck was neglected, and the elastic effect of the track system was also neglected. The rail irregularity is approx described by a simple harmonic wave as follows:

$$r(x) = \frac{1}{2}\bar{a} \left[1 - \cos\left(\frac{2\pi x}{L}\right) \right], \quad (6)$$

where x – coordinate in the beam length direction; L, \bar{a} – the wave length and wave amplitude, respectively. In this paper, the wave trough was presumed in the mid-span of the beam, and the wave length and wave trough were defined 1.0 m and 0.5 mm, respectively.

The LIM trains are the result of cooperation between Japanese and Chinese companies. The total length of the train is 71 m with four vehicles. The width of the vehicle body is 2.8 m. The average axle weight is 101 kN. The max design velocity of the LIM train is 90 km/h. The main parameters (Pang, Gao 2006) of the LIM vehicle are shown in Table 1.

Table 1. Main calculation parameters of LIM vehicle

Vehicle parameters	Value
Full length of a coach L , m	18.37
Distance between two bogies $2s$, m	11.14
Distance between two wheelsets $2d$, m	2
Mass of car body M_c , t	33.45
Mass of bogie M_p , t	2.85
Mass of wheelset M_w , t	1.15
Primary vertical spring stiffness k_p , kN/m	350
Pitch mass moment of car body J_c , tm^2	1500
Pitch mass moment of bogie J_p , tm^2	7
Secondary vertical spring stiffness k_s , kN/m	300
Vertical distance of secondary spring to center of bogie h_2 , m	0.46
Primary vertical dashpot c_{s1} , kNs/m	100
Secondary vertical dashpot c_{s2} , kNs/m	30
Design value of air gap d_0 , mm	10
Design value of vertical electromagnetic force F_0 , kN	32.917

5.2. Vertical dynamic response analysis

The Newmark- β method is used to solve the equation of motion. A special program was developed in MATLAB to calculate the vertical dynamic response of the bridge. If the electromagnetic force is neglected, the LIM system can be looked at as a traditional railway system. For comparison, the dynamic responses of different span simply supported PC box girder bridges are calculated. A total of seven different velocities from 40 km/h to 100 km/h are considered. Representative calculated dynamic displacement-time histories of 30 m simply supported bridge are shown in Figs 3, 4 and 5, and max dynamic displacements (MDDs) and computed dynamic factors (DFs) are listed in Table 2 and compared in Fig. 6 and can be summarized as follows:

- 1) an increase of vehicle speed changes MDDs of different span bridges slightly, but the higher MDD values occur at a velocity of 50 km/h;
- 2) increasing vehicle speed increases dynamic effects in some degree for almost all the DFs of different

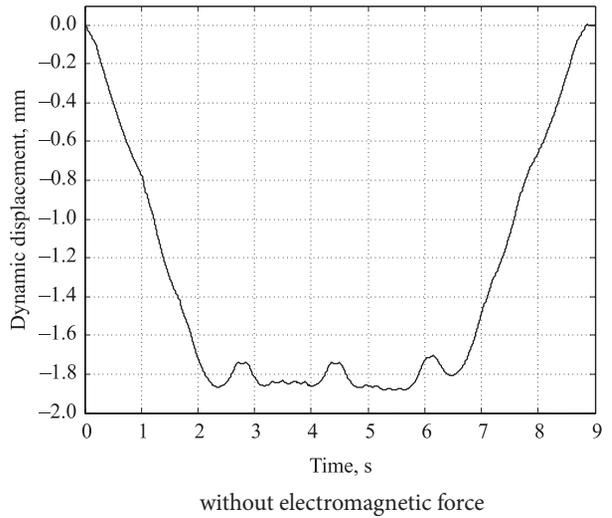
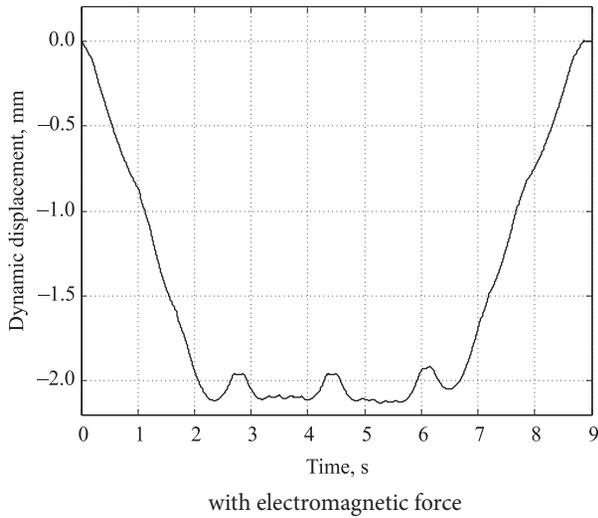


Fig. 3. Calculated dynamic displacement time-histories of 30 m simply supported bridge for velocity 40 km/h

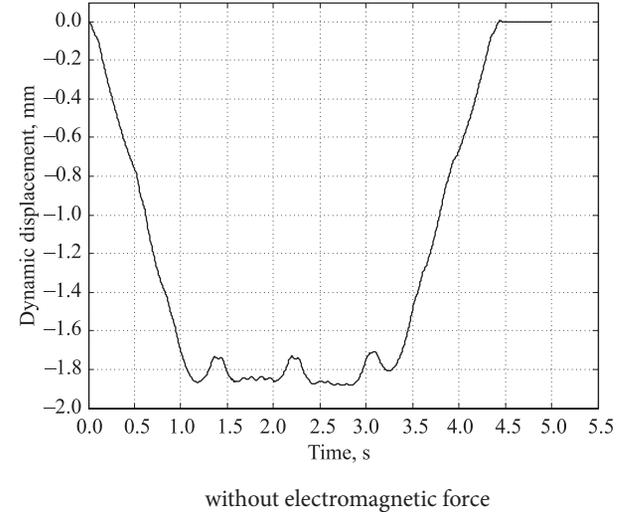
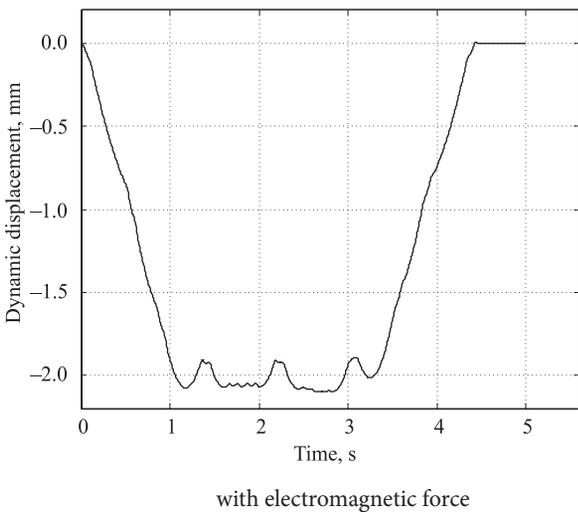


Fig. 4. Calculated dynamic displacement time-histories of 30 m simply supported bridge for velocity 80 km/h

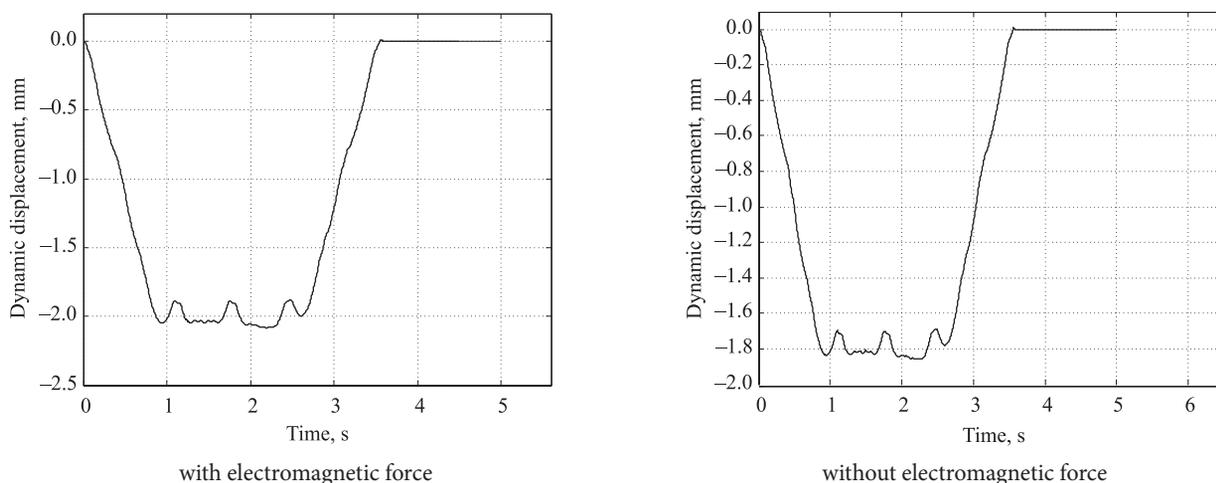


Fig. 5. Calculated dynamic displacement time-histories of 30 m simply supported bridge for velocity 100 km/h

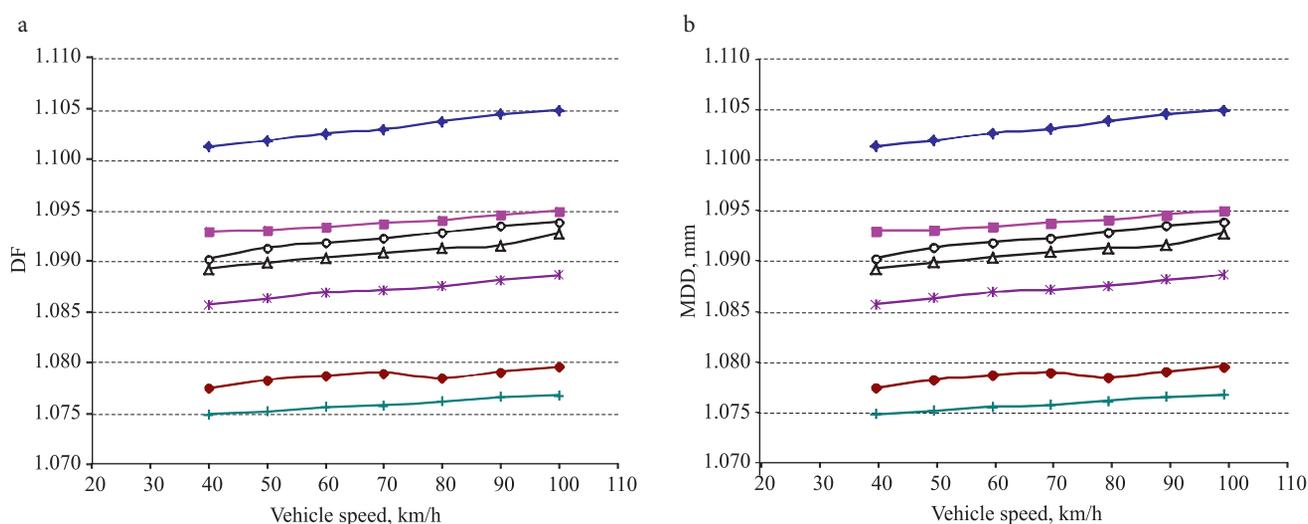


Fig. 6. Calculated MDD and DFs comparison of 30 m simply supported bridge: —◆— 20 m, —■— 25 m, —○— 27.5 m, —▲— 30 m, —*— 32.5 m, —●— 40 m, —+— 41.7 m

Table 2. Comparison of theoretical dynamic responses with electromagnetic force

Velocity, km/h		Span, m/section height, m						
		20/1.7	25/1.7	27.5/1.7	30/1.7	32.5/1.7	40/2.3	41.9/2.3
40	MDD	0.6379	1.2418	1.6507	2.1406	2.7183	2.0472	2.3362
	DF	1.1012	1.0929	1.0902	1.0892	1.0857	1.0775	1.0749
50	MDD	0.6511	1.2652	1.6798	2.1747	2.7562	2.0805	2.3837
	DF	1.1018	1.0930	1.0913	1.0898	1.0863	1.0783	1.0752
60	MDD	0.6362	1.2360	1.6407	2.1240	2.6916	2.0317	2.3199
	DF	1.1025	1.0933	1.0918	1.0903	1.0869	1.0787	1.0756
70	MDD	0.6353	1.2330	1.6356	2.1154	2.6779	2.0236	2.3114
	DF	1.1029	1.0937	1.0922	1.0908	1.0871	1.0790	1.0758
80	MDD	0.6345	1.2301	1.6305	2.1069	2.6643	2.0157	2.3016
	DF	1.1037	1.0940	1.0928	1.0912	1.0875	1.0785	1.0762
90	MDD	0.6337	1.2271	1.6252	2.0918	2.6501	2.0074	2.2911
	DF	1.1044	1.0945	1.0934	1.0915	1.0881	1.0791	1.0766
100	MDD	0.6327	1.2239	1.6196	2.0824	2.6355	1.9988	2.2801
	DF	1.1048	1.0949	1.0938	1.0927	1.0886	1.0796	1.0768

span bridges have an increasing trend while increasing vehicle speeds;

- 3) the max bridge displacements without considering the electromagnetic force are smaller than those with the electromagnetic force. The max values of dynamic displacements with electromagnetic force are increased about 13.1% relative to those without electromagnetic force. The comparison of results implies that the electromagnetic force can increase the dynamic effects of the bridges and should not be ignored in the LIM vehicle-bridge coupled analysis.

6. Field dynamic testing and analysis

6.1. Field dynamic testing

Field dynamic testing was performed in March 2009. Since dynamic displacement measurement requires falsework to install the displacement transducers, the tested bridge is selected based on a short pier bridge span. Three WA type displacement transducers are installed on the bottom of the box girder. The HBM MGCplus data acquisition system was used to record dynamic displacement time-histories of the LIM train moving across the bridge. Fig. 7 shows the WA style displacement transducer and acquisition system.

Due to the tested bridge being located between two adjacent metro stations, the measured velocities of LIM trains in the two directions are in the range of 70–80 km/h. Many dynamic displacement time-histories induced by moving LIM train were recorded. Typical measured dynamic displacement time-histories are shown in Fig. 7.

6.2. Maximum dynamic displacements

The measured dynamic displacement time-histories are similar to the theoretical results at velocities of 70 km/h and 80 km/h. The wave shape changes of bogies moving

across the bridge are prominent in both theoretical and experimental dynamic displacement time-histories. The theoretical and experimental MDDs and DFs of the simply supported box girder bridge are compared in Table 3. The measured max values of dynamic displacement are in the range from 1.78 mm to 1.84 mm, which are smaller than the calculated values and closer to those obtained by calculation without electromagnetic force. It seems unreasonable since the real bridge response contains the effect of the electromagnetic force. The main reason was the lighter axis weights of real vehicle since passenger numbers were not enough resulted in smaller static deformation of the bridge. The other reason is that the actual rigidity of the bridge is larger than theoretical. Consequently, the MDDs obtained by the in situ tests are smaller than those of calculation.

6.3. Dynamic factors (DFs) analysis

Bridges are dynamically stressed by vehicles crossing over them. The DF can be defined as the ratio of the max dynamic response to the static response as follows:

$$1 + \mu = \frac{R_d}{R_s} = 1 + \frac{R_d - R_s}{R_s} 100 (\%), \quad (7)$$

where μ – impact factor; R_d – max dynamic response; R_s – max static response. The response value can be displacement or stress.

In national and international of railway bridge standards, the DFs are formulated on the basis of theoretical and experimental research, which has demonstrated that span length L is one of the primary parameters of affecting DF. DF formulas of several countries are reviewed and listed in Table 4. Most of the formulas are based on the heavy engine draught freight train. In addition, operating velocities of typical passenger trains are higher than those of the

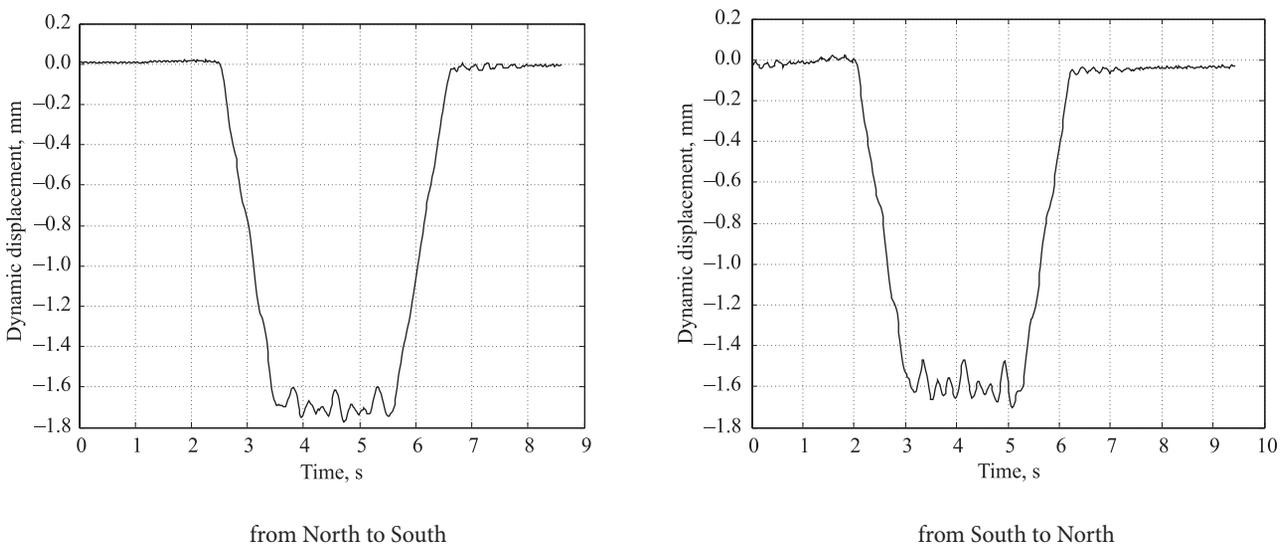


Fig. 7. Measured dynamic displacement time-histories

LIM train. Therefore, it is inappropriate to directly adopt these formulas for the design or assessment of urban rail transit bridges because of their highly conservative nature. DFs obtained by the various national codes or standards are also shown in Table 3 for the 30 m simply supported bridge.

Both theoretical and experimental dynamic displacement time-histories of bridges on the Guangzhou metro line 4 were obtained. By using Eq (7), the dynamic amplification factors $1 + \mu$ are obtained based on the theoretical and experimental dynamic time-histories. The max static displacement was obtained from the displacement-time history by curve fitting.

As shown in Table 2 and Table 3, the calculated values of DFs with electromagnetic force are larger than those without electromagnetic force. The measured DFs of the 30 m simply supported PC box bridge of Guangzhou metro line 4 ranges from 1.045 to 1.10. The theoretical results show good agreement with those from testing, and both are less than the design value: $1 + \mu = \frac{1 + 9.6}{L + 30} = 1.16$ and those provided by railway code values of most countries.

Due to the characteristics of less axis weight, lower moving speed etc, the dynamic amplification factor should be less than that of traditional railway bridges. Thus, on the basis of the LIM vehicle-bridge interaction analysis and testing studies of typical bridges in Guangzhou metro line 4, and combination of China railway bridge design and assessment codes, a formula for determination of the DF is proposed as follows:

$$1 + \mu = 1 + \frac{8.8}{L + 30} \tag{8}$$

For example, for $L = 30$ m, the calculated value of DF using Eq (8) is: $1 + \mu = 1 + \frac{8.8}{30 + 30} = 1.147$. This value is larger than all of the theoretical and experimental results of Guangzhou metro line 4, and less than that of formula of China railway bridge codes.

7. Conclusions

On the basis of analysis of electromagnetic force, the equation of LIM vehicle-bridge interaction is derived in terms of the principle of total potential energy with a stationary

Table 3. Comparison of theoretical and experimental dynamic responses

Velocity, km/h	Without electromagnetic force		With electromagnetic force		Experimental value	
	MDD, mm	DF	MDD, mm	DF	MDD, mm	DF
40	1.884	1.046	2.1406	1.0892	-	-
50	1.898	1.058	2.1747	1.0898	-	-
60	1.883	1.072	2.1240	1.0903	-	-
70	1.876	1.068	2.1154	1.0908	-	-
80	1.874	1.066	2.1069	1.0912	1.78–1.84	1.045–1.10
90	1.869	1.065	2.0918	1.0915	-	-
100	1.865	1.067	2.0824	1.0927	-	-

Table 4. Different DFs formulas of railway bridges codes of different countries

Codes name or country	DFs formula	Vehicle speed, km/h	DFs value ($L = 30$ m)
China	$1 + \frac{12}{30 + L}$	≤ 140	1.200
Japan	$1 + K_{\alpha} a + \frac{10}{65 + L}$	≤ 130	1.270
British BS5400	$0.73 + \frac{12.16}{\sqrt{L} - 0.2}$	≤ 160	1.125
Former Soviet Union	$1 + \frac{12}{20 + L}$	≤ 200	1.200
German DS804	$0.82 + \frac{1.44}{\sqrt{L} - 0.2}$	≤ 160	1.084
USA	$L \geq 24.4m$ $1.234 + \frac{1.646}{L - 9.15}$	-	1.313

value in elastic system dynamics. A special dynamic analysis program based on the MATLAB language was developed for LIM vehicle-bridge interaction. Good agreement was obtained between theoretical and experimental dynamic responses.

The calculated analysis results show that the electromagnetic force can increase the bridge vertical dynamic response. The electromagnetic force cannot be neglected in the dynamic analysis of LIM vehicle-bridge interaction. Because the LIM train has less axis weight, lower moving speed etc., the DFs based on referenced railway codes or highway codes are shown to be conservative. Adopting the proposed formula for dynamic factor is considered to be more appropriate and the proposed equation can be used for the development of bridge design criteria for urban rail transit.

Acknowledgements

The work described in this paper was supported by grants from the National Natural Science Foundation of China (Project No. 50808175) and Guangzhou Metro Company (Project No. J4KCO37).

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Received 29 September 2010; accepted 7 March 2011