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Preface

This Geotechnical Special Publication contains 12 papers that were accepted and presented at the GeoHubei International Conference on Sustainable Civil Infrastructure: Innovation Technologies and Materials, held in Yichang, Hubei, China, July 20 to 22, 2014.

The topics cover various aspects of bridge engineering. The overall theme of the GSP is bridge design, construction and maintenance, and all papers cover various aspects of this theme. The information contained in the papers is well-balanced between theoretical analyses and practical applications. It would thus be well-worth to bridge engineers, researchers and practitioners to take note of the information as it should assist them in providing improved bridge infrastructure to their stakeholders.

The editors would like to acknowledge the effort of the authors in preparing high-quality papers for these sessions, as well as the effort of the reviewers who conducted thorough reviews of each paper.

The following reviewers assisted ably in the review process for the papers in this GSP and their contribution is acknowledged:

Prof. N. W. Dekker
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Table of Contents

Vehicle Bridge Resonance Judgment Method for Continuous Rigid Frame System

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ABSTRACT： Numerical analysis method was presented in this paper to solve the response of the vehicle-bridge coupled vibration. In this method the bridge model and vehicle model were set up separately in the ANSYS environment. Then the relationship of the response of the coupled vibration was calculated by APDL language. Finally the vibration time response was obtained by imposing the coupled relationship on vehicles and bridges at any time. This method proved to be reasonable by comparing with exist literatures and experimental results. The paper also presented the judging method and formulas of the response of the coupled vibration based on the conditions of single vehicle and multi vehicles driving on the continuous rigid frame bridge and raised the judging models for resonance of different driving conditions. The results are in good agreement with the fact. The results showed that continuous rigid frame bridges are likely to cause response of resonance under the conditions of single vehicle and the equally spaced traffic flow. The load effect of the pier increases much more sharply than that of the main girder when the resonance occurs. Based on the results of this paper, it is suggest that disrupting the traffic flow by setting the deceleration traffic signs at the different longitudinal position on the bridge deck is an applicable way to decrease the frequency of the resonance of the continuous rigid frame bridges.

INTRODUCTION

The study of coupled vibration of vehicle-bridge system can be dated back to the late 1990s. Many researchers overseas used Railway Bridge as a typical example and derived the bridge-vehicle coupling equations to study the coupled vibration, through which the inertia moment usually was neglected. Compared with the in-situ test data, the analysis results although pretty close, slightly differences were always existed. Similarly in our country, the study of the coupled vibration started from the railway bridge system, Li[1], for example, studied the forced vibrations on bridge which based on a real engineering case of a suspended cable bridge. In the beginning of this century, Xia[2] published a textbook on the interactions between railways and bridge system, in which the state of the art of the knowledge of the coupled vibrations of railway bridge system was introduced and could be traced back to the 1950s. Sheng and Wang[3,4] have established coupled differential equations for vehicle-bridge system and provided numerical solutions that based on computational software. He[5-7] has successfully solved the differential equations for vehicle bridge system at transient dynamic state that based on the ANSYS and APDL. His analysis results were compared with the measured in-situ data which indicated that his method was very practical. Due to the advantages of mature technologies, short construction period and large span, continuous rigid frame bridges are widely used in the construction of the highway transportation, especially in gully regions of western China. The study about the response of vehicle-bridge coupled vibration is usually neglected owing to the relatively small vehicle loads and low impact factor[8-9]. Among the references, the response of vehicle-bridge coupled vibration is rare referred to either. Due to the existence of resonance effect, load effect has multiplied at an astonishing rate. Therefore even if the vehicle static load is relatively low, the meaning of research on the response of vehicle-bridge coupled vibration is pretty important. This paper first presents a numerical analysis method of coupled vibration based on ANSYS, then studies the response of vehicle-bridge coupled vibration based on the bridges of continuous rigid frame system.

NUMERICAL MODELING FOR THE RESPONSE OF COUPLED VIBRATION OF VEHICLE-BRIDGE SYSTEM

Modeling in ANSYS

ANASY is a very popular tool among engineers, especially in bridge analysis. The model of the vehicle and the model of the bridge were developed at the same ANSYS environmental; however, the two models were independent, which was slightly different from the previous published methods. The coupling between those two models was achieved by APDL, which could be applied at any time to the system[10-14]. For developing the model of bridge in ANSYS, the authors recommend to refer to those published research papers because it is a very robust and premature method. The method of developing vehicle model has utilized MASS21、COMBIN14 and BEAM4 elements, the following chart (Figure 1) shows an example of a vehicle model, which is a three axis vehicle and has 5 degree of freedoms.

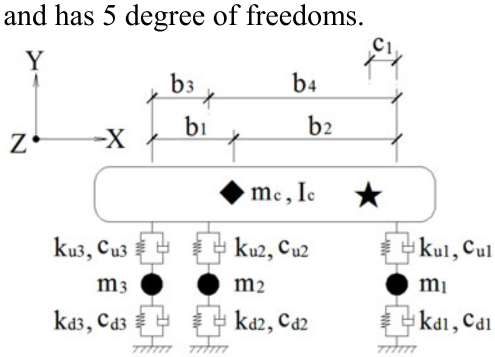


FIG.1. Model for the 3 Axis 5 degree freedom Vehicle

Note： m_c=mass of the vehicle, I_c=Moment at z Axis，m_i、k_{ui}、c_{ui}、k_{di} and c_{di}（i=1,2,3）were the mass of the wheel, stiffness and damping ratio, respectively，b_1 *and* b_2 are the distance between centroid of the vehicle to the front and back axial，b_3 *and* b_4 are the distance of the middle axial to the front and back axial，c_1 is the distance between driver to the front axial.

Determination of the Coordinates of Wheels

The starting point M and ending point N of vehicles were used to define the direction of vehicle movement (M_x, M_y, M_z a are the coordinates of point M, N_x, N_y, N_z are the coordinates for N), the coordinates of the wheels on each vehicle could be determined by the initial speed v_0, acceleration a, and running time t.

$$\left.\begin{aligned} c_{1x} &= M_x + z(N_x - M_x)/l_c \\ c_{1y} &= M_y + z(N_y - M_y)/l_c \\ c_{1z} &= M_z + z(N_z - M_z)/l_c \\ c_{2x} &= c_{1x} - b_4(N_x - M_x)/l_c \\ c_{2y} &= c_{1y} - b_4(N_y - M_y)/l_c \\ c_{2z} &= c_{1z} - b_4(N_z - M_z)/l_c \\ c_{3x} &= c_{2x} - b_3(N_x - M_x)/l_c \\ c_{3y} &= c_{2y} - b_3(N_y - M_y)/l_c \\ c_{3z} &= c_{2z} - b_3(N_z - M_z)/l_c \end{aligned}\right\} \quad (1)$$

At which: $l_c = \sqrt{(M_x - N_x)^2 + (M_y - N_y)^2 + (M_z - N_z)^2}$;

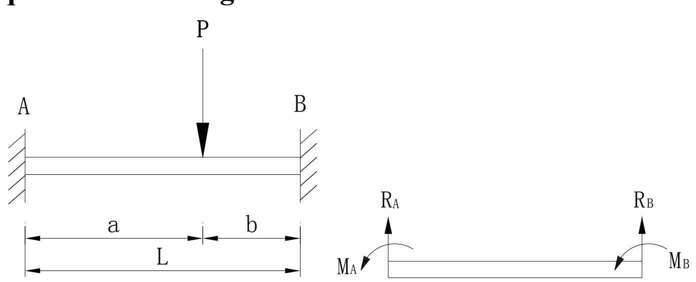
$$z = \begin{cases} \dfrac{-v_0^2}{2a} & (a < 0 \;\&\; at < -v_0) \\ v_0 t + \dfrac{at^2}{2} & (otherwise) \end{cases};$$

c_{ij} =wheel coordinates, i=wheel number, j=direction; refer to Figure

Vertical Loading and Deflection Transformation at the Intersect between Wheels and Bridge Element Points

Once the coordinates of the wheels are determined, which may not be coincide with the bridge element points, the vertical loading and deflection generated underneath the wheel has to be transformed so that to meet the model requirements.

(1) The Equivalent Loading at the Nearest Element Point



(a)Before (b) After

FIG.2. Equivalent load transformation

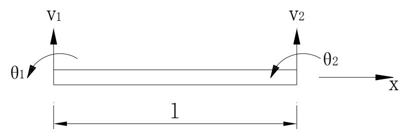


FIG.3. Displacement transformation

The equivalent load on the beam element could be calculated based on equation (2), the result is shown in equation (3), at which the W^e is the work from outside of the element, $\overline{p}(x)$ is the loading function, $v(x)$ is the displacement function, $N(x)$ is the element shape function, and q^e is the element point displacement function (see Figure 2).

$$W^e = \int_l \overline{p}(x) \cdot v(x)\,dx = \left[\int_l \overline{p}(x) \cdot N(x)\,dx\right] \cdot q^e = \left[R_A M_A R_B M_B\right] \cdot q^e \qquad (2)$$

$$\left.\begin{aligned} R_A &= -(Pb^2/L^3)/(3a+b) \\ R_B &= -(Pa^2/L^3)/(a+3b) \\ M_A &= -Pab^2/L^2 \\ M_B &= Pa^2b/L^2 \end{aligned}\right\} \qquad (3)$$

（2）The Vertical Displacement at Wheels

The displacement field (Figure 3) of the pure bending beam is calculated by equation (4) [15], in which the $v(x)$ is the displacement function, θ_1、v_2 and θ_2 are the angle of rotations at both side of the beam and the deflection, l is the length of the beam element.

$$\left.\begin{aligned} & v(x) = (1-3\xi^2+2\xi^3)v_1 + l(\xi-2\xi^2+\xi^3)\theta_1 + (3\xi^2-2\xi^3)v_2 + l(\xi^3-\xi^2)\theta_2 \\ & \xi = x/l \end{aligned}\right\} \qquad (4)$$

Numerical Analysis of the Coupled Interactions between Vehicles and Bridges

Take the vehicle model in Figure 1 as an example, the displacement array of the vehicle is $\{Z_v\}$, which includes 5 degree of freedoms: z_c、r_c are the vertical displacements and the angle of rotation, and the vertical displacement at the wheel are z_1、z_2、z_3, the vibration equation is shown in (5).

$$\left[M_v\right]\{\ddot{Z}_v\} + \left[C_v\right]\{\dot{Z}_v\} + \left[K_v\right]\{Z_v\} = \{G_v\} + \{F_{bv}\} \qquad (5)$$

In which：the $[M_v]$ is the mass matrix；$[K_v]$ is the stiffness matrix；$[C_v]$ is the damping matrix；$\{G_v\}$ is the gravity loading matrix；$\{F_{bv}\}$ is the coupled loading vector.

From structure dynamics， the i and j in $[M_v]$（$[C_v]$、$[K_v]$） means：the unit acceleration (speed, and displacement) that caused by the j degree of freedom that existed on the i degree of freedom. Thus when the vehicles move on the surface of a bridge, the element points between the vehicle and the bridge will have vertical displacement, but the displacement is independent with $[M_v]$、$[K_v]$、$[C_v]$ and $\{G_v\}$, and the $\{F_{bv}\}$ in the vehicle vibration equation varies as the time and the vehicle location changes. Take the vehicle model in Figure 1 as an example, the $\{F_{bv}\}$ could be calculated as shown in (6), at which the y_1、y_2、y_3 were the vertical displacements of the element points where the wheels contact with the bridge surface.

$$\{F_{bv}\} = \{0,0,y_1k_{d1} + \dot{y}_1c_{d1}, y_2k_{d2} + \dot{y}_2c_{d2}, y_3k_{d3} + \dot{y}_3c_{d3}\}^T \tag{6}$$

When the bridge and vehicle models have been set up, the $\{F_{bv}\}$ in equation (6) could be taken care of by APDL as the vehicles moving, and combined with $\{G_v\}$ as a force acted on from outside. In equation (5) $\{G_v\}+\{F_{bv}\}$ the part on left could be applied to all the element points, so that by adjusting the ANSYS time domain analysis, the calculation could be carried out by steps. Assume the wheels contact perfectly with the surface of the bridge, once the displacement d_i, speed $\dot{d}_i$, and the contact point's displacement y_i, speed $\dot{y}_i$, the uneven degree w, have been determined, the force *F(t)* between the vehicle and the bridge could be calculated by equation (7), and thus the time domain response of the vehicle passing the bridge could be achieved.

$$F(t) = (d_i - (y_i + w))k_{di} + (\dot{d}_i - \dot{y}_i)c_{di} \tag{7}$$

The parameters $\dot{d}_i$ and $\dot{y}_i$ could be obtained by the differentia theory, by using equation(8)or(9). In the equations (8) and (9), x_i and y_i are the horizontal and vertical coordinates of the function f(x), and h is the unit length.

$$f'(x_i) = f'(x_{i+1}) \approx (y_{i+i} - y_i)/h \tag{8}$$

$$\left.\begin{aligned} f'(x_i) &\approx (-3y_i + 4y_{i+1} - y_{i+2})/2h \\ f'(x_{i+1}) &\approx (-y_i + y_{i+2})/2h \\ f'(x_{i+2}) &\approx (y_i - 4y_{i+1} + 3y_{i+2})/2h \end{aligned}\right\} \tag{9}$$

JUDGING METHOD FOR THE VEHICLE BRIDGE RESONANCE OF CONTINUOUS RIGID FRAME BRIDGES

Resonance is defined as a phenomenon that the amplitude of the structure greatly increases when the excitation frequency approaches the natural frequency, which commonly leads to great structural deformation and high dynamic stress. There are plenty of serious accidents in the history of engineering caused by the resonance effects. The design methods and construction techniques of the bridges of continuous rigid frame system are gradually maturing, while the impact factor of the bridges with high pier and long-span is extremely low. And there are less studies for the possibilities and criterions of the response of resonance about bridges of low basic frequency. Given all these considerations, this paper researches the criterions of the resonance effect and the response of vehicle-bridge coupled vibration based on a continuous rigid frame bridge model with high piers and long-span.

Bridge Model and Vehicle Model

The PC continuous rigid frame bridge in this study has a dimension of (100+160+160). The main girder has a section of single cell and single box. The height