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Computers and Structures 84 (2006) 759–769
Computers & Structures
www.elsevier.com/locate/compstruc

Bridge roughness index as an indicator of bridge dynamic amplification

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Received 19 July 2005; accepted 1 February 2006

Abstract

The concept of a road roughness index for bridge dynamics is developed. The international roughness index (IRI) is shown to be very poorly correlated with bridge dynamic amplification as it takes no account of the location of individual road surface irregularities. It is shown in this paper that a bridge roughness index (BRI) is possible for a given bridge span which is a function only of the road surface profile and truck fleet statistical characteristics. The index is a simple linear combination of the changes in road surface profile; the coefficients are specific to the load effect and span of interest. The BRI is well correlated with bridge dynamic amplification for bending moment due to 2-axle truck crossing events. A similar process can be used to develop a BRI for trucks with other numbers of axles or combinations of trucks meeting on a bridge.
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Keywords: DAF; DAE; BRI; Dynamic; Roughness; Bridge; Vehicle

1. Introduction

The dynamic amplification factor (DAF) for a bridge is defined as the maximum total (dynamic plus static) load effect divided by the maximum static load effect. DAF is influenced by many factors. Speed is particularly important, as noted by many authors [1–6] and in particular the ratio of speed to bridge 1st natural frequency [7]. Road roughness is also a key factor [3,4,8], particularly for short bridges.

In the highway industry, indices for the evaluation of pavement surface evenness have been developed since the 1960s. The most popular parameters are the international roughness index (IRI) [9–11] which was developed and recommended by the World Bank to evaluate pavement roughness, and the power spectral density (PSD) [12].

Olsson [13], Lin [14], Henchi et al. [15], Liu et al. [3] and Majumder and Manohar [16] are just some of the authors that use finite element analysis with six degrees of freedom per node to model bridges dynamically. Olsson [13] compared the results of finite element analysis with different beam models. Green and Cebon [17] modelled two bridges in the U.K. with finite elements. Chompooming and Yener [18] present a finite element model of a beam and slab bridge. This type of section is also modeled by Kou and Dewolf [19] who use plate elements for the deck and beam elements for the girders. González [20] couples displacements and velocities at the bridge/vehicle contact points at each time step in an iterative formulation. Yau and Yang [21] allow for instability and inertial effects in a finite element model of a cable stayed bridge.

The effect of road surface irregularities on bridge vibration has been examined by DIVINE [1], Green et al. [4], Kou and Dewolf [19], Law and Zhu [22], Lei and Noda [23] and Chatterjee et al. [24]. Vehicle and bridge models have been used to simulate the vehicle-bridge interaction system and to determine the effect of profile unevenness. However, these papers investigate the influence of different PSD levels. It has been found by Li et al. [25] that there are substantial differences in dynamic amplification between road profiles with the same PSD level and the same IRI value.

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doi:10.1016/j.compstruc.2006.02.008

Michaltsos [26] and Pesterev et al. [27,28] have shown that the position of an irregularity is important for bridge dynamic amplification. In a previous paper [25], the authors confirm this and show that if bridge deflections are negligible [28], the principle of superposition applies for the dynamic response to individual road surface irregularities. This makes possible the estimation of dynamic amplification by adding together the DAFs due to each irregularity that makes up the road surface profile. Very good agreement with critical DAF values is reported for a range of 'good' road surface profiles. A significant problem is that the resulting dynamic amplification estimate is specific to the properties (spring stiffness etc.,) of that vehicle.

Yang et al. [12], Zhu and Law [29] and Brady and OBrien [30] examine cases of two following loads and compare the effects to single load crossings. Axle spacing is identified as being particularly important [30,31] and it quickly becomes clear that an amplification factor derived from a 1-axle vehicle model is of limited value as an indicator of DAF for multiple-axle vehicles.

The goal of this paper is to develop the concept of a BRI which can be used as an estimator of DAF for a given vehicle class, and in particular in this paper, a BRI for 2-axle vehicles. The BRI will be a function of the road profile only; it will not be dependent on the speeds or properties of particular vehicles. A BRI potentially constitutes an extremely useful measure of road surface roughness that could be used by bridge maintenance managers as an indicator of the level of dynamic amplification that might be expected on a bridge.

2. Bridge vibration

2.1. Vehicle-bridge interaction model

A half-car model crossing a simply supported Bernoulli-Euler beam at a constant speed is used to simulate 2-axle vehicle events (Fig. 1). The motion controlling this system is defined by the ordinary differential equations [32]:

$$-I\frac{\mathrm{d}^2\varphi(t)}{\mathrm{d}t^2}+(-1)^iD_i(Z_i(t)+Z_{\mathrm{b}i}(t))=0 \tag{1a}$$

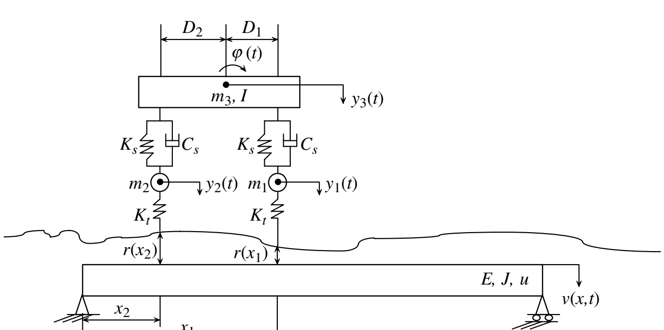

Fig. 1. Schematic of the two-axle vehicle and bridge interaction system.

$$-m_3\frac{\mathrm{d}^2y_3(t)}{\mathrm{d}t^2}-\sum_{i=1}^{2}[Z_i(t)+Z_{bi}(t)]=0 \tag{1b}$$

$$m_{3i}g+m_ig-m_i\frac{\mathrm{d}^2y_i(t)}{\mathrm{d}t^2}+Z_i(t)+Z_{\mathrm{b}i}(t)-R_i(t)=0 \quad i=1,2 \tag{1c}$$

$$EJ\frac{\partial^4v(x,t)}{\partial x^4}+\mu\frac{\partial^2v(x,t)}{\partial t^2}+2\mu\omega_b\frac{\partial v(x,t)}{\partial t}=\sum_{i=1}^{2}\varepsilon_i\delta(x-x_i)R_i(t) \tag{1d}$$

where I and $\varphi(t)$ are the mass moment of inertia and rotational degree of freedom of the body mass respectively; D_i is the horizontal distance between the centroid of sprung mass and unsprung mass i; m_1, m_2, m_3 are masses of the front axle, rear axle and vehicle body respectively and $y_1(t)$, $y_2(t)$ and $y_3(t)$ are the corresponding vertical displacement of their centers of gravity; g is acceleration due to gravity; $v(x,t)$ is the displacement of the bridge at location x and time t; E, J, μ and ω_b are modulus of elasticity, inertia of the cross-section, mass per unit length and circular frequency of damping of the bridge respectively; $\varepsilon_i=1$ if axle i is present on the bridge and $\varepsilon_i=0$ if not; $\delta(x-x_i)$ is the Dirac function. Therefore,

$$Z_i(t)=K_s[y_{3i}(t)-y_i(t)] \tag{2a}$$

is the force in the spring between the ith axle and the vehicle body, where K_s is the suspension spring stiffness.

$$Z_{bi}(t)=C_s\left[\frac{\mathrm{d}y_{3i}(t)}{\mathrm{d}t}-\frac{\mathrm{d}y_i(t)}{\mathrm{d}t}\right] \tag{2b}$$

is the damping force between the ith axle and the vehicle body, where C_s is a suspension linear damper.

$$y_{3i}(t)=y_3(t)-(-1)^iD_i\varphi(t) \tag{2c}$$

is the displacement of the contact point between the ith axle and the vehicle body.

$$m_{31}=m_3\frac{D_2}{D_1+D_2} \qquad m_{32}=m_3\frac{D_1}{D_1+D_2} \tag{2d}$$

are the masses of the sprung part of the vehicle by axle.

$$R_i(t)=K_t[y_i(t)-\varepsilon_iv(x_i,t)-r(x_i)]\geqslant 0 \tag{2e}$$

is the tire force imparted to the bridge by the ith axle, where K_t is tire stiffness and $r(x_i)$ is height of road profile at location of axle i. Negative values of the tire force, representing loss of contact with the road surface, are set to zero. Based on the work of Frýba [32], numerical results are found in the time domain through the Runge–Kutta–Nyström method [33].

2.2. Dynamic amplification due to 2-axle vehicle

In a previous study [25], the authors have proven that the effect of individual road irregularities can be superposed for a quarter-car model traveling on a short-span bridge with a good road profile. Bending moment is found

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