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Pitching Effect in an Amplifier Enhanced Vehicle Model for Vehicle Scanning Method

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Abstract

In this study, a three-mass vehicle model enhanced by an adjustable amplifier is proposed to enhance the resolution of frequency identification in the vehicle scanning method. The analytical formulation of the proposed vehicle-bridge system is derived. It is found that the visibility of fundamental and higher bridge frequencies can be achieved through the tuned mass damper effect of the amplifier in its spectrum, while such an effect has almost no influence on the resolution of frequency identification in the vertical and rotational vehicular spectra. The pitching effect has shown that the rotational vehicle spectrum has better resolution than the amplifier spectrum without tuning amplifier frequency.

Keywords: amplifier, three-mass vehicle, pitching; vehicle scanning method.

1 Introduction

In 2004, using the dynamic responses obtained from a test vehicle to scan the bridge frequencies was proposed [1,2]. With the rapid growth of research related to this top, the vehicle scanning method (VSM) was first named in the monograph [3].

To enhance the resolution of frequency identification in VSM, various approaches have been proposed so far, aiming at resolving the noisy signals in the vehicular spectrum caused by the pavement irregularity. For instance, the contact response between the vehicle and bridge was shown to be free of vehicular frequency in the spectrum [4,5]. The residual response obtained from the two-connected vehicles was proposed to eliminate the adverse effect [6]. Based on the idea of elimination, using the acceleration residual spectrum from the front and rear contact points in a two-axle vehicle was recently proposed as an extension [7].

On the other hand, the design of vehicle models provides an alternative approach. In view of the adjustable characteristic of the tuned mass damper (TMD), a single degree-of-freedom (DOF) amplifier was added to the sprung mass vehicle model [8]; it was shown that the bridge frequencies can be better scanned in the amplifier spectrum than those in the vehicle spectrum without tuning amplifier frequency. To consider the pitching effect, the pitching vehicle model is proposed herein based on a three-mass vehicle model.

2 Methods

The mathematical model of an amplifier-vehicle-bridge (AVB) system is drawn in Figure 1, where a four-mass vehicle moving constantly at a speed v on a simply supported bridge with length L and pavement irregularity $r(x)$ is assumed. The parameters of the vehicle are listed below: the rigid mass m_v, pitching moment of inertia I_v, unsprung mass m_u, amplifier mass m_a, axle distance d, suspension unit with spring constant k_v and damping coefficient c_v, and amplifier stiffness k_a. The DOFs of the AVB system are described as follows: the vehicle body with q_v and θ_v, unsprung masses with q_{ui} and q_{uj}, and amplifier with q_a.

The finite element (FE) formulation of the AVB system is derived in this study, with the following equations for the amplifier and vehicle:

$$m_a\ddot{q}_a + k_a\left(q_a - q_v\right) = 0 \tag{1}$$

$$m_v\ddot{q}_v + c_v\left(2\dot{q}_v - \dot{q}_{ui} - \dot{q}_{uj}\right) + k_v\left(2q_v - q_{ui} - q_{uj}\right) + k_a\left(q_v - q_a\right) = 0 \tag{2}$$

$$I_v\ddot{\theta}_v + \frac{1}{2}d^2c_v\dot{\theta}_v + \frac{1}{2}d^2k_v\theta_v = \frac{1}{2}d\left[m_u\left(\ddot{q}_{ui} - \ddot{q}_{uj}\right) + c_v\left(\dot{q}_{ui} - \dot{q}_{uj}\right) + k_v\left(q_{ui} - q_{uj}\right)\right] \tag{3}$$

As the bridge equations are the same as those given in the three-mass vehicle model, the interested readers can refer to our previous work [9]. Nevertheless, due to the inclusion of the amplifier mass in the vehicle model, an additional term $\frac{1}{2}m_a g$ (g denoting the gravitational acceleration) needs to be included in the contact forces, which is different from the one given in Ref. [9]. The final form of the equations of the AVB system is given by

$$\mathbf{M}\begin{Bmatrix}\ddot{q}_a\\ \ddot{q}_v\\ \ddot{\theta}_v\\ \ddot{\mathbf{q}}_b\end{Bmatrix}+\mathbf{C}\begin{Bmatrix}\dot{q}_a\\ \dot{q}_v\\ \dot{\theta}_v\\ \dot{\mathbf{q}}_b\end{Bmatrix}+\mathbf{K}\begin{Bmatrix}q_a\\ q_v\\ \theta_v\\ \mathbf{q}_b\end{Bmatrix}=\mathbf{F} \tag{4}$$

where the mass, damping, and stiffness matrices of the AVB system are **M**, **C**, and **K**; **F** is the force vector.

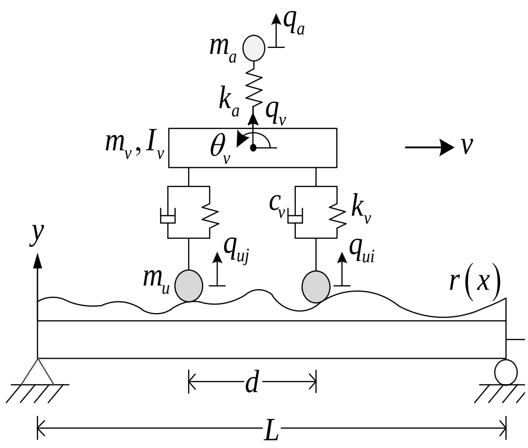

Figure 1: Mathematical model.

3 Results

The parameters of vehicle and bridge adopted in this study are summarized in Table 1. For clarity, the theoretical frequencies of bridge, vehicle, and amplifier are computed in Table 2.

Table 1: Vehicle and bridge parameters.

vehicle		bridge	
m_v (kg)	1500	E (GPa)	29
I_v (kg · m^2)	2738	I (m^4)	0.2422
m_u, m_a (kg)	75, 15	$\bar{m}$ (kg/m)	5000
k_v, k_a (kN/m)	450, 80	L (m)	30
d (m), v (m/s)	2.5, 5	No. elements	40

3.1 Effect of amplifier mass

The weight of amplifier is generally small in comparison with the vehicle. As it is the key component adopted in the AVB system, the influence of amplifier mass is investigated herein by considering $m_a = 0$, $m_v / 500$, $m_v / 100$, and $m_v / 50$. It is noted that the amplifier frequency is kept unchanged, i.e. $f_a = 11.623$ Hz, and the results are shown in Figure 2. By observation, for all spectra obtained in the amplifier, vertical vehicle, and rotational vehicle responses, the resolution of frequency identification remains almost the same, which indicates that the amplifier mass does not have much influence in the VSM.

Table 2: Theoretical frequencies.

frequency	bridge			vehicle		amplifier
	f_{b1}, f_{b1L}, f_{b1R}	f_{b2}, f_{b2L}, f_{b2R}	f_{b3}, f_{b3L}, f_{b3R}	f_v	f_θ	f_a
Hz	2.069, 1.987, 2.152	8.274, 8.107, 8.441	18.618, 18.368, 18.868	3.898	3.607	11.623

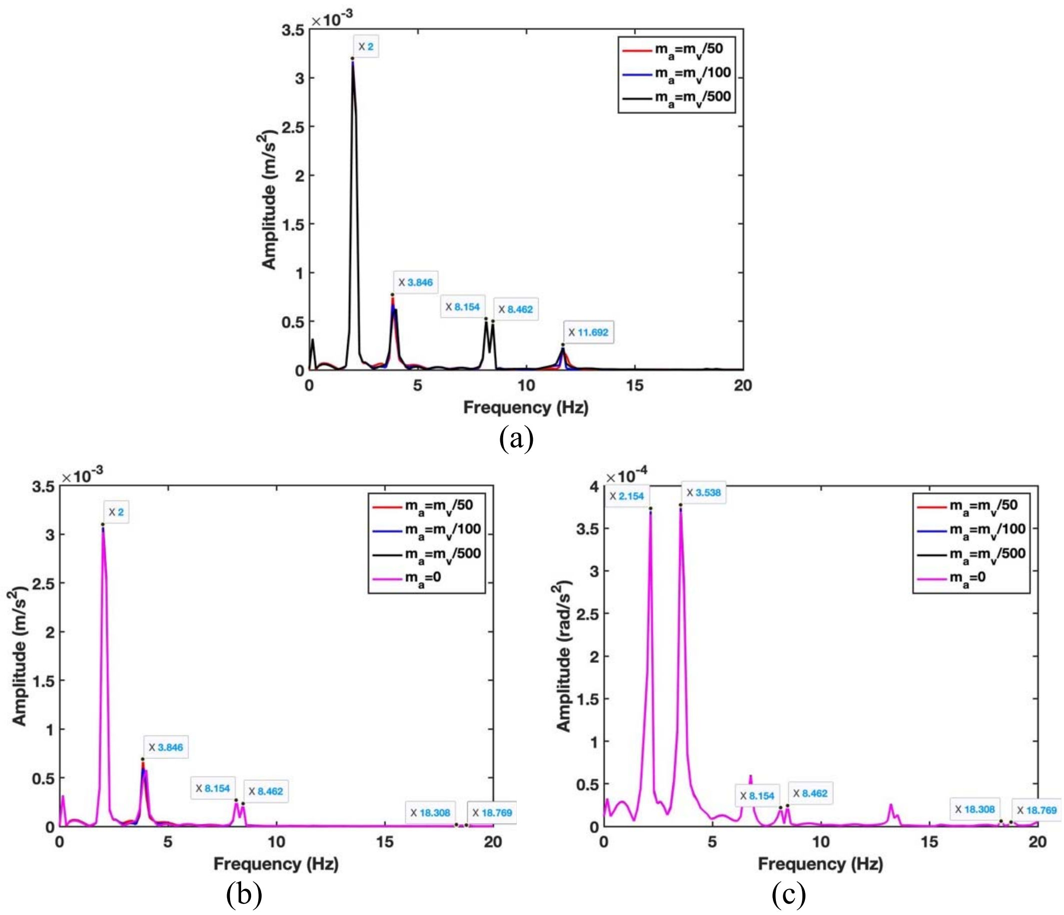

Figure 2: Spectra obtained by various m_a: (a) amplifier, (b) vertical vehicle, and (c) rotational vehicle..

3.2 Tuned mass damper effect

To understand the influence of amplifier frequency on the frequency identification, three cases are considered, i.e. $f_a = 1.1 f_{b1}$, $f_a = 1.1 f_{b2}$, and $f_a = 1.1 f_{b3}$, and the spectra are shown in Figure 3. From Figure 3 (a), it is observed that the higher bridge frequencies can be identified clearly as the amplifier frequency is tuned closely to the higher bridge frequency. More specifically, for $f_a = 1.1 f_{b2}$, the first and second bridge frequencies are identified; for $f_a = 1.1 f_{b3}$, the first three bridge frequencies are identified. The shifted bridge frequencies are also observed for higher modes. In contrast, as shown in Figure 3 (b) and (c), the change of amplifier frequency has almost no influence on the identification of bridge frequencies in both vertical and rotational vehicle spectra.

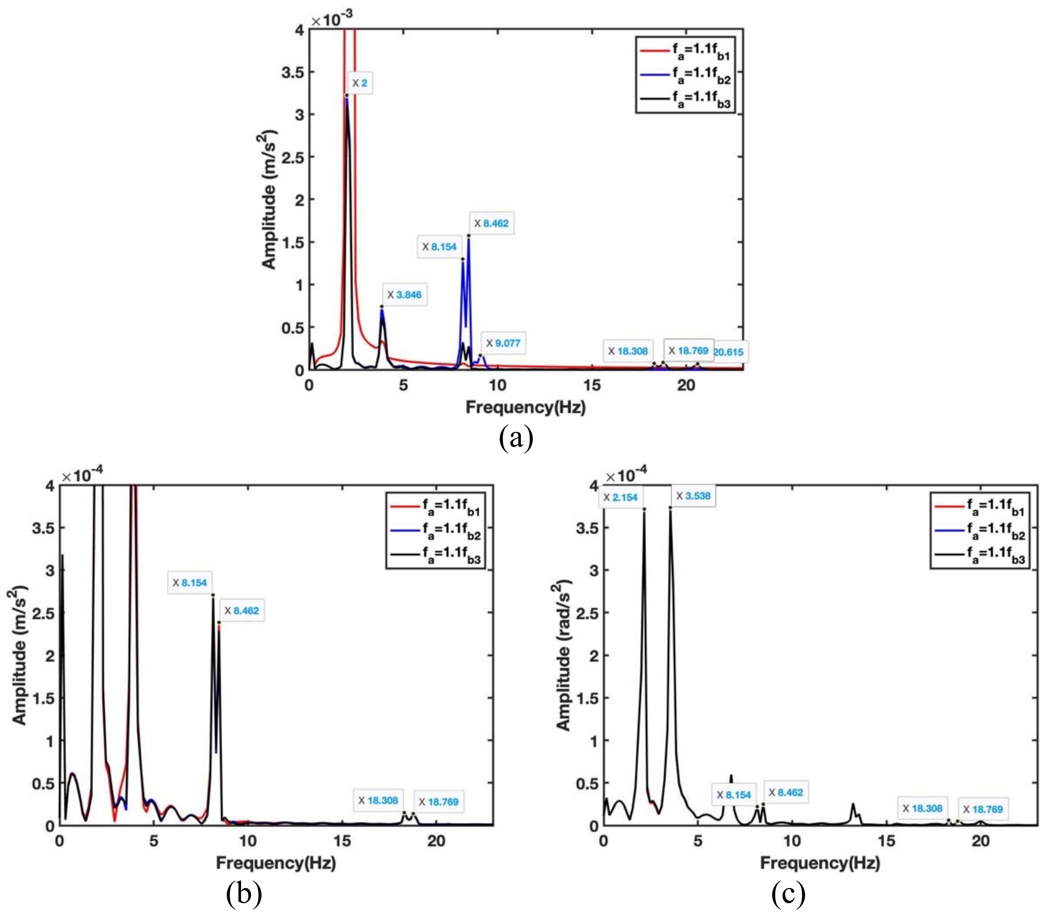

Figure 3: Spectra obtained by various f_a: (a) amplifier, (b) vertical vehicle, and (c) rotational vehicle.

3.3 Effect of pavement irregularity

For demonstration, the Class C pavement irregularity defined in ISO 8608 [10] is considered. For comparison, both the original amplifier frequency f_a and tuned amplifier frequency $f_a = 1.1 f_{b3}$ are studied with the results given in Figure 4. From Figure 4 (a), besides the frequencies of amplifier and vehicle, tuning amplifier frequency can make the third bridge frequency visible. In Figure 4 (b) and (c), the first three bridge frequencies along with the vehicular vertical and rotational frequencies can be identified. Again, tuning amplifier frequency has no influence on vehicular spectra.

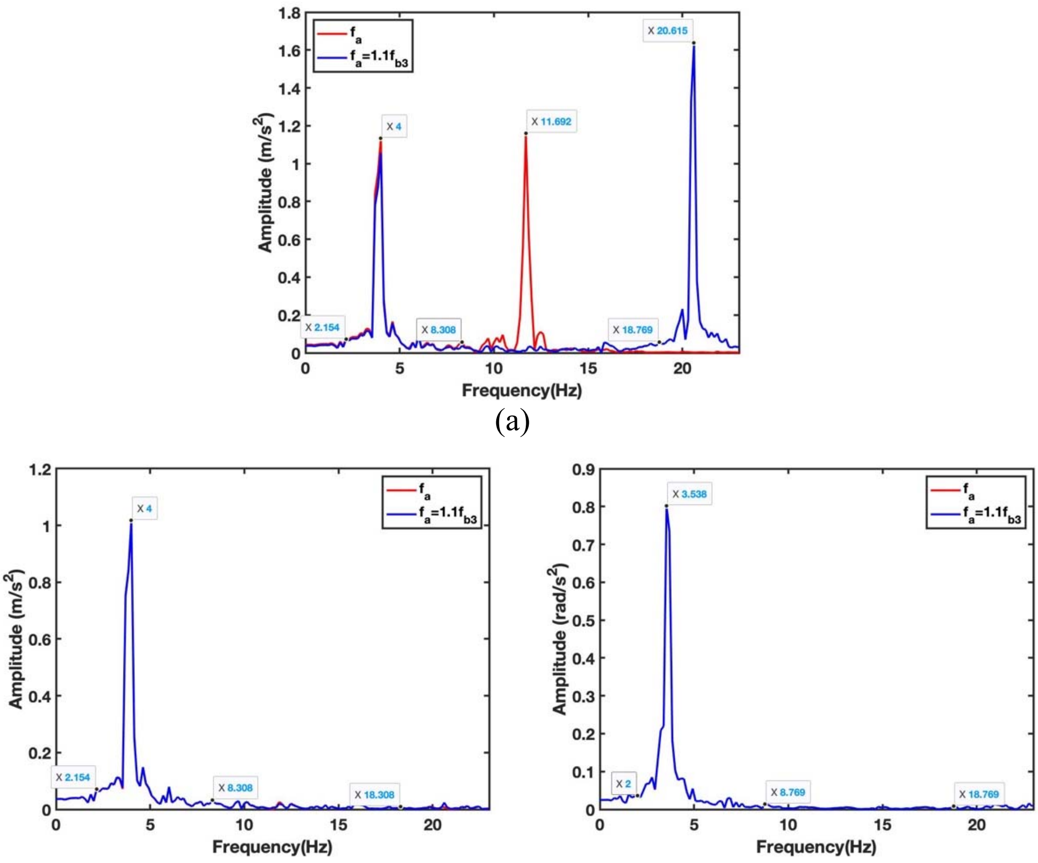

Figure 4: Spectra under pavement irregularity: (a) amplifier, (b) vertical vehicle, and (c) rotational vehicle.

4 Conclusions and Contributions

From the numerical investigation, the proposed AVB system has shown its ability to scan the bridge frequencies with considerable accuracy. The following remarks are made: (1) The influence of amplifier mass in VSM is almost negligible. (2) The merit of tuned mass damper effect can be used to scan the bridge frequencies up to the *n*th mode in the amplifier spectrum through the adjustment of amplifier frequency closely to the *n*th bridge frequency. (3) Under the pavement irregularity, the pitching effect shows that both vertical and rotational vehicular spectra have better resolution than the amplifier spectrum for scanning bridge frequencies without tuning amplifier frequency.

Acknowledgements

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