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# Railway vehicle induced vibration energy harvesting and saving of rail transit segmental prefabricated and assembling bridges

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ABSTRACT

Taking a continuous rigid segmental prefabrication and assembly bridge on Guangzhou Metro No.14 as example, railway vehicle induced vibration energy harvesting and saving was studied in this paper. By modeling multi-body dynamics system of B-type railway vehicle and the wheel-rail interaction relationship, train-track-bridge (TTB) response was calculated accurately. Through dynamic analysis of the TTB system with two different track irregularity conditions, vertical acceleration time histories of the track slab were acquired. Based on this, a new type of electromagnetic vibration energy harvesters (EM-VEHs) is proposed. Utilizing the track slab vibration, the EM-VEHs set adjacent to the track slab are demonstrated to be feasible to supply enough power for strain collection units or GPS data transmission units in bridge health monitoring system. Compared with previous research, the power density of the proposed EM-VEH device is much higher. The application prospect of the proposed EM-VEH on urban mass transit SPA bridges is worthy to be anticipated.



## 1. Introduction

Segmental Prefabrication and Assembly (SPA) is known as a kind of Accelerated Bridge Construction (ABC) method (Xiang et al., 2015). Compared with those cast-in-place, segmental prefabricated and assembled (SPA) bridges have advantages of shorter construction period, lower total cost and much less negative influence on the existing traffic and natural environment. All the advantages are accord with the aims of national economic development, namely 'green, effective & energy-saving'. In recent decades, with the rapid development of rail transit and high-speed railway in China, the application of SPA bridges has been greatly increased (Deng, 2015; Zeng and Meng, 2012; Xu et al., 2014). Compared with conventional cast-in-place bridges, the integrity and durability of SPA bridges have been the focus due to the existence of spliced joints. To ensure the normal service condition of bridges and provide detailed data for bridge maintenance, long-term health monitoring is really necessary for SPA bridges, especially for those applied in rail transit and high-speed railway.

Usually, embedded sensors are needed for bridge health monitoring (BHM). To the various power supply of the embedded sensors, persistence and stability are the key points. Thus, the choice of energy sources is particularly important. In bridge surroundings, wind, solar, acoustic, and vibration energies are abundantly available for energy harvesting. However, except vibration energy, the other three are all restricted by the environment. By contrast, for mass transit bridge, traffic-induced structural vibration is the main kind of vibrations, which is low-frequency random vibration with low frequency and low acceleration. As a result, the traffic-induced vibration energy could be collected by energy harvester. On the other side, during the railway vehicle running, the characteristics of short intervals and large density are helpful to produce sustained and stable traffic-induced vibration energy. Therefore, bridge vibration energy harvesting for powering monitoring sensors is not only feasible but also economic valuable in environmental protection and energy saving.

So far, two types of bridge vibration energy harvesters are developed and reported, namely piezoelectric vibration energy harvesters (PE-VEHs) (Jo et al., 2012; Amin, 2010; Zhang et al., 2014; Baldwin et al., 2011; Li, 2014) and electromagnetic vibration energy harvesters (EM-VEHs) (McEvoy et al., 2011; Kwon et al., 2013; Khan and Ahmad, 2014; Galchev et al., 2011a; Miao, 2013). PE-VEHs are made from commercially available piezoelectric material, have simple structure and are easy to use with no auxiliary power supply. But the service life and conversion efficiency of PE-VEHs are lied on the mechanical and piezoelectric properties of the

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piezoelectric materials. EM-VEHs are made of wound coils and permanent magnets, producing relatively low voltage, high output current and power levels because of low internal impedance. Till date, the majority of the reported bridge vibration energy harvesters are based on electromagnetic transduction mechanism. Kulkani (Kulkarni et al., 2007), University of Southampton, placed magnets on copper cantilever beams to induce external vibrations, and the coils remained stationary to calculate the output electrical power density. Sari (Sari et al., 2007), the Middle East University of Science and Technology, adopting MEMS technology, set coils on cantilever beams with different lengths. The induced vibration on the cantilever beam lead the relative motion between the coils and the magnet. Meanwhile, combining different cantilever beams together would increase the output power density. There are a variety of EM-VEHs proposed by other researchers, but most of them are still in the laboratory stage. In order to make more efficient use of ambient vibration and enhance energy response, Yu Jia (Jia et al., 2015) et al. designed a bridge EM-VEHs which combines both direct resonance and parametric resonance. And the efficiency of the EM-VEHs was studied in situ on a real road bridge. Though the measured power efficiency was pretty poor, it is feasible to power the wireless structural health monitoring systems in real world infrastructure.

It should be noted that most of the current research on bridge VEHs are mainly aiming to long-span highway bridges. Related research on the rail transit bridges is seldom reported. Rail transit bridges are usually composed of simple supported bridges, continuous bridges or continuous rigid frame bridges, with single span of 40–50 m. But the total bridge length accounts for a large proportion in the total length of the rail lines, which is up to over 40%. Thus, the practical applicability of VEHs on rail transit bridges are more significant and realistic.

In this paper, taking a continuous rigid SPA bridge with span arrangement of (4 × 40 + 4 × 40) m as example, the railway vehicle-induced vibration was obtained through vehicle-bridge coupled dynamic analysis with the consideration of wheel-rail contact and railway track irregularity. Based on the acquired bridge vibration, a kind of EM-VEHs was proposed aiming to supply power for long-term bridge health monitoring sensors, and the energy efficiency and potential economic value of the EM-VEHs is discussed.

## 2. Description of train-track-bridge relationship

To carry out EM-VEHS research on transit SPA bridge, railway vehicle induced vibration should be obtained firstly through vehicle-bridge coupled dynamic analysis, in which the accurate train-track-bridge (TTB) relationship should be included. The TTB relationship description includes multi-body dynamics system of the railway vehicle, the wheel-rail interaction relationship.

### 2.1. Multi-body dynamic system of the railway vehicle

Usually, Cartesian method, based on absolute coordinates, is more widely used to describe multi-body dynamic problems in mechanical field (Huston, 1991). In multi-body dynamics system, inertial system is often defined as the reference system. The position of a spatial rigid body could be clearly defined through the Cartesian coordinate system, which is aligned with the spatial rigid body. To describe the motion of a multi-rigid system, an inertial reference base vector should be determined for the system and a body fixed base vector should be determined for each rigid body. Thus, the Cartesian coordinate array of the multi-body system is composed of the relative coordinates of the rigid body centroid to the inertial reference base vector ($\boldsymbol{x_i}$,$\boldsymbol{y_i}$,$\boldsymbol{z_i}$) and the Caldan angle ($\boldsymbol{\alpha_i}$, $\boldsymbol{\beta_i}$, $\boldsymbol{\gamma_i}$) of the body fixed base relative to the inertial reference base:

$$q_i = (x_i \quad y_i \quad z_i \quad \alpha_i \quad \beta_i \quad \gamma_i)^T \quad (i = 1, \cdots, n) \tag{1}$$

where, $\boldsymbol{n}$ is the number of the rigid bodies in the multi-body system.

Caldan angle of each rigid body could be replaced by Euler Quaternion:

$$q_i = (x_i \quad y_i \quad z_i \quad \lambda_{0i} \quad \lambda_{1i} \quad \lambda_{2i} \quad \lambda_{3i})^T \tag{2}$$

For a system composed of $\boldsymbol{n}$ rigid bodies, describing each rigid body with Cartesian coordinates based on the Eulerian quaternion, then the total number of the coordinates to describe the entire multi-body system position is $7\boldsymbol{n}$. Obviously, these coordinates are not independent. Besides the quaternion constraint equation, constraint equations also exist between adjacent rigid bodies. Accordingly, a redundant constraint equation group is formed by these equations. Through kinematics analysis, $\boldsymbol{s}$ dependent constraint equations could be acquired, constraint equations of velocity and acceleration could be obtained by first and second order derivation of time, respectively.

### 2.2. Wheel-rail interaction relationship

(1) ***Wheel-rail contact geometric relationship***

During the railway vehicle running time, the contact relationship between the wheel and rail keeps changing. And the geometry of the wheel tread has great influence on the dynamic response between wheel and rail. To describe the practical wheel-rail constraint relationship better, accurate simulation of the wheel-rail contact geometric relationship is the necessary precondition. There are many kinds of the wheel-rail contours, some of them could be represented by simple analytic formula, but most of them are difficult or even impossible to be represented by precise analytical expressions. Equivalent taper and discrete curves are the most usual methods to describe the wheel-rail surface shape.

(2) ***Wheel-rail interaction force***

Assuming the wheel-rail contact point is a single point, then the contact area is elliptical. The semi-major axis and semi-minor axis of the elliptical contact area could be obtained according to Hertz theory:

$$a = m\left(\frac{3\pi P(k_1 + k_2)}{4(A+B)}\right)^{\frac{1}{3}}, \quad b = n\left(\frac{3\pi P(k_1 + k_2)}{4(A+B)}\right)^{\frac{1}{3}} \tag{3}$$

where, $\boldsymbol{m}$ and $\boldsymbol{n}$ are related to the geometrical parameters of the rail and the wheel; $\boldsymbol{k_1}$ and $\boldsymbol{k_2}$ are related to the Poisson's ratio and the tensile modulus of the wheel and the track, respectively.

The normal force between the wheel and the rail could be obtained by elastic contact compression method, which is also based on the Hertz elastomer contact theory. Assuming the elastic compression between the wheel and the rail is $\boldsymbol{p}$ ($\boldsymbol{N}$), then the wheelbase normal force $\boldsymbol{N}$ can be obtained (Pascal, 1994):

$$N = \left(\frac{p(N)}{p(1)}\right)^{1.5} \tag{4}$$

where, $\boldsymbol{p}$ **(1)** is the elastic penetration produced by unit normal vector, which can be calculated by: