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Realizing a Self-powered Real-time Monitoring System on High-speed Trains

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ABSTRACT

The development of the worldwide high-speed rail network is expanding at a rapid pace, imposing great challenges on the operation safety. Recent advances in wireless communications and information technology can integrate the Internet of Things and cloud computing to form a real-time monitoring platform of high-speed trains. To realize this system, a sustainable power source is indispensable. In this case, an ideal solution is to deploy a vibration-based energy harvester instead of batteries for the electrical supply of wireless sensors/devices, as vibrations induced by rail/wheel contact forces and vehicle dynamics are an abundant energy source. To address this challenge, a multi-stable, broadband and tri-hybrid energy harvesting technique was recently proposed, which can work well under low-frequency, low-amplitude, and time-varying ambient sources. In this work, we will introduce our idea, following the recently proposed energy harvester and the dynamic responses of a train vehicle, to design a self-sustained sensing system on trains. Supported by this self-powered system, accelerometers and microphones deployed on an in-service train (in axle boxes/bogie frames) can measure

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vibration and noise data directly. The correlation of the vibration and noise data can then be analyzed simultaneously to identify the dynamic behavior (e.g., wheel defects) of a moving train.

1. INTRODUCTION

High-speed rail (HSR) systems have been planning and developing in many countries worldwide (e.g., Japan, France, Germany and the UK). In China, a monumental construction plan, extending the longest HSR network to 37,900 km by 2020 [1], has been completed to satisfy the rapidly growing demand for intercity services. To underpin the role of Hong Kong as the southern gateway to the Chinese mainland, the Guangzhou-Shenzhen-Hong Kong Express Rail Link has also plugged into the nationwide network in late 2018. Indeed, HSR is an environmentally friendly transportation infrastructure that can act as a catalyst to reshape urban transportation systems. The average growth rate of the annual ridership of HSR in China since its debut in 2008 is over 30%, and the daily ridership across the entire network is more than 1.3 million passengers [2]. Because of the massive daily flow of commuters, operational safety and ride comfort are of paramount importance for HSR planning and development. Any excessive vibrations and progressive fatigue of the mechanical components in high-speed trains during its operation may cause catastrophic injuries.

The operation speed of high-speed trains is over 200 km/h, vibration is an unavoidable problem caused by wheel/rail contact forces, imperfect suspension systems and aerodynamic drag forces [3]. It is considered to pose only a very mild risk of motion sickness given sufficiently good design practice of train vehicles. To sustain the carbody weight and control the wheelsets for stable running on tracks, bogie frames (a welded high-strength steel structure) are the linchpin. The long-term vibration of bogie frames and suspension systems may possibly increase the risk of causing progressive fatigue, e.g., a fracture crack occurred in a bogie of a Shinkansen bullet train in 2017, nearly led to a derailment incident [4]. To monitor the health status of bogie structures, a smart sensing system for reliable on-board monitoring is highly desired. Advanced technologies of using high-precision wireless communications are recently used for data acquisition, signal monitoring and information transmission on high-speed trains [5]. The presence of a wireless sensing system not only can evaluate the full conditions of bogie frames, and also evaluate potential factors to cause faults on aged structures. However, the power supply of a wireless sensing system deployed at various locations of the bogie structures to monitor its operational status is still a crucial but unresolved issue. Using conventional batteries for sensors (e.g., accelerometers, microphones etc.) is far from efficient, it is because they are limited in life-time problems. In this regard, an alternative solution is to use a vibration-based energy harvesting technique instead of electrochemical batteries for the power supply of wireless sensors and devices, such that a self-powered monitoring system can be realized.

Vibrations induced by rail irregularities, rail/wheel contact forces, and aerodynamic instabilities are a common phenomenon under the operation of high-speed trains, but this results in a potential source for energy harvesting. In real practice, the vibration characteristics of high-speed trains are low-frequency, low-intensity, time-varying and speed-dependent. Generally, there are various working mechanisms for energy scavenging, e.g., electromagnetic, piezoelectric, thermoelectric, and triboelectric approaches [6–13]. Among them, both piezoelectric and electromagnetic mechanisms are the potential candidates for generating sufficient energy from mechanical vibration [14]. In the past two decades, many vibration-based energy harvesters were designed by a single-degree-of-freedom nonlinear model, but they can only perform well under a dominant resonant frequency. When it is subject to random excitation frequencies, the working performance of such energy harvesters will degrade rapidly in the non-resonant bandwidth [15]. This problem would seriously restrict their potential applications in real-world engineering conditions. In addition, the power generated by a resonant-based energy harvester decreases dramatically, because it is rather difficult to harness sufficient energy under low-frequency excitation sources [16].

To develop a vibration-based energy harvester under the working conditions of high-speed trains, its entire operating bandwidth must contain multiple dominant frequency regions. To go beyond the aforementioned technical barriers, the authors strived to develop various low-frequency, broadband and multi-stable vibration-based energy harvesting techniques [17–21]. One of the recent works is to design an ultra-low-frequency multi-stable energy harvester that can perform well at 1−11 Hz under 1 g (= 9.8 m/s^2) [21]. This is a tri-hybrid mechanical design, coupling the piezoelectric, electromagnetic and triboelectric mechanisms together, in a smart and compact manner. Motivated by the present design, in this work, we aim to introduce our idea to develop a self-powered monitoring system on high-speed trains for vibration and noise measurements [22]. Through this research, we also expect that a faster technology transfer from research to commercialization can be achieved to benefit the railway industry.

2. SYSTEM DESCRIPTION

Recent advances in wireless communications and information technology can integrate a cloud computing platform to form a self-powered and real-time monitoring system of high-speed trains, as presented graphically in Figure 1 [23]. In the design concept, a sensing network consists of multiple wireless sensors (e.g., accelerometers and microphones) and access points, where data can be transferred to a cloud computing platform via Wi-Fi or ZigBee protocols. The cloud computing platform can offer high-efficient data analysis, data storage, and early warning function without time-delay. This platform can be easily accessed by a user-friendly network interface through web systems or mobile applications. Unleashing the potential of this design system can offer a great opportunity for direct integration into the traditional railway industry to evaluate the operational performance of high-speed trains.

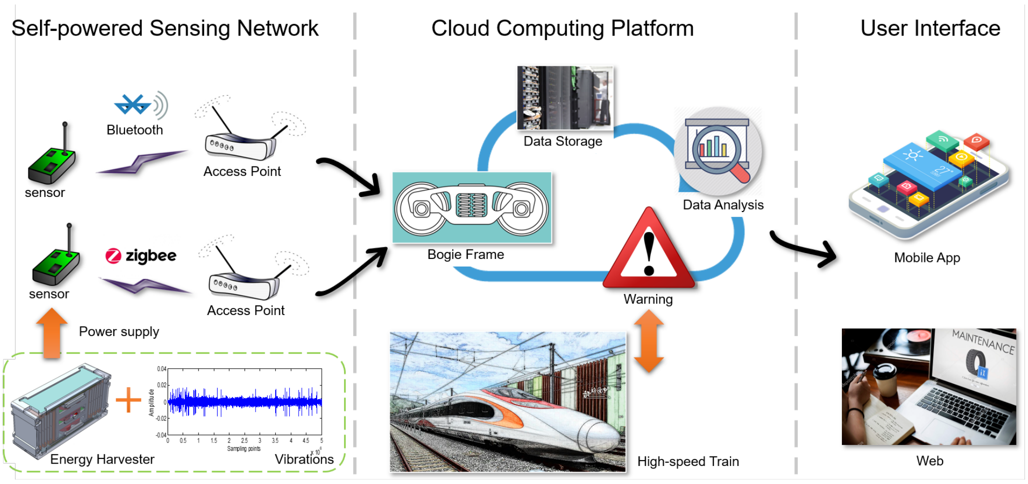
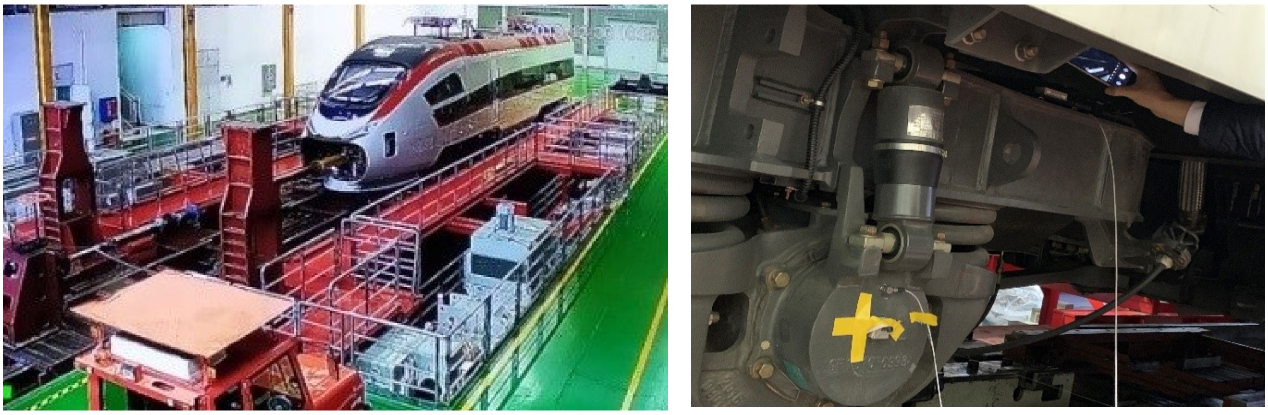


Figure 1: A vibration-based self-powered monitoring system for high-speed trains.

2.1. Vibration Characteristics of Train

In normal train operations, a critical problem encountered by the welded components of bogies is under fluctuating cyclic load effects. Generally, mechanical stresses and vigorous vibrations are the major reasons for progressive and localized structural fatigue to cause damage cracks of the welded components. Using an on-board monitoring system, data (e.g., stress, displacement and noise) measured from self-powered sensors can be directly transmitted through a wireless network to a computer sever for data analysis. To develop an efficient energy harvesting technique for a self-powered monitoring system, an important step is to investigate the vibration dynamic responses of high-speed trains. In this connection, a full-scale rolling-vibration test was conducted in a national train laboratory, which can help understand the dynamic behavior of bogie frames under various speeds and excitations (see Figure 2). A tri-axial accelerometer (Slam Stick Model: LOG-0002-025G) was deployed on a bogie frame to measure three directions (i.e., x-axis = operation direction of the bogie; y-axis = lateral direction of the bogie; and z-axis = vertical direction of the bogie) under various train speeds and excitation forces. The measured acceleration signals were stored in a data logger with a sampling rate of 5000 Hz for data analysis. In this vibration test, the train speeds and excitation forces (exerting on the train wheels) are presented in Table 1. Both hunting and vertical motion excitations were exerted on the wheels to model the real scenarios of wheel-rail interaction. The vibration results are presented in Section 3 below.



(a) (b)

Figure 2: (a) Rolling-vibration test of a full-scale train carriage; and (b) Installation of a tri-axial accelerometer on bogie for vibration test.

Table 1: Train rolling-vibration test (60 minutes).

Time (min.)	Train speed (km/h)	Excitation force on wheelset
0–16	15	-
16–17	50	-
21–25	100	-
26–29	150	-
29–33	230	Hunting excitation
33–35	280	-
36–38	300	-
38–40	Decelerated to 120	-
40–42	120	Vertical excitation
44–46	180	-
46–47	180	Vertical excitation
47–48	200	-
48–49	200	Vertical excitation
49–50	220	-
50–52	220	Vertical excitation
52–52.5	230	-
52.5–53.5	230	Vertical excitation
53.5–55.5	250	-
55.5–56.5	250	Vertical excitation
56.5–60	Decelerated to stationary	-

2.2. Energy Harvesting Technique

As aforementioned, to realize a self-powered and real-time monitoring system, the essential element is an energy harvesting device. Several solutions have been proposed to improve the performance of vibratory energy harvesters when it is subjected to a wideband vibration with low frequencies, including generator array [24], nonlinear spring stiffness [25], magnetic coupling [26], and mechanical impact [27]. To further advance the mechanical design of vibration-based energy harvesting techniques under the low-frequency and wideband conditions, a novel ultra-low-frequency multi-stable tri-hybrid energy harvester has been recently proposed [21].

As shown in Figure 3, integrating a fan-folded piezoelectric generator (PEG), an array-type electromagnetic generator (EMG) and a sliding-mode triboelectric generator (TENG) can be transformed into an interactive prototype. Hybridizing multiple transduction mechanisms into one package is a superior solution that can generate more electrical energy from a single mechanical movement. This energy harvester was developed in accordance with a "*multi-stable frequency up-conversion*" approach, which can work well under low-frequency excitation sources. Referring to Figure 3(b), the tri-hybrid prototype is light, small and compact. The total volume and weight of the prototype are 5.28×2.54×1.73 cm^3 and 85.7 g, respectively. This ingenious cube design possesses a high level of flexibility as a built-in core component on bogie frames subjected to low-frequency, random and time-varying sources. Under a electrodynamic shaker test, the device can generate a maximum output power of about 86 mW, i.e., the normalized power density of 3.7 mW cm^{-3} g^{-2} at 3 Hz under 1 g. The working principle, electronic circuit management and performance efficiency of this new energy harvester have been comprehensively reported and discussed in Ref. [21], readers may refer to this work for details. In the next section, the applicability of this tri-hybrid device on a high-speed train will be evaluated and discussed.

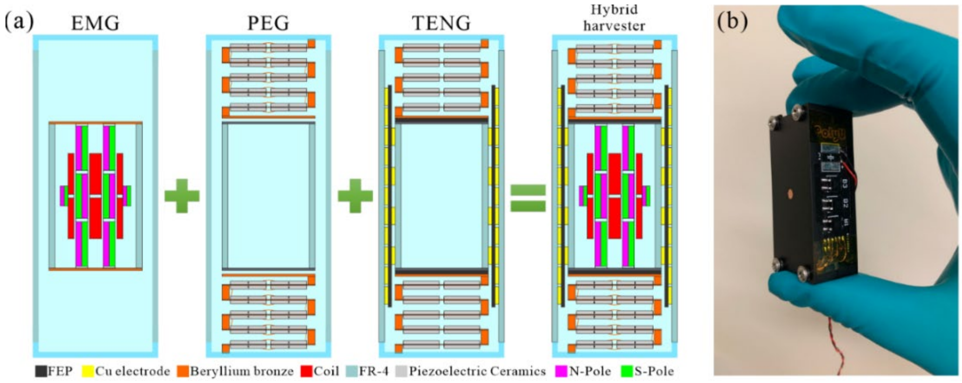


Figure 3: Schematic design and prototype of the tri-hybrid energy harvester [21].

3. RESULTS AND DISCUSSION

To evaluate the applicability of vibration-based energy harvesting techniques on high-speed trains, a 60-minute laboratory test on a train bogie was conducted. Figure 4 shows the time-history responses of a train bogie in accordance with the rolling-vibration test schedule stated in Table 1. In the figure, the vibration amplitude increased to 2g as the train speed accelerated to above 200 km/h. As the normal operation speed of high-speed trains is over 200 km/h, we mainly focus on the dynamic characteristics of the train speed over 200 km/h. In the vibration test, both hunting and vertical excitations were exerted on the train wheels to model real-case scenarios.

To explore the frequency-amplitude relationships, a FFT analysis was applied to extract the information of time-domain responses to understand the dynamic behavior of tri-axial directions (x, y and z) on the train bogie. Under a hunting excitation and a train speed of 230 km/h (29–33 mins in Table 1), the frequency-amplitude responses are presented in Figure 5(a). In this case, the main frequency range is at 15–25 Hz in the three directions. When the train speed accelerated to 280 km/hr without excitation (33–35 mins in Table 1), the frequency-amplitude responses are mainly at 25 Hz (Figure 5b). Under a vertical excitation effect (e.g., wheel polygonization, rail corrugation or irregularities [28–30]), the main frequency range of the train bogie (at 180 km/h and 200 km/h, 46–49 mins in Table 1) shifted to the low-frequency range of 3.5–15 Hz, see Figures 5(c) and 5(d). In reality, vibration strengths of the bogies are much larger under the real-life environment conditions.

The working efficiency of many multi-degree-of-freedom vibration-based energy harvesters to harness sufficient energy under a low-frequency range (<10 Hz) has long been a bottleneck, because they are confined in mono-stable and bi-stable nonlinear mechanisms, which either lead to valleys between successive peaks in the voltage response or require much higher intensity excitations to induce large-amplitude inter-well oscillations. To address this technical issue, this study proposed a tri-hybrid multi-stable energy harvester with a high power density to achieve sustained and uniform power output over a wider range of frequencies under low excitation levels, i.e., 1–11 Hz and 0.5–1.5 g. The present device has the potential as a power source for supporting a self-powered monitoring system on trains, since it can scavenge energy from low-frequency as well as low-acceleration ambient vibration sources. Based on the normalized power density of 3.7 mW cm^{-3} g^{-2} (stated in Section 2.2), for estimation, the device (per 1 cm^{-3}) can at least operate a sensing network of 400 mW for 17 s within a 30-min period, ignoring the energy loss of storage process.

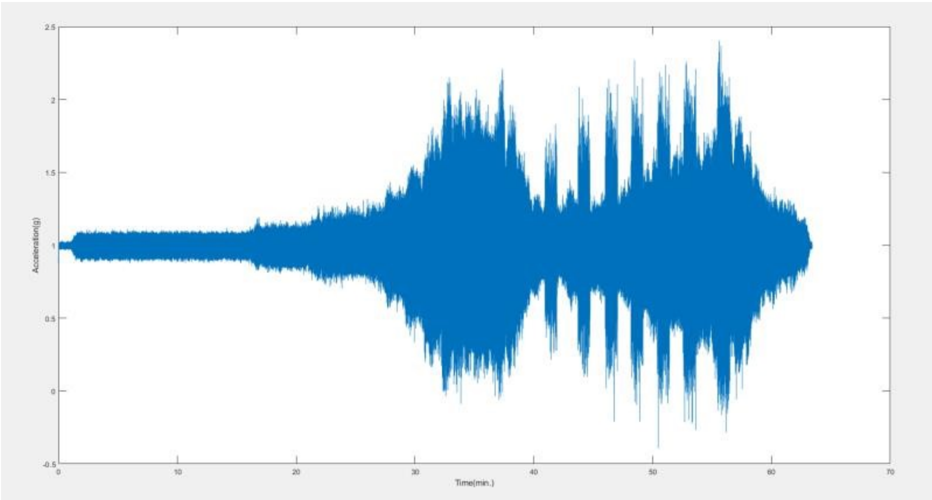
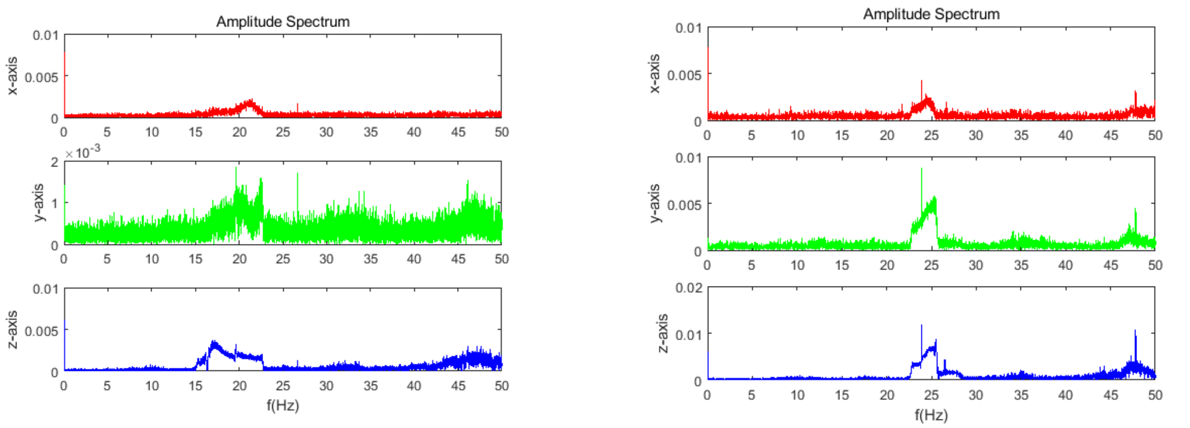
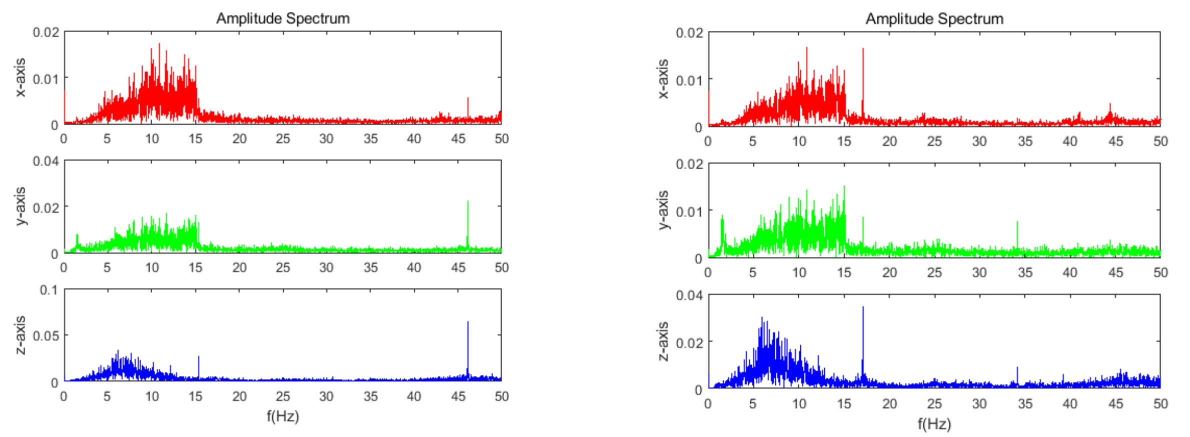


Figure 4: Time-history responses of the full-scale rolling-vibration test.



(a) Train speed at 230 km/h under hunting excitation

(b) Train speed at 280 km/h without excitation



(c) Train speed at 180 km/h under vertical excitation (d) Train speed at 200 km/h under vertical excitation

Figure 5: Results of the full-scale rolling-vibration test under various conditions (the unit of vibration amplitudes in the x, y and z directions is g^2/Hz).

4. CONCLUSIONS

To provide an applicable way for power supply of wireless sensors deployed on an in-service high-speed train, a low-frequency and broadband energy harvesting system should be designed. It is because the operating bandwidth of a high-speed train contains multiple dominant frequency regions. The work presented herein aims to evaluate the frequency ranges and vibration amplitudes of a high-speed train. The full-scale rolling-vibration test results showed that the dynamic behavior of the bogie is at 3.5–15 Hz under vertical excitations. A recently proposed hybrid-type energy harvester can cover this frequency range. It is able to harness energy from low-amplitude (0.5–1.5 g) and low-frequency (1–11 Hz) vibration sources, thereby facilitating the advancement of a self-powered wireless sensing system on trains. The energy conversion efficiency of the proposed energy harvester will be examined by an on-board testing study in the next stage. Besides, the application of a self-powered real-time monitoring system on trains, using IoT/cloud computing platforms as a whole system, will also be explored, e.g., how to pair the energy harvester with noise/vibration sensors and wireless data connections.

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