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Efficient electromagnetic energy harvester for railroad transportation☆

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ABSTRACT

An electromagnetic energy harvester is designed to produce electricity from rail track deflections induced by passing trains. Whereas typical existing vibration energy harvester technologies are built for low power applications of milliwatts range, the proposed harvester will be designed for higher power applications for major track-side equipment such as warning signals, wireless communications, track switches, track health monitoring systems, etc., which typically require a power supply ranging between several watts (continuous) to thousand watts (with intermittent duty cycle). Facing the challenge of large pulse vibrations on the track when trains pass by, a mechanical motion rectifier (MMR) with single shaft design is introduced to streamline the motion and force transmissions, by transforming bidirectional pulse vibrations into the unidirectional rotation at relatively steady speed. Bench tests indicate that 10–100 W of energy harvesting capability from train induced vibration and up to 74% efficiency. Simulations also indicate that the MMR mechanism can significantly increase the power output over the traditional harvesters while substantially reducing the average force amplitude under the same displacement input.

1. Introduction

Rail transportation systems, including subways, commuter rails, freight trains and inter-state passenger rails play a substantial role in people's daily life and are also essential to an economy. Track-side electrical equipment (warning/signal lights, track switches, grade crossings, track-health monitoring systems, wireless communication networks, positive train control systems, hot boxes etc.) has become necessary to ensure the safe operation of modern railroad systems. It is very important to have safe and reliable power supplies for these electrical devices as they help railway operators make informed decisions to keep quality service and reduce unnecessary maintenance, and ensure the safety of nearby passengers or cars crossing railroad cross-sections.

Unfortunately, railroad tracks passing through remote areas or certain underground tunnels often have limited, or no access to electrical power. [1–3]. According to the U.S. Federal Railroad Administration, 60,915 out of 129,469 (47.1%) public highway-rail crossings are still only equipped with passive warning signs making them a safety hazard [4]. To address these potentially dangerous issues, it is worthwhile to work towards a convenient, reliable, efficient, and cost-effective power supply solution for track-side devices.

When a train passes over a section of track, the track deflects vertically due to the load exerted by the train car. The normal load exerted by typical freight trains ranges from 9 to 14 tons-force (20–30 kips) [5–7]. Overall, when a train passes through at a speed of 64 km/h (40 mph), the amplitude of track vibration is in the range of 1–12 mm depending on track structure and vehicle weight. The frequency of track vibration is in the range of 1–4 Hz depending on the separation between bogies and train speed [7–8]. This vibration of the track provides a large amount of energy that can potentially be harvested, and utilized to power track-side devices.

Even though piezoelectric, inductive voice coil, tuned mass, and linear electromagnetic energy harvesting solutions are viable, they are focused on low-power sensor applications. Several groups have developed such harvesters with milli-Watt or sub-Watt capability [9–12]. Notably, Pourghodrat et al. investigated railroad energy harvesting extensively and developed several electromagnetic harvesters which were tested under lab and in-field conditions [13]. In comparison to piezoelectric and tuned mass harvesters, motion driven electromagnetic harvesters seem to yield much larger energy potential. However, the large impact forces caused by the irregular pulse vibration excitation [10, 14–15] remain a challenge to researchers.

The conventional direct-motion-driven electromagnetic vibration

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energy harvester is composed of several stages of mechanical components [16]. The problems in such harvester are typically low energy conversion efficiency and limited output power. Mentioned in Nelson's work [10], the reasons for such problems are: 1. Oscillating/irregular/pulse-like input vibration from train track results in large impact forces on the energy conversion components; 2. Erratic and low generator rotational speed when switching between two opposite direction results in low energy conversion efficiency, irregular output power, and fast component fatigue and wear.

To overcome these problems, Zuo et al. and Penamalli (2011) (2011) [17, 18, 13, 19], developed motion mechanisms with rack pinion and one-way clutches in electromagnetic railway track energy harvesters. Like electrical rectifier converts AC voltage into DC, the mechanisms regulate the bidirectional track vibration into a unidirectional rotation, which can potentially improve the energy harvesting capacity. Device reliability and life span can also be improved by reducing the impact forces when the track motion changes directions [17, 18]. Penamalli and co-workers [18, 14] designed the MMR based energy harvester for railroad application, provided the working principle, and tested it for railroad application. Lab test illustrated up to 1.4 W average power harvested with mechanical efficiency ranging 10–25%. The low efficiency was due to the complicated design of the MMR mechanisms, which involves many gear motion transmissions and misalignments in the multiple shafts and bearings. Pourghodrat et al. [13, 19] presented the feasibility study of several types of energy harvesting device for railroad application. In field testing, an average power of 0.22 W was harvested under loaded train traveling at 18.5 km/h (11.5 mph).

In this paper, we propose a new harvester design with single shaft and flywheel to achieve the full function of MMR with simplified components to approach high mechanical transmission efficiency, high power output, and smaller average force amplitude. We will report the detail design and working principle of motion rectification, and experimentally study under the influences of vibration amplitude, frequency, and electrical load to the energy harvesting efficiency and power output. Through bench tests, modeling, and simulation, we will demonstrate MMR based harvester can significantly increase the power output and reduce average force amplitudes over the traditional energy harvesters, especially under the recorded pulse vibrations of the rail track.

This paper is organized as follows: In Section 2, the characteristics of railway track vibration and trackside electrical infrastructures are introduced. Section 3 presents the working principle and design of the proposed harvester. In Section 4, experiment results based on a full-scale prototype are presented and discussed. Section 5 presents the modeling and simulation of the MMR based harvester. Section 6 gives concluding remarks.

2. Vibration input and harvesting potential

2.1. Characteristics of track vibrations

When a train moves over a section of track, the track deflects vertically. The induced displacement of track varies in: frequency and magnitude depending on the speed of the train, weight of the train car, track substructure, components properties, and even varies due to maintenance history of the track [7, 9].

Fig. 1 illustrates that track vibration occurs in intermittent pulses with each passing wheel. The track deflection amounts and patterns are almost independent with the train speed. The track deflection vibration frequency is proportional to the train speed. The peak velocity of deflections can be 10 cm/s or even higher for a typical freight trains moving at a velocity of 64 km/h (40 mph) [7].

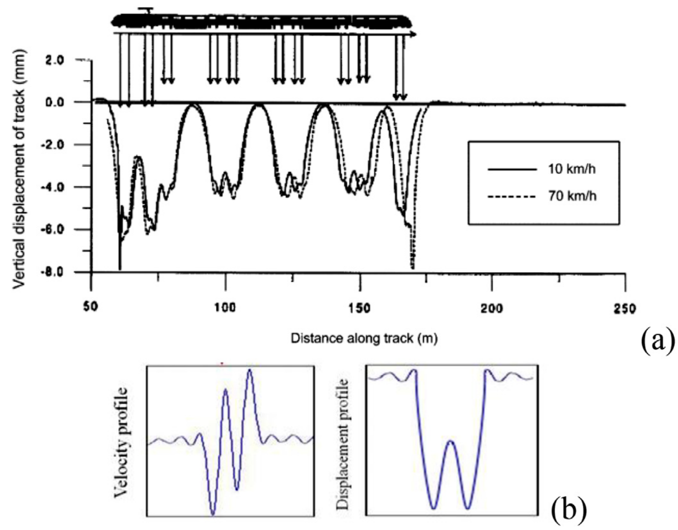

Fig. 1. Vibration profiles of railroad tracks. [18, 20] (a) Track deflection illustration (b) Velocity and displacement profile in time domain.

2.2. Estimation of available energy

Despite the fact that the track displaces with a small amplitude, the energy that is potentially available is quite large due to the high tonnage of the train load. The average power available for a typical track site can be estimated as follows:

$$P_{avg} = \frac{2F\delta}{\Delta T} \tag{1}$$

where F is the normal force exerted by a wheel on the track, δ is the total up and down vertical displacement of the track, and ΔT is the duration of the force action. The factor of *2* comes from the fact that power is available from both upward and downward motion.

Since track vibration conditions are highly dependent on its structure and services provided, the median of major track vibration parameters are selected for this investigation: the normal force is 89 ~ 133 kN (9 to 14 tons-force) [5–7], and the total displacement of the track is expected to be between 1 mm and 12 mm at a frequency of 1 to 4 Hz [7]. For instance, a train that is 160 m (525 ft) long moving at a speed of 40 km/h can provide a total energy of 400 W to 5 kW. If a small fraction of such energy is converted into electricity without affecting the track's dynamic properties, one may obtain 10–100 W power during train passing time.

2.3. Energy budget and management

The harvester only produces electricity while a train passes by. It is important to assess the total energy demand and manage the harvester energy properly. Table 1 lists some common trackside equipment and

Table 1
Power requirements of trackside equipment.

Trackside accessories/duty cycle	Power requirements	Function mode
Track switch	1000–1500 W*	15–30 s
Lights/signal (LED)	3–25 W	Continuous
Wireless communication	3–7 W	During train pass
Relays	5–20 W	Various
Axle counter	100–150 W	During train pass
Grade crossing	150–200 W*	5–10 s
Hot box/wheel detection	5–30 W	During train pass
Lubrication station	20–200 W	During train pass

Note: Data is gathered from commercial railroad products. [21–22].
* Power requirements indicate devices' operation power rating.