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Modeling and field testing of an electromagnetic energy harvester for rail tracks with anchorless mounting

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HIGHLIGHTS

- Anchorless mounting design simplifies the installation and preparation requirement.
- Dynamic model developed for parameter determination and performance prediction.
- Conducted lab tests to evaluate the characteristics of harvester system.
- Field tests completed in the high tonnage test loop under the real condition.

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ABSTRACT

This paper presents the design, modeling, lab test and field demonstration of a railroad energy harvester featuring rapid anchorless mounting. By harvesting energy from rail track deflections, the proposed system can be used as an alternative energy source along the trackside of railroads. Compared to the widely electrified passenger rails, most freight rails are still lack of cost-effective access of electricity because of the long haul and remoteness of the geographic location. This paper aims to address two challenges: increase power capacity and ease of installation. A spring preload and reset mechanism is used to eliminate the need of anchoring the harvester into the railroad foundation, allowing the harvester to be installed rapidly without affecting the track substructures. A dynamic model including the AC generator, the mechanical motion rectifier, and the spring preload is created and the design parameters are obtained from numerical simulations. Lab and in-field tests are carried out to verify the model and simulation. In-field test results show 7 W (average)-56 W (peak) electrical power are generated with a freight train traveling at 64 km/h (40 mph) under 5.7 mm deflections. The proposed harvester has the potential to support many track-side electrical devices and serves as an alternative energy source to enhance rail operational safety.

1. Introduction

Riding along industrial developments, railroad carries people's life and dream. Nowadays, it is vital to keep rail networks operating safely, efficiently and punctually. To achieve such goals, track-side electrical devices are essential, such as warning and signal lights, track switches, grade crossing signals, track-health monitoring systems, wireless communication devices, positive train control systems, and hot boxes. However, many freight trains pull long hauls in remote areas with poor accessibility to electricity from the national grid, or it may require too much economic efforts. The need of an alternative track-side power supply is urgent: by harnessing energy from train-induced track vibration, trackside devices can be enabled anywhere along the tracks.

As a train moving along, rail track deflects vertically due to the dynamic force excitation from moving wheelsets. Train induced track vibration varies in amplitude and frequency depending on rail types, railroad ties (sleepers), track foundations, train loads and velocities, and separation between wheelsets. The amplitude of the track vibration varies from 1 to 12 mm, while the frequency ranges from 1 Hz to 4 Hz [1–6]. The harvestable mechanical energy contained in track vibration can be in the range of hundred to kilowatts, an insignificant portion of which can be utilized to power many trackside electrical devices [7].

Known for its broad geographic coverage and vast energy potential, railroad energy harvesting started to attract researchers' attention. Many existing energy harvesting technologies, like piezoelectric, inductive voice coil, tuned mass and rotational electromagnetic

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harvesters have been studied. Researchers have applied these technologies for wireless sensing and other low-power consumption applications for railroad. For example, Gatti et al. conducted a fundamental study to determine how much energy could be harvested from a passing train with a tuned mass linear harvester [8]. Mian proposed an electromagnetic coil harvester that induce induction currents from changing magnet field strength when ferrous wheels are passing [9]. Gao et al. performed a feasibility study of rail-borne energy harvesting and concluded electromagnetic transducer is more suitable to the low-frequency of rail vibration [10]. Lallart et al. and Brennan et al. specifically looked into energy harvesting techniques under time-limited harmonic vibrations, where harvester performance may be dominated by transients [11,12]. In the past decade, the piezoelectric type harvesters are studied extensively due to its high energy density [13–17]. At the milli-watt or sub-watt power level, these technologies are suitable for low-power consumption applications for the railroads, such as wireless sensing and communication.

Committed to converting more energy from track vibration, several groups have studied the direct-motion-driven harvester to harness electricity in watts level. Zuo and Penamalli, et al. [18,19], and Pourghodrat and Nelson, et al. [20,21] developed more elaborate electromagnetic railway track harvesters featuring motion mechanisms that utilize rack-and-pinion and one-way clutches to rectify bidirectional track vibrations into the unidirectional rotation and directly drive an electromagnetic generator. In the previous investigation [7], a single-shaft mechanical motion rectifier (MMR) electromagnetic energy harvester has been developed and demonstrated up to 71% mechanical efficiency and up to 50 W average power output during the bench tests. It is also worth noting that, Pourghodrat et al. [19] conducted a field test, with a loaded freight train passing at 18.5 km/h (11.5 mph) on a local track, the prototype produced 0.22 W with a measured track displacement of 12.7 mm (0.5 in.). Later, Zhang et al. [22,23] developed a harvester with a similar mechanical vibration rectifier mechanism, which achieved 55.5% efficiency and 58 V output under sinusoidal input.

Among the technologies, motion-driven harvesters reveal higher power potential but require a stationary anchor support for the motion conversion mechanism to function properly. However, construction of any traditional anchor in existing railroad networks is impractical due to the potential risk of jeopardizing the integrity and safety of track ballast structure. It also takes days for the anchoring cement to cure, which will cause interruption to the transportation operation. To address such problems, an anchorless mounting design for the harvester is proposed in this study.

The contributions of the paper are summarized as follows. (1) An anchorless mounting design is proposed and integrated to the harvester to reduce the installation difficulty and time and to simplify preparation requirement. (2) The dynamic model of the harvester is developed for system parameter determination and performance prediction. (3) Lab tests are conducted to evaluate the characteristics of vibration damping and harvesting power capacity. (4) Field tests are carried out in the high tonnage train test loop. The installation and functionality of the anchorless mounting design are validated and evaluated under the real condition of a freight train.

The rest of the paper is organized as follows. In Section 2, the proposed anchorless energy harvester design is introduced and explained. Section 3 describes the dynamic modeling and simulation. In Section 4, lab tests are presented. Section 5 reports the field test setup and results. The paper is concluded in Section 6.

2. Design of the energy harvester

Fig. 1 illustrates the overall energy harvester system that includes the anchorless mounting, MMR mechanism, a gearbox, and an electrical generator. The harvester body is fixed on the rail ties (sleepers), the base plate rests on the ballast (30–45 cm (12–18″) deep). Furthermore, the springs give a preload between the harvester and the base plate.

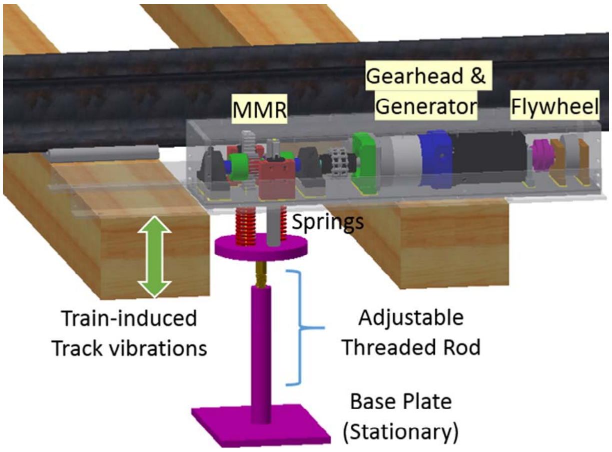

Fig. 1. Overview of the developed anchorless energy harvester.

The anchorless mounting design is developed to simplify the installation and avoid any potential risk of physical anchor in altering the track foundation. During initial setup, the adjustable rod is set to pre-compress the springs to secure the base plate to the supporting foundation. As the harvester moves with sleepers, the base plate shall remain stationary to maximize the relative motion transmitted to the input rack-pinion of MMR.

Fig. 2 illustrates how the single-shaft MMR design converts up-and-down bidirectional motion into unidirectional rotation. A pair of oppositely facing racks drives two pinions to rotate in the opposite direction. The one-way clutches are paired in a way that one one-way clutch only allows motion transmission to the generator shaft when the racks are moving up whereas the other does the opposite. The gearhead and generator always rotate in the same direction. In the diagram, the blue arrows indicate the pinions rotation direction when racks move into the page and the right-hand side clutch engages. When the racks move out of the page and the left-hand side clutch engages, pinions rotate in the direction indicated by red arrows. In this regard, the bidirectional (up-and-down) rack motion is rectified into a unidirectional rotation.

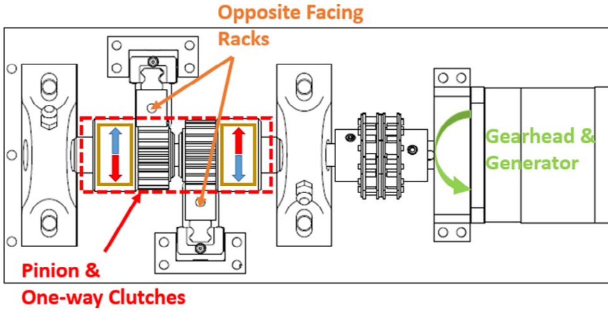

Fig. 2. Illustration of mechanical motion rectifier (MMR) mechanism.

In consideration of railroad operation safety, the overall height of harvester is limited to avoid interference with a running train; sandwich type fixtures are designed to secure the harvester on the sleeper to avoid any damages. In addition, the enclosures are designed with water resistant features to be weather proof.

3. Dynamic model and simulation

As a wheelset approaches, the track's downward deflection drives the harvester towards the base plate and compresses the springs; as the