University Transportation Research Center - Region 2

Final Report

Energy Harvesting from Rail Track for Transportation Safety and Monitoring

Performing Organization: Stony Brook, State University of New York

February 2014

Sponsor:
University Transportation Research Center - Region 2

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16. Abstract

An efficient electromagnetic energy harvester featured with mechanical motion rectifier (MMR) is designed to recover energy from the vibration-like railroad track deflections induced by passing trains. Comparing to typical existing vibration energy harvester technologies can only harvest sub-watts or milliwatts power applications, the proposed harvester is designed to power major track-side accessories and possibly make railroad independent from national grid. Trackside electrical infrastructures for safety and monitoring typically require a power supply of 10-100 Watts, such as warning signals, switches, and health monitoring systems. To achieve such a goal we implement the MMR, a patented motion conversion mechanism which transforms pulse-like bidirectional linear vibration into unidirectional rotational motion at a high efficiency. The single-shaft MMR design further improved our previously developed motion mechanism, increased energy harvester efficiency and expanded power harvesting potential. Major advantages of implementing MMR include bidirectional to unidirectional motion conversion and flywheel speed regulation. The proposed new design improved reliability, efficiency, and provided steadier power output. Bench test of the harvester prototype illustrate the advantages of the MMR based harvester, including up to 71% mechanical efficiency and 50W power output.

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Energy Harvesting from Rail Track for Transportation Safety and Monitoring

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Abstract— **An efficient electromagnetic energy harvester featured with mechanical motion rectifier (MMR) is designed to recover energy from the vibration-like railroad track deflections induced by passing trains. Trackside electrical infrastructures for safety and monitoring typically require a power supply of 10-100 Watts, such as warning signals, switches, and health monitoring systems, while typical existing vibration energy harvester technologies can only harvest sub-watts or milliwatts power. The proposed harvester is designed to power major track-side accessories and possibly make railroad independent from national grid. To achieve such a goal we implement the MMR, a patented motion conversion mechanism which transforms pulse-like bidirectional linear vibration into unidirectional rotational motion at a high efficiency. The single-shaft MMR design further improved our previously developed motion mechanism, increased energy harvester efficiency and expanded power harvesting potential. The proposed new design improved reliability, efficiency, and provided steadier power output. Bench test of the harvester prototype illustrated the advantages of the MMR based harvester, including up to 71% mechanical efficiency and large power output.**

Keywords- railway; railroad; vibration energy harvesting; energy recovery; mechanical motion rectifier; electromagnetic

I. INTRODUCTION

Rail transportation systems, including freight train, commuter rail and subways, play an important role in people's daily life and also provide substantial supports for the economy. Track-side electric infrastructures are essential for the operation of modern railroad systems. To make informed decisions and provide safe quality service, railroad systems rely on track-side electric infrastructures. Warning and signal lights, track switches, grade crossing signals, track-health monitoring systems, wireless communication access points, positive train control systems, and etc. reliable and low-maintenance power supplies are essential prerequisites.

Unfortunately, railroad tracks often exist in remote areas or certain underground regions in which there is little electrical infrastructure. In these regions, installment of equipment such as warning signal lights, wireless sensors for railway track monitoring, bridge monitoring, and train positioning [1,2,3] have limited practical deployment due to the lack of a reliable power supply or low-maintenance battery[4]. Some regions still only use railroad crossing signs at grade crossings and do not implement flashing lights, moving gates, or whistles [5]. In response to the growing need for electronically powered trackside devices, it is worthwhile to design a cost-effective and reliable power supply solution for track-side devices.

When a moving train passes over the track, the track deflects vertically responding to the load exerted by the train's bogies. The majority of currently existing railway energy harvesting technologies utilizes the peak-valley nature of the motion and focusing on piezoelectric and electromagnetic harvesters. Many of these technologies harvest energy in the milliwatt or subwatt range, largely for wireless sensor applications. The technologies include: tuned vibrational harvesters by a British company Perpetuum Ltd [7], coils th at induce induction currents through passing wheels developed by Zahid F. Mian[8], and basic piezoelectric and electromagnetic solutions as studied by Nelson et al [9][10]. At the time, Nelson et al [11] also looked into motion driven electromagnetic harvesters. Their first prototype produced 0.22 Watts in field test results for a loaded train passing at 11.5 mph.

If the oscillating vertical motion of the track can be directly used to engage and drive a mechanical energy harvester, the power potential is enormous. The regeneration of power can be stored and used by trackside accessories. However, there are various challenges. Firstly, track only oscillates in small displacement in comparison to the amount of power consumed by track-side equipment [6]. Moreover, another major issues prevalent in harvesting energy from railroad tracks were usually the irregular pulse-like nature of railroad track vibrations and low amplitude of displacement of the railroad track [6,11]. Motion driven electromagnetic harvester seemed to have the most promise in dealing with these issues because motion amplification or rectifiers can be designed to directly deal with these issues. Otherwise, one would rely heavily on electric signal processing and rectification [6].

Although simple induction, piezoelectric, and tuned mass energy solutions are viable and effective for low-power sensor applications, the focus of our studies aims toward efficiently harvesting a larger amount of power from the rail. We intend to power the track side equipment which has power ratings of up to 100 Watts, including safety light, warning devices, and possibly even switching devices and crossing gates if combined with power storage systems. To accomplish this goal, a motion driven electromagnetic based harvester would be more appropriate.

The conventional direct-motion-driven electromagnetic vibration energy harvesting system is typically composed of: an element for mechanical input motion conversion (rack and pinion, ball screw, or hydraulic piston), a motion magnification element (gears, levers, hydraulics, etc.), an electromagnetic generator, electrical rectifier, power regulator, and energy storage element [12-17]. These designs may be extended for railroad harvesting applications, but simple retrofit of these energy harvesting technologies however will result in low efficiency energy conversion and poor output quality due to the pulse-like nature and low amplitude of displacement of the track. The simple rack and pinion harvester Nelson et al created illustrated these issues [11]. When dealing with irregular pulse-like inputs, an electromagnetic generator will be driven at an erratic range of speeds resulting in less efficient operation and power output of low quality. An oscillating input such as from the train track can also introduce large impact forces within the device when the track switches direction of motion, which contributes to component fatigue and wear.

Recently to address these issues of the conventional harvester Penamalli [18] (2011), Zuo et al (2011) [19], Pourghodrat et al [20] (2011), and Phillips along with Nelson [21] (2011), and have developed more elaborate electromagnetic railway track harvesters featuring mechanisms for mechanical motion conversion. Notably these harvesters, which were also rack and pinion based, were designed to convert bidirectional linear motion into unidirectional rotational motion, through specific placement of unidirectional roller clutches. The bidirectional to unidirectional motion conversion feature improves the power harvested by the device by harnessing both upward and downward motions. Device reliability and lifetime also improves by eliminating the number of components which switches directions with the track motion [6].

In previous investigations, the authors [6] developed a motion conversion based energy harvester, consisting of a bidirectional to unidirectional motion conversion mechanism and a flywheel. The flywheel helped address the issue of having a pulse-like input. It allowed the electromagnetic generator to operate over a more consistent range of speeds. This improves generator operating efficiency and also eliminates pulse-like characteristics in the power output. By stabilizing the power output, conversion of electrical output power becomes a more efficient process. Maintenance of generator and component speeds furthermore helps improve harvester component lifetime by reducing the cyclic loading of pulse-like forces. In this investigation, a prototype was developed that harvested up to 1.4 Watts with 10-25% mechanical efficiency. Simulations were conducted using 1Hz frequency at 3mm displacement.

Recent motion conversion based devices suffer from similar issues of low mechanical efficiency, and simulation results which do show the capacity to harvest enough power for trackside equipment requiring above 10 Watts power [6, 18-20]. Some of the mechanical efficiency issues as discussed by Wang et al [6] were likely due to frictional losses in large diameter bearings, meshing gears, and misaligned shaft components. To address such power and efficiency issues, the proposed new mechanical motion rectifier (MMR) based harvester was developed in this paper. The main issue addressed by the developed harvester was the low efficiency of motion conversion mechanisms. Other improvements such as increasing the harvestable power of the device, increasing device reliability, and further optimizing the MMR design have all been linked in some ways to improving the efficiency of the device.

In the currently proposed rectifier design, the harvester is simplified into a single shaft system. The number of gear engagements used for conversion of bidirectional motion has been reduced. Efficient smaller diameter bearings have also been selected at the flywheel shaft. As a result, frictional losses have been greatly reduced. Misalignment of shaft components has also been made less of a practical issue.

This paper is organized as follows: In section 2, the characteristics of railway track vibration are discussed briefly. In section 3, the overview of the power requirements of trackside accessories are presented. In section 4, the proposed energy harvester design is introduced and explained. In section 5, simulation experiments done on a full scale prototype and these results are presented and discussed. In section 6, concluding remarks.

II. Railway Track Vibration Characteristics

A. Properties Relevant for Harvester Input

Energy harvester design is based upon information drawn from train and railroad dynamics. When the loaded train is moving over the track, the track will displace vertically as shown in Figure 1 below [22].

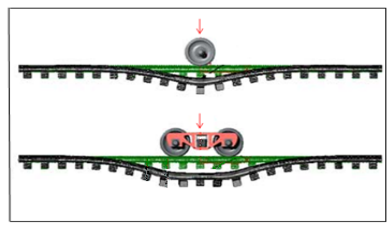

Fig 1. Vertical deflection of the railroad track [22]

The velocity, frequency, and magnitude of displacement will depend on: the load exerted by the train, speed at which trains are moving, track substructure (ballast composition, underground soil) properties, nature of service of the train, and maintenance history of a track. Larger track displacements also occur due to plastic deformation of the ballast material, which is referred to as ballast settlement [6].

The normal load exerted by the freight train wheels on the track is 20 to 30 kips [23, 24, 25]. Average track displacements range from 7mm to 12mm [22, 26-30]. Track displacements go as high as 25mm, which has been recorded for regions servicing trains of over 300 kips weight [23]. Usually freight trains have different cart lengths so the distance between bogies is not uniform. For a train moving at 40 mph, track vibration frequencies can fall between 1.6 Hz to 4Hz, depending on the distance between bogies and the distance separating wheel pairs of a bogie [6].

Figure 2 shows that track vibration is like discontinuous pulses occurring with each passing wheel [24]. The peak speed of track deflection mainly depends on the velocity of the train. Peak track speeds can be of values of 10 cm/s or higher for trains moving at an average velocity of 40mph [19]. Track deflections are often even larger at grade crossings due to sudden changes in track structure and stiffness at these installments.

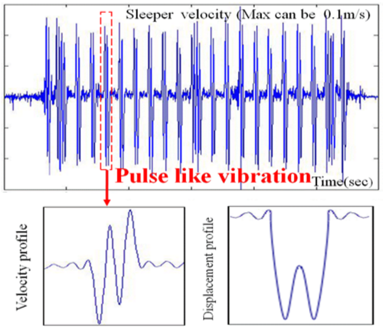

Fig 2. Pulse-like vibration profiles of railroad tracks [18][24]

B. *Estimation of Available Energy*

The normal force used is between 89 to 133 kN, the total distance moved by the track is estimated to be between 20 mm and 28 mm. For a train with160m length between bogies moving at a speed of 40km/hr, an average available power of 3kw to 5kw can be harvested from railroad track deflections. Considering the goal to power equipment with up to 100 Watts rating, we only use less than 3% of the available power of the track.

III. Harvester Power Expectations

The proposed harvester is designed to power major track-side accessories and possibly make railroad independent from national grid. Track operation equipment typically require a power supply of 10-100 Watts, such as warning signals, switches, and health monitoring systems. In this chapter, an overview of the power requirements of trackside equipment is given.

Table 1. Power Requirements of Trackside equipment

Trackside Accessories	Track Switch (A)	Lights/Signal (LED) (B)	Wireless Communication Systems (C)	Relays (D)	Axle Counter	Grade Crossing
Power Requirements	1000-1500W	3-25W	3-7W	5-20W	100-150W	150-200W
Function Mode	15-30 sec	Continuous	During train pass	Various	During train pass	5-10 sec X 2

As shown in Table 1 above, a list of trackside equipment is listed along with their power requirement. While some of them need to be powered continuously and others only need power intermittently. Overall, there is sufficient energy available in the track if a 100 Watt energy harvester is to be designed.

A. *Track Switching Devices*

Alstom distributes a railroad switching product operating at 85-140 VAC, 16-160 VDC voltage at 25 Amps peak current, requiring an average of 1000-1500 Watts to operate. [31]

B. *Color Light Signals*

Color light signals require 3 - 25 Watts, operating typically at 10 VDC. These products include highway light signals, color light signals, incandescent and LED lights. Safety lights used at grade crossings can require as low as 3 Watts to power, but also as high as 100 Watts for certain incandescent or beam lamps. These are shown in figure6 [31]

C. *Long Range Wireless Communication Systems*

Alstom wireless communication systems send and receive data through microwave data systems. It requires 7 Watts to transmit and 2.8 Watts to receive data.[31]

D. *Relays*

Relays are vital components used to control electronic trackside components. They can detect lamp failures, synchronize trackside equipment operations, control lights at vital regions, store and release energy. The power specifications vary upon application, as relays can utilize power of 5 Watts or lower and up to 20 Watts or higher. [31]

IV. Design of High Efficiency MMR Based Harvester

A. *Concept and Prototype Review*

In initial design shown in figure 7, a prototype was developed by Wang et al [6] for concept approval purpose. Two input points are used to achieve bidirection to unidirection transmission shown in Figure 1. Whereas one rack contributes power in upwards motion, the other rack contributes power in downwards motion. The harvester design mainly composed of a motion conversion mechanism, an electromagnetic generator, and a fly wheel. The bidirectional to unidirectional transmission includes three shafts, three spur gears, a pair of rack and pinion, and two roller clutches. The two racks move together in up and down direction. The roller clutches installed at the two input shafts control transmission of motion to the two large gears labeled gears 1 and 2. Both gears are only allowed to rotate in the counter-clockwise direction. This results in Shaft 3 rotating permanently in the clockwise direction. Shaft 3 engages the generator and flywheel through the bottom of the plate.

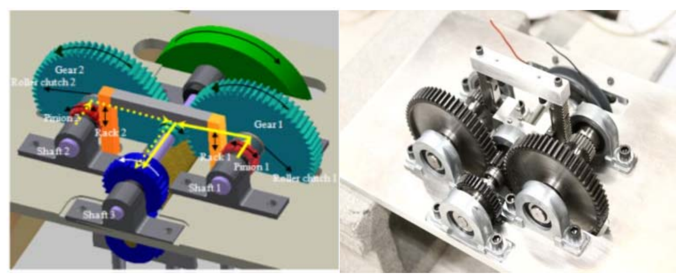

Fig 7. Working principle of first prototype

B. Design and Prototype

One of the main motivations for development of proposed MMR prototype was to achieve high efficiency in energy transformation. In previous design, we found out that the major efficiency losses were from: frictional losses in bearings, shaft component misalignments, and frictional losses due to gear meshing. While each bearing contributed to 4%-8% of the friction losses, depending on its location in the harvester. Each gear engagement roughly contributed up to 10% efficiency loss. Component misalignment issues during assembly could cause further losses in efficiency. As a result and conclusion, the direction of improving design was simplification of the MMR mechanism.

As shown in figure 4.4, an illustration of MMR mechanism is provided for direct comparison. Frictional losses were reduced by achieving MMR function by an optimized single-shaft design, furthermore, improved design further redeced gear, bearing quantity and eliminated misalignment issues.

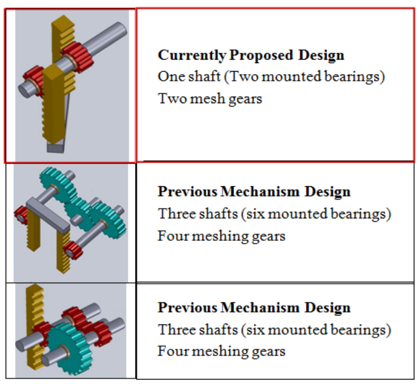

Figure 4.4. Power transmission mechanism comparison.

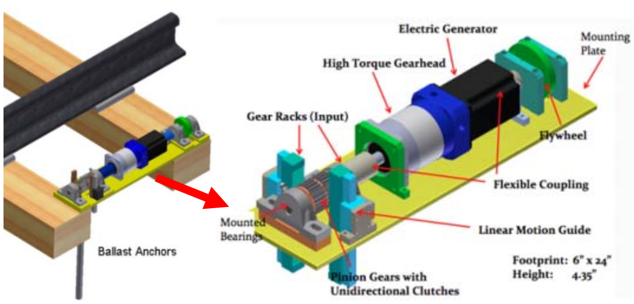

Fig 8. Drawing of the MMR based harvester prototype assembly

The updated MMR harvester system can be described by its two major halves. The first half is input assembly, which acts to convert bi-directional linear motion into single directional rotational motion. The input assembly consists of two rack and pinions, and two roller clutches. The roller clutches are fitted into the two pinions, either of them engage input shaft at a single direction. The mechanism of one-way clutch is attached in figure 9.

Fig 9. Roller clutch embedded pinion, and roller clutch working principal.

The next half of the energy harvester consists of the gearhead, power generator, and flywheel. These components are tasked to condition the unidirectional rotational motion and then convert the motion into useful energy.

Input assembly consists of 2 linearly guided gear racks (turquoise), 2 mounted bearings, 2 pinion gears meshed with the racks, 2 unidirectional roller-clutches which are fitted into the pinions, and a shafts fitting in between the roller clutches. Mounted bearings support the shaft, a flexible coupling is used, friction reducing washes separate rotating components from static environments. The output assembly consists of an electric generator (black), a gearhead (blue), flywheel (green), and various mounting brackets. All of the aforementioned components are mounted onto a metal plate. Flexible couplings are used throughout the design.

For mounting onto the railroad track, the gear racks are anchored into the ballast material while the rest of the components on the harvester base plate are mounted over the track ties. This is also depicted earlier in Figure 8 as well as Figure 10 for the finished prototype.

Fig 10. Finished prototype of the MMR based harvester.

C. Working Principle of the Proposed Innovation

As shown in figure 11, the device functions as follows: The racks transmit vertical up and down motion to the two pinions. The rack pinion assembly causes the two pinion gears to rotate in opposite directions with respect to one another. The pinions are fitted with unidirectional roller clutches. The roller clutches, engage the shaft only when rotating in a specific direction of rotation. In either direction of rack motion, one of the pinions will engage the input shaft and the other pinion will disengage it. By installing both roller clutches to engage the input shaft in the same direction, the shaft moves in a unidirectional motion. Figure 11 illustrates this principle.

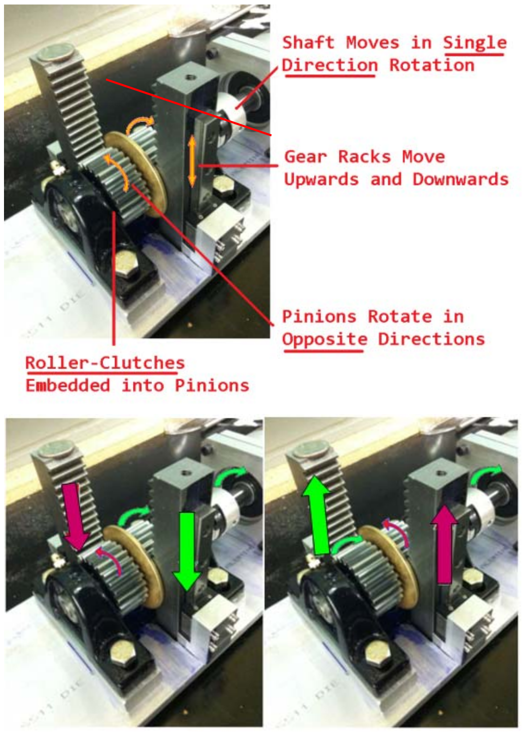

Fig 11. Illustration of roller-clutch rack pinion assembly performing bidirectional to unidirectional motion conversion. Green arrows indicate components engaged in transmitting motion. Violet arrows indicate disengaged components.

The unidirectional rotational input motion is then fed to a generator gearhead, which amplifies the low speed input of the pinion shaft to optimal generator speed values. The electric generator thus spins in unidirectional motion at its efficient operating speeds. Electrical power will be produced from the electric generator as it spins.

It is important to note that the input shaft may also coast, or spin freely. In this case, both pinions disengage. This is a crucial feature for flywheel implementation. The generator contains an output shaft in which a flywheel is installed. This flywheel stores kinetic energy through spinning. The flywheel is designed to lend its kinetic energy to the generator when there is no input motion from the track. Moments in which there is no input motion to the gear racks occur in between bogies. During these moments, the generator is powered by the flywheel, allowing for generation of consistent continuous voltage output.

D. *Physical Insights as a Motion Rectifier*

In order to give better physical insight of the harvester, we can analogize the mechanical motion mechanism with an electric voltage rectifier, as depicted in Figure 12. The input is an oscillating AC power supply, which is similar to the bidirectional input motion of the train track. The AC power is fed through two transformers, which act like the racks and pinions of the harvester. The two transformers are in series with diodes, which act similarly to roller clutches. In our circuit analogy, a sinusoidal wave may transform into a positive function of its absolute values.

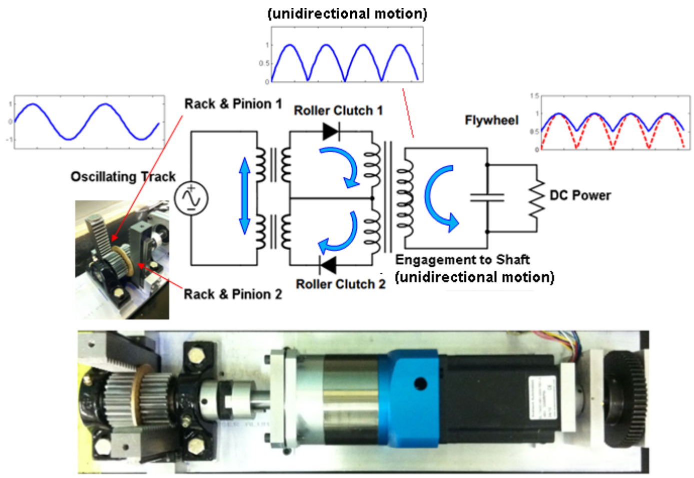

Fig 12. Working principal of prototype using circuit analogy

The diodes currents are fed through a single transformer, resulting in a unidirectional current output that is conditioned. On the energy harvester, this is similar to the motion coupled to a single shaft, which feeds unidirectional rotational motion to the geared generator. Lastly, the unidirectional voltage output is smoothed by a capacitor while being fed through a resistor. The capacitor effect is analogous to the flywheel inertial effect, while the resistor is any device powered by the energy harvester. In our circuit analogy, the capacitor will cause the positive sinusoidal to no longer decay below a certain threshold and stabilize the DC voltage, in analogy to the flywheel stabilizing the generator rotation.

V. Bench Test

A. *Test Setup*

A full scale prototype is built according to the presented design, as seen in Figure 10. Laboratory tests are conducted using a servo-hydraulic testing system, the "858 Mini Bionix II". The characteristics of the MMR based harvester are studied by performing experiments using various resistors, at various loading speeds. The force input, displacement input, resistive load, and electrical signal output values are recorded using computers and oscilloscopes.

A testing system moves the racks up and down, generating a voltage output. The experiments are done for sinusoidal displacements of 3mm amplitude, simulating vertical track speeds of up to 8cm/sec by generating frequencies from 1 Hz to 5 Hz. For each experiment, the generator's voltage output is recorded using an oscilloscope. Testing is done using a resistive loads of 2 Ω , 0.15 Ω , and open circuit. The displacement input and forces applied onto the device are recorded using the load cell and position sensor of the servo hydraulic testing machine. Figure 13 shows the harvester mounted into the servo-hydraulic testing machine powering two 50 Watt rated light bulbs.

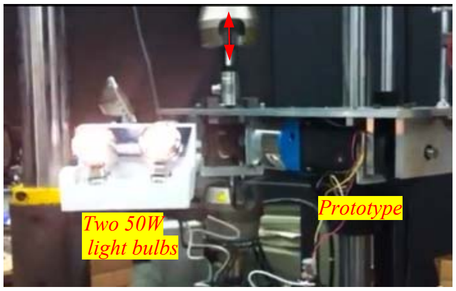

Fig 13. Prototype mounted to servo-hydraulic testing machine, driven at 2 Hz with 3mm displacement to operate two light bulbs rated at 50 Watts

B. Test Results for Loading at Various Frequencies Using a 2Ω Resistor

In this section, experiment results are presented with the harvester device loaded at 2Hz to 5Hz with a 2Ω resistor at 3mm displacement amplitude to determine the relationship between input speed and power output. Graph of 2Hz data is plotted for voltage, displacement, and force recorded in Figures 14. Mechanical and electrical powers are calculated and plotted too. Efficiencies are calculated and described in Table 2.

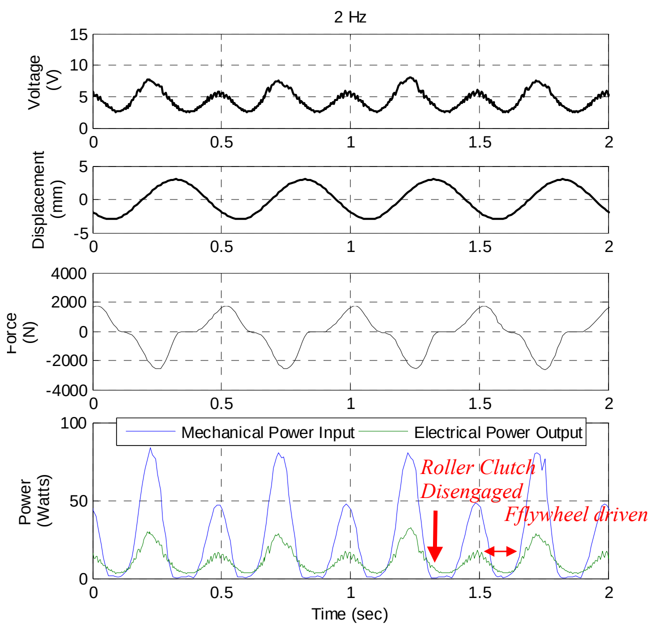

Fig 14. Voltage, displacement, force, and comparative input/output power plotted against time for device operated at 2Hz. Average overall efficiency is 46.5%.

Increasing the loading frequency increases the input speed of harvester. As a result, input power and output power share a direct relationship to the loading frequency. When the instant input power is zero, the roller clutches have disengaged with the input shaft, and the device is driven by the flywheel. This is depicted in the Figures 14. The efficiency of the device is very consistent throughout each of the experiments of 2Hz - 5Hz, as seen in Table 2. Moreover, as input speed goes up, power output boosts as well.

Table 2. Table of Results for Various Frequencies Using a 2Ω External Resistor

Frequency (Hz)	2.0	3.0	4.0	5.0
Amplitude (mm)	3.0	3.0	3.0	3.0
RMS Velocity (cm/sec)	2.6	3.9	5.2	6.3
Resistive Load (Ω)	2.0	2.0	2.0	2.0
Mechanical Power Input (Watts)	24.5	46.4	74.2	102.7
Mechanical Power Lost (Watts)	12.4	23.4	37.5	52.9
Average Voltage Output (Volts)	4.5	6.4	8.1	9.6
Usable Output Power(Watts)	11.4	21.7	34.7	47.0
Total Electrical Power (Watts)	12.1	23.0	36.7	49.8
Overall System Efficiency	46.5%	46.7%	46.7%	45.8%
Electrical Efficiency	94.3%	94.3%	94.3%	94.3%
Mechanical Efficiency	49.3%	49.5%	49.5%	48.5%

The results illustrate working features for the MMR harvester, including bidirectional to unidirectional transmission and flywheel speed regulation. Both up and down motions are also being utilized by the harvester for energy generation. More importantly, the output voltage generated is continuous and smooth. There are also instances where output electrical power is greater than the input mechanical power. This is directly due to the flywheel effect, where both roller clutches disengage and kinetic energy is drawn from the flywheel. Generating continual voltage signals above certain thresholds is advantageous for allowing electrical power rectifiers to operate more efficiently.

Asymmetric loading patterns can be seen in these figures, and are due to misalignment during device testing setup. The mounting fixture used to conjoin both gear racks may not have been aligned well, causing one of the rack and pinion inputs not to operate at optimal mechanical efficiency, especially during higher force loading. As a result, more force is distributed to that particular rack and pinion.

C. Test Results for Close to Matching Resistor Values

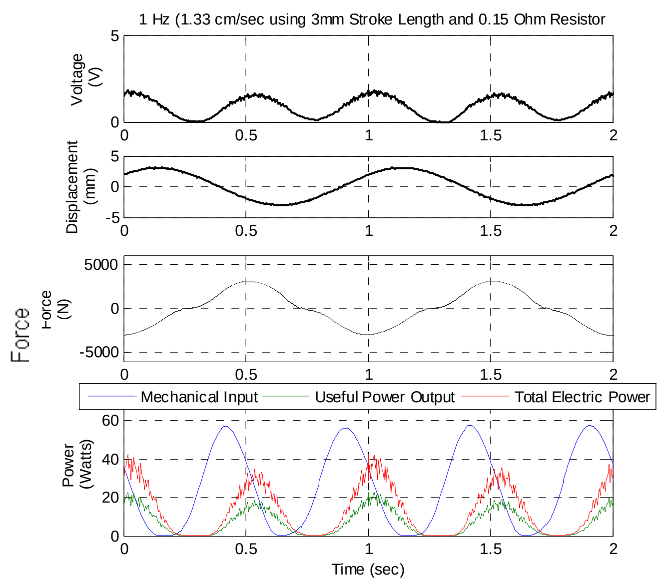

Fig 15. Experiment using 0.145Ω, 3mm amplitude, operated at 1Hz. Mechanical efficiency is 68%, total electrical efficiency is 54.7%, and overall system efficiency is 33.2%.

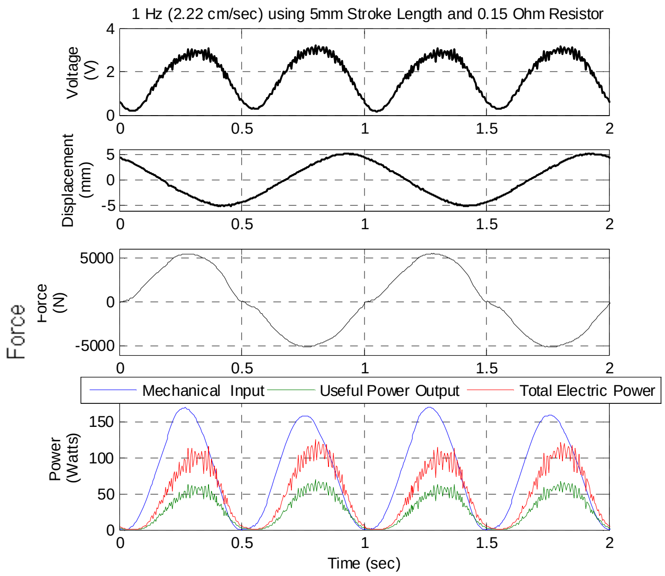

Fig 16. Experiment using 0.149Ω, 3mm amplitude, operated at 1Hz. Mechanical efficiency is 62.6%, total electrical efficiency is 56%, and overall system efficiency is 34.8%.

The generator in this prototype has an internal resister 0.12Ω. When the external resistor is the same as the internal one, the output power will be maximum (with the assumption that the generated voltage is constant). We shunted the prototype with a resistor value of 0.15Ω, close to the matching value 0.12Ω. The results under 1 Hz excitation are shown in Figures 15 and 16. Results for an experiment using 0.19Ω under 2Hz excitation are also plotted in Figure 17 to illustrate the maximum mechanical efficiency achieved thus far. The total generated electric power is derived, consisting of both the usable electric power and wasted electric power dissipated through the harvester. Mechanical efficiency is calculated, as listed in the captions of the figures.

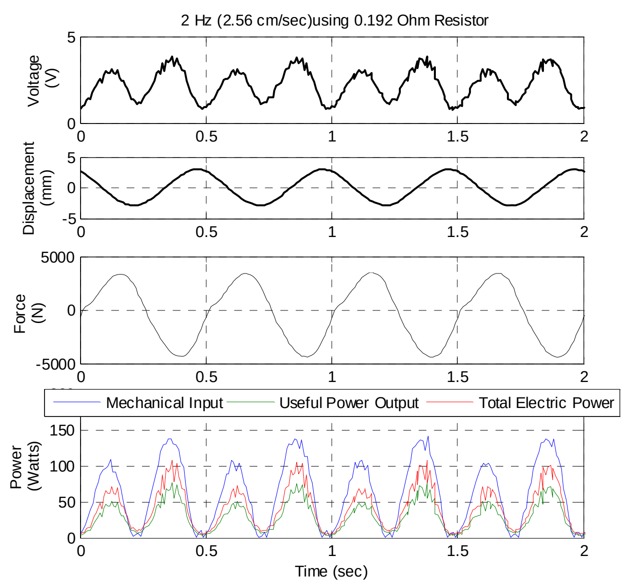

Fig 17. Device with 0.192Ω load, 3mm amplitude, operated at 2Hz. The mechanical efficiency is 71%, total electrical efficiency is 64%, and overall system efficiency is 45.6%.

D. Test Results for Open Circuit

The prototype is driven with no electric load. Results for open-circuit are plotted for 2Hz and 5Hz in Figures 18 and 19. The mechanical power input is shown. Asymmetrical loading patterns are also observed, probably due to a misalignment during device testing setup.

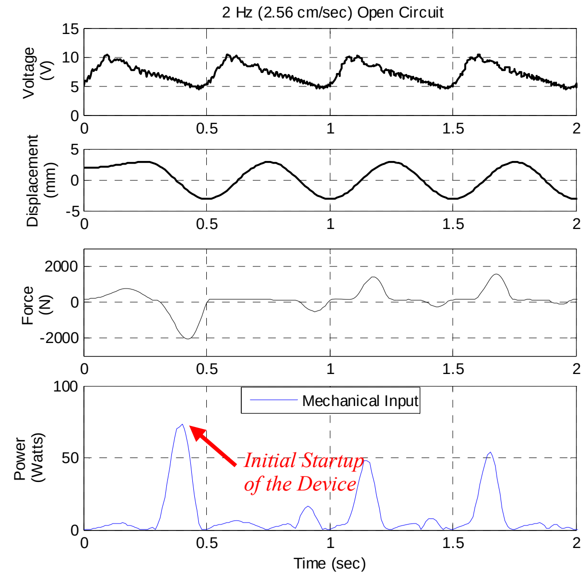

Fig 18. Experiment with open circuit, operated at 2 Hz. The average mechanical power lost was 11 Watts.

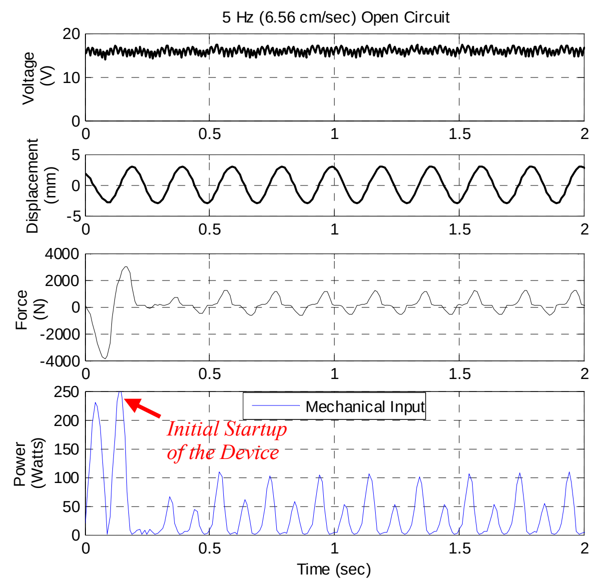

Fig 19. Experiment with open circuit, operated at 5 Hz. The average mechanical power lost was 31 Watts.

E. Force Displacement Loops

The force displacement loops are plotted in Figures 20-22, where the loop area represents the mechanical energy input. Figure 23 illustrates that increase the amplitude at the same excitation frequencies will increase the energy harvested by the device. Loops for open circuit results in Figures 21 and 22 illustrate how much mechanical power is lost, since power dissipated is purely mechanical in open loop cases.

When changing resistive loads, it can be seen that the mechanical power lost is of relatively similar value, which is important for understanding the efficiency relationships of the device.

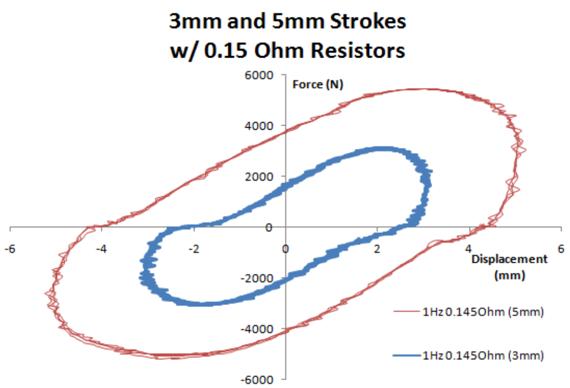

Fig 20. Force displacement loops for 1Hz 0.145Ω experiments at loading amplitudes of 3mm and 5mm.

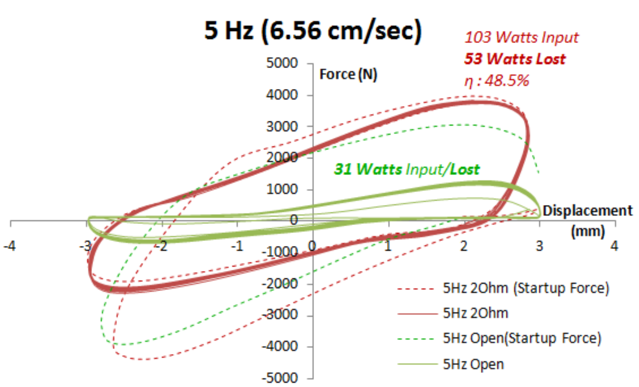

Fig 21. Force displacement loops for 5Hz open circuit(green) and 2Ω(red) experiments. The mechanical energy lost, mechanical efficiency, and input power of the experiment is displayed.

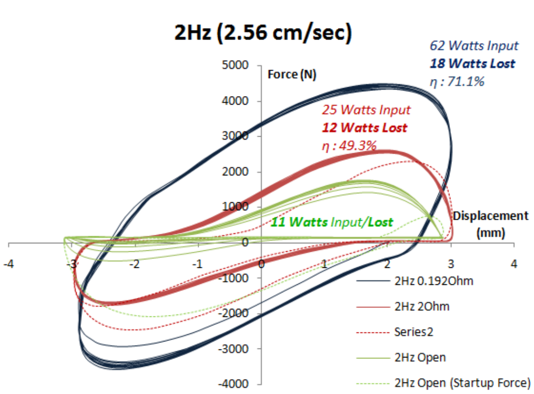

Fig 22. Force displacement loops for 2Hz open circuit(green), 2Ω(red), and 0.192Ω(blue) experiments. The mechanical energy lost, mechanical efficiency, and input power of each experiment is displayed.

The force displacement loops also shows what seems in some cases like energy returning to the force actuator, seeming almost elastic. This is actually due to inertial effects of the flywheel and the bidirectional to unidirectional motion conversion. Before the rack reaches its peak, certain loading cases the flywheel to accelerate fast enough to drive the shaft for some of the returning motion. Thus the loading force sometimes decreases during return motion.

F. Summary of Energy Convert Efficiency

The overall efficiency of the harvester peaks at about 47% as shown in Figure 23. Decreasing the loading frequency and speed will cause efficiency decay (Figures 23 and 24). This is a typical pattern found in most electromagnetic harvesters, such as energy harvesting shock absorbers developed by Z. Li in [16]. The MMR based railroad harvester is designed to harvest from tracks oscillating at frequencies between 1.6Hz and 4Hz, and moving at speeds even higher than those simulated around 10 cm/sec. This should be in range to operate the harvester almost at peak efficiency.

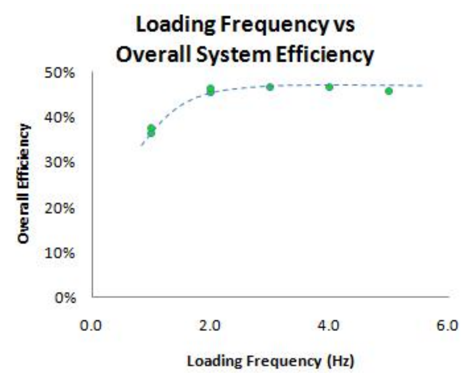

Fig 23. Overall system efficiency at various frequencies, where the amplitude is 3mm and the external load is 2 Ω. The mechanical efficiency is overall efficacy divided by electrical efficiency 94.3% for is 2Ω external load.

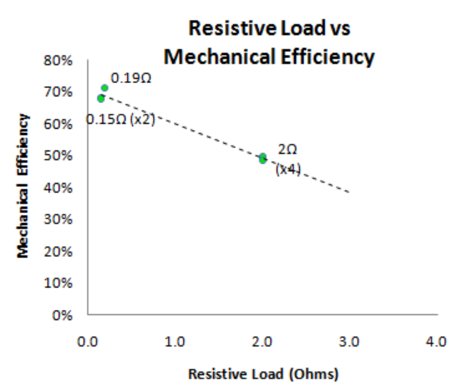

Fig 24. The mechanical efficiency at different resistive loads, where the vibration amplitude is 3mm and frequency is 1-5 Hz.

Figure 25 shows the electric power generated and the mechanical power lost in our bench tests. The data in this figure around 2.6 cm/s indicate that the mechanical power lost remains the same or relatively close to one another when the electrical load changes from o.15Ω to 2Ω. At higher RMS vibration velocity, both electric power and mechanical loss will increase.

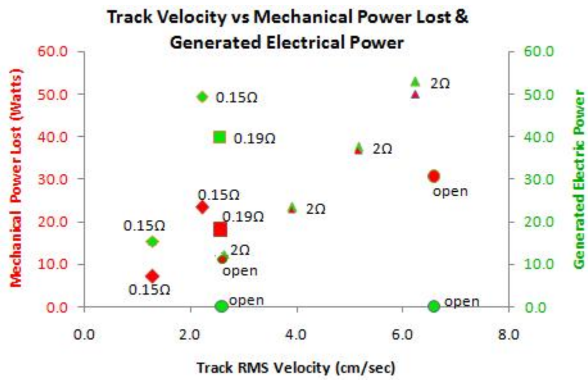

Fig 25. Generated electric power and power lost from various experiments. Resistor values are labeled near data points, and are separated by shape. Green represents generated electric power, red represents mechanical power lost.

Table 3. Summary of Overall Experiment Results Ordered by Frequency

Frequency (Hz)	1.0	1.0	2.0	2.0	2.0	3.0	4.0	5.0	5.0
Amplitude (mm)	3.0	5.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
RMS Velocity (cm/sec)	1.3	2.2	2.6	2.6	2.6	3.9	5.2	6.3	6.6
Resistive Load (Ω)	0.15	0.15	0.19	(inf)	2.0	2.0	2.0	2.0	(inf)
Mechanical Power Input (Watts)	22.5	72.8	62.0	11.6	24.5	46.4	74.2	**102.7**	30.6
Average Voltage Output (Volts)	1.0	1.7	2.1	8.5	4.5	6.4	8.1	**9.6**	**15.8**
Usable Power Output (Watts)	8.2	27.3	28.2	-	11.4	21.7	34.7	**47.0**	-
Total Electrical Power (Watts)	15.3	**49.4**	39.7	-	12.1	23.0	36.7	**49.8**	-
Overall System Efficiency	36.4%	37.5%	45.6%	-	46.5%	**46.7%**	**46.7%**	45.8%	-
Electrical Efficiency	54.7%	55.6%	64.7%	-	94.3%	94.3%	94.3%	94.3%	-
Mechanical Efficiency	**68.0%**	**67.9%**	**71.1%**	-	49.3%	49.5%	49.5%	48.5%	-

The efficiency values of all the bench tests are shown in Table 3. The best mechanical efficiency of 71.1% was achieved from loading conditions with a 2Hz frequency and 0.192Ω external resistor.

VI. Modeling and Simulation

As a part of the system, flywheel plays an important role in optimizing harvester's performance. As proved in bench test, flywheel effect was found to help keeping constant power output. However, flywheel also adds a huge inertia to the system, thus, an optimized flywheel need to be determined. In order to optimize flywheel parameters, following modeling and simulation are conducted.

When the rotation speed of the input shaft to the motion rectifier is smaller than the rotation speed of the output shaft, the one-way bearings inside would disengage from the output shaft, and torque transmitted would fall to zero, then the angular speed and the rotational acceleration of the flywheel shaft can be represented as:

$$\omega(t) = \omega_{\max} \cdot e^{-\frac{k}{J}t}$$

$$\alpha(t) = \dot{\omega}(t) = -\frac{k}{J}\omega_{\max} \cdot e^{-\frac{k}{J}t}$$

On the other hand, when excitation exceeds system's speed, flywheel will be charged and the torque can be expressed as below:

$$\textit{Charging Mode } M = J\alpha = -k\omega_{\max}(1 - e^{-\frac{k}{J}t})$$

Circuit based modeling (Figure 11) and dynamic modeling (Figure 12) can be implemented to simulate the dynamic properties of the railroad energy harvester. Since the mechanical elements can be transferred into electrical elements, we can easily make an analogy between mechanical motion rectifier and electrical voltage rectifier by using various software tools incuding Matlab, Simulink, SimPowerSystem and etc. And also, dynamic simulation of the whole system can be conducted in Matlab/Simulink, shown in Figure 12.

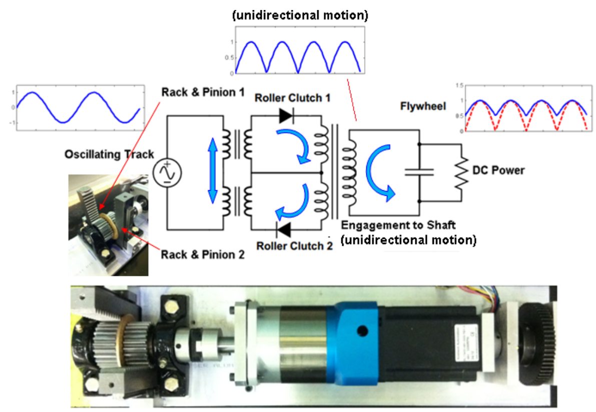

Fig 1 Circuit based modeling for the railroad energy harvester

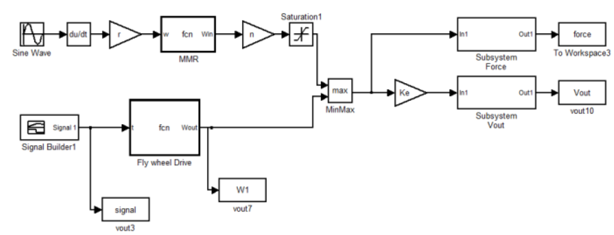

Fig 12 dynamic modeling for the railroad energy harvester

VII. Conclusions

A single-shaft MMR based energy harvesting prototype has been developed and demonstrated much better performances than existing technologies in the field of railway energy harvesting. By converting up-and-down oscillating vibration into a unidirectional rotation of the generator, significant improvement has been made in the harvesting efficiency and the amount of power harvested by the prototype. These improvements are illustrated in the laboratory bench test results.

The current prototype operated shows to be capable of harvesting 10 - 50 Watts. It is also able to harvest 28 Watts for very low track oscillations of 1 cm/second. For normal track motion, the overall system efficiencies consistently stay within 45-47% range. The mechanical efficiencies ranged from 49% to 71% depending on the type of resistor used and the load pattern on the device. As a comparison, in a previous design [6], 1.0 - 1.4 Watts were harvested in the similar conditions. The overall efficiencies ranged between 10-22% and mechanical efficiencies were only 11-25% [6]. The new MMR harvester has improved both the overall and mechanical efficiency by a factor of 2 -3 times, and harvests energy at a much larger power scale than many existing technologies.

A properly designed MMR based harvester has the potential to power major railroad trackside equipment and electrical infrastructures, representing both a safety benefit and energy benefit for remote areas lacking viable power solutions. The energy technique used in this study may be extended into other fields of energy harvesting and recovery from other oscillating sources with erratic behavior such as vehicle suspensions, ocean waves, speed bumps, etc.

VIII. Recognition of this Project

This project has received a number of awards and media highlights. The selected ones are in the following

- **Best Student Paper Award**, by ASME Design Engineering Division Mechatronic and Embedded Systems and Applications Technical Committee, for the paper “High efficiency electromagnetic energy harvester for railroad application" by John Wang, Teng Lin, and Lei Zuo at the 9th ASME/IEEE International Conference on Mechatronic and Embedded Systems and Applications (MESA 2013) (08/2013)
- This project of railway energy harvesting was featured in *ASME Mechanical Engineering Magazine*, March Issue, 2013 (03/01/2013)
- "New Technology Harvests Energy from Train Track Vibrations!", featured story by Kim Scorcher of TYT NerdAlert , an internet TV news show (12/06/2012)
- "Award-winning device harvests energy from railway track vibrations", interviewed and reported by By Paul Ridden of *Gizmag* , New and Emerging Technology News (11/28/2012)
- U*.S. Representative Tim Bishop* delivered some nice remarks about my research in the House on Nov 27th. "Congratulating Professor Lei Zuo" (11/27/2012)
- **“Winner of Best Application of Energy Harvesting**” for railroad energy harvesting in the Energy Harvesting & Storage USA 2012 conference, held in Washington DC on Nov 7-8, 2012
- “Man on the move”, Prof Lei Zuo was highlighted on the cover page of *Newsday*’s Long Island Business Section: “Stony Brook scientist seeks to harvest kinetic energy” (09/16/2012)

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References

[1] National Transportation and Safety Board (2013) “Most Wanted List: Implement Positive Train Control Systems”

[2] E. Aboelela, W. Edberg, C. Papakonstantinou, and V. Vokkarane, 2006, “Wireless Sensor Network Based Model for Secure Railway Operations,” Proc. of the IEEE IPCCC, pp. 623–628.

[3] K. Chebrolu, B. Raman, N. Mishra, P. K. Valiveti, and R. Kumar, 2008, “BriMon: A Sensor Network System for Railway Bridge Monitoring,” Proc. of the ACM MobiSys, pp. 2–14.

[4] H-P. Tan, P. WQ. Lee, W. KG. Seah, and Z. A. Eu, Impact of Power Control in Wireless Sensor Networks Powered by Ambient Energy Harvesting (WSN-HEAP) for Railroad Health Monitoring, 2009 IEEE International Conference on Advanced Information Networking and Applications Workshops, Bradford, United Kingdom.

[5] U.S. Department of Transportation Federal Highway Administration, “Railway-Highway Grade Crossing”

[6] J. Wang, G.P. Penamalli, and Lei Zuo, 2012, “Electromagnetic Energy Harvesting from Train Induced Railway Track Vibrations,” MESA 2012 IEEE/ASME International

[7] Perpetuum Ltd, Southampton, UK, http://www.perpetuum.com/

[8] Z. F. Mian, 2009, Wireless railroad monitoring US patent 12/493,789.

[9] C. Nelson, S. Platt, S. Farritor, D. Albrecht, and V. Kamarajugadda, 2007, “Regenerative Power for Track-Health Monitoring.” Reported to Federal Railroad Administration.

[10] C. A. Nelson, S. R. Platt, D. Albrecht, V. Kamarajugadda, and M. Fateh, 2008, “Power Harvesting for Railroad Track Health Monitoring Using Piezoelectric and Inductive Devices,” Proc. of the SPIE: Active and Passive Smart Structures and Integrated Systems, vol. 6928(1).

[11] C A. Nelson, S R Plattb, S E. Hansen, M Fateh, 2009, “Power Harvesting for Railroad Track Safety Enhancement using Vertical Track Displacement,” Proc. of SPIE: Active and Passive Smart Structures and Integrated Systems, Vol. 7288.

[12] R. B. Goldner and P. Zerigian, 2005, “Electromagnetic linear generator and shock absorber,” US Patent Specification 6,952,060 B2 (inventors; Trustees of Tufts College, assignee.

[13] L. Zuo, B. Scully, J. Shestani and Y. Zhou, 2010, “Design and characterization of an electromagnetic energy harvester for vehicle suspensions,” *Smart Materials and Structures.*

[14] X. Tang, L. Zuo, T. Lin, and P. Zhang, 2001, “Improved Design of Linear Electromagnetic Transducers for Large-Scale Vibration Energy Harvesting,” Smart Structures and Materials: Proceedings of SPIE. CA.

[15] X. Tang and L. Zuo, 2009, “Towards MESO And Macro Scale Energy Harvesting of Vibration,” Proceedings of the 2009 ASME International Mechanical Engineering Congress and Exposition, Florida.

[16] Z. Li, Z. Brindak, and L. Zuo, 2011 “Modeling of an Electromagnetic Vibration Energy Harvester with Motion Magnification”, 2011 ASME International Mechanical Engineering Congress and Exposition

[17] P. Zhang, Master thesis, 2010, “Study of Road Energy and Regenerative Electromagnetic Shock Absorber”, SUNY Stony Brook.

[18] G.R Penamalli, 2011, "Study of Road Energy and Regenerative Electromagnetic Shock Absorber", Master Thesis, State University of New York at Stony Brook

[19] L.Zuo, G.R. Penamalli, J. Wang, R. Zheng, X. Lei, J. Lam-ki, Z. Li, and T, Lin, 2011, "High-Efficiency Energy Generator for Harnessing Mechanical Vibration Power" US Patent 61/476,019.

[20] Pourghodrat, 2011, "Energy Harvesting Systems Design for Railroad Safety" Master Thesis, University of Nebraska-Lincoln

[21] K.J. Phillips, C.A. Nelson, and M. Fateh "Simulation and Control System of a Railroad Track Power Harvesting Device" 2011, Proc, of SPIE Volume 7984

[22] J. Igwemezie, 2007, "Understanding Stresses in Rails," Interface Journal of wheel/Rail interaction.

[23] S. Farritor, R. Arnold, and S. Lu, B. McVey, C. Hogan, and C. Norman, 2006, "Real-Time Vertical Track Modulus Measurement System from a Moving Railcar," Reported to Federal Railroad Administration.

[24] H. Grabe, 2010, "Axle load and track deflection on a heavy haul line*", Civil Engineering*,

[25] W. Powrie and J. Priest, 2011, "Behaviour of ballasted track during high speed train passage", University of Southampton, UK.

[26] D. Bowness, A. C. Lock, W. Powrie, J. A. Priest, and D. J. Richards, 2006, "Monitoring the dynamic displacements of railway track," *Proceedings of the IMEE, Rail and rapid transit*.

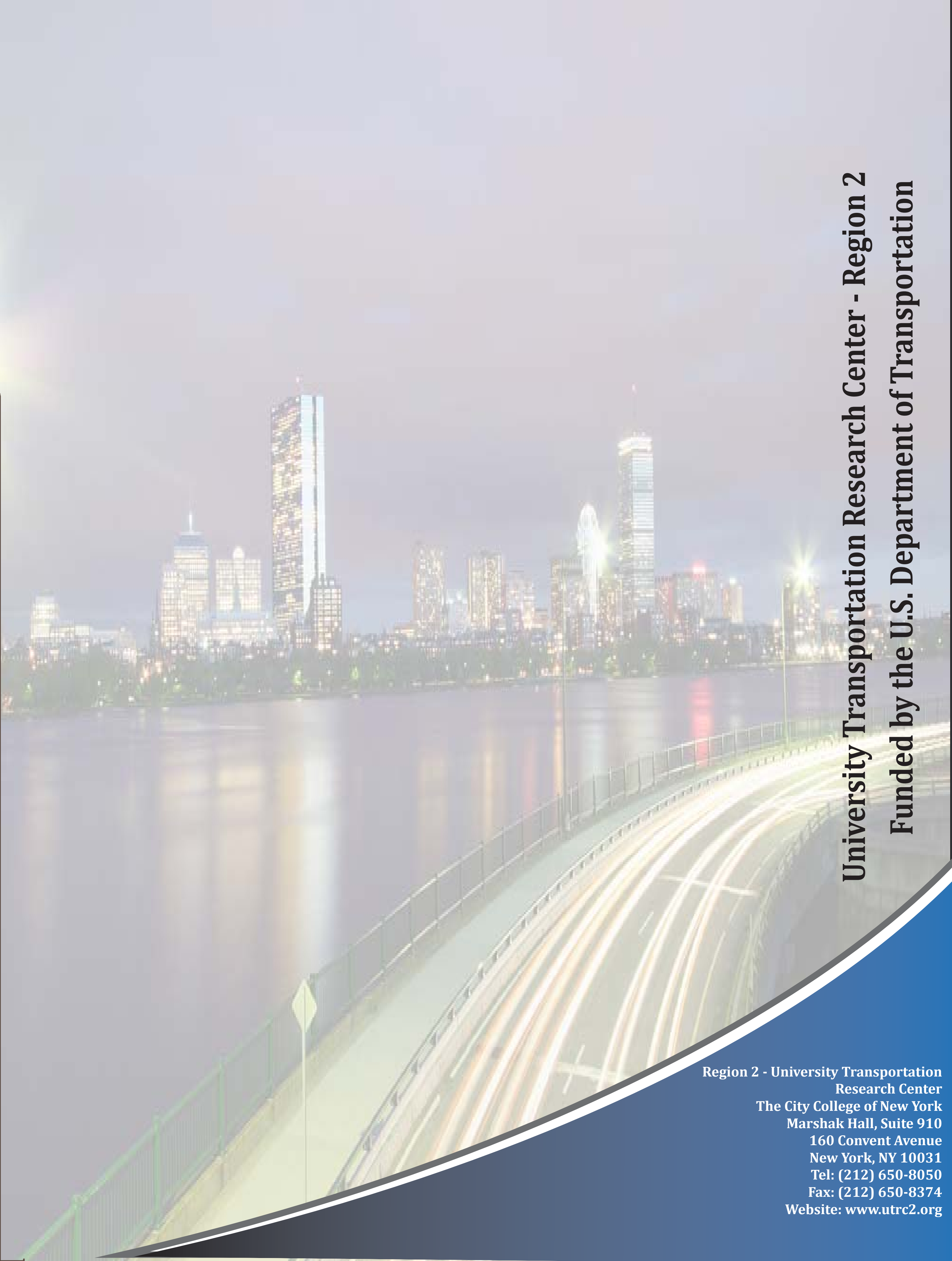
[27] A D Quinn, M Hayward, C J Baker, F Schmid, J A Priest and W Powrie. 2010, "A full-scale experimental and modelling study of ballast flight under high-speed trains. *Proc I Mech E, Part F, J Rail and Rapid Transit* 224 (F2), 61-74.

[28] B Coelho, P Hölscher, J A Priest, W Powrie and F Barends.201, 2011, "An assessment of transition zone performance" *Proc I Mech E, Part F, J Rail and Rapid Transit* 225(F2), 129-139.

[29] K. Oldknow, R. Reiff, 2006, "Use of Dynamic Rail Deflection as a Means of Determining Changes in Top of Rail Friction," Reported to Federal Railroad Administration.

[30] W. Powrie and J. Priest, 2011, "Behaviour of ballasted track during high speed train passage", High Speed Track Railways Day, Institution of Civil Engineers, One Great George Street, London.

[31] Alstom Signaling, NY, USA, http://www.alstomsignalingsolutions.com



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