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Electromechanical Energy Harvesters for Railroad Applications

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Summary

The details of the engineering, development, and testing of a vibration-based electromechanical energy harvesting system intended for freight railcar applications are described in this *Technology Digest*. The Railway Technologies Laboratory at Virginia Tech developed the energy harvester under the Technology Outreach Strategic Research Initiative of the Association of American Railroads Affiliated Laboratories Program. Laboratory and field proof testing of the prototype energy harvesters showed they could be capable of providing sufficient power for onboard monitoring of freight cars or components.

The energy harvester is designed such that it can fit within a D5 spring, to move in response to the relative motion across the truck suspension. The relative motion across the suspension is converted to a reasonably high-speed rotation motion that can rotate one or more high-efficiency electrical generators, to provide sufficient amount of electrical energy for operating low-power electronics such as GPS units, transducers, data loggers, and signal conditioners, among other possible onboard devices that may be of interest to the railroads. The results of laboratory tests indicate that under certain conditions the energy harvester can generate several tens of watts of electrical energy, in direct relationship with the relative velocity across the unit. The results of field testing conducted at the Facility for Accelerated Service Testing at the Transportation Technology Center in Pueblo, Colo., show that the harvested energy is in the range of 1 to 2 watts because of significantly smaller velocities at the suspension. The harvested energy is independent of the railcar loading. Additionally, the results of the laboratory tests and on-track testing indicate that the developed energy harvester is reliable and could be operated in conditions representative of revenue service without any significant problems.

INTRODUCTION

There is a continued need for electrical power onboard freight railcars. Although locomotives and passenger cars have power on board, freight cars are without any easy-to-access-and-maintain source of electricity. The availability of electrical power has become more critical in recent years with the desire to implement various types of onboard electronics to provide more capabilities in railcars for location monitoring, health condition assessment, etc.

Batteries are commonly used, but they require a special management system to ensure they stay charged. Another possible solution is a generator axle bearing developed in the 1990s,[1,2,3] which although effective in providing electricity has not been widely adopted by the railroads because of cost, need to maintain two sets of inventory, and relative difficulty to install in existing equipment.

Under the AAR Strategic Research Initiatives Program, the Affiliated Laboratory at Virginia Tech has developed an electromechanical energy harvester. Placed inside a coil spring of the truck suspension, it is intended to harvest a portion of the mechanical energy that exists due to the suspension motion. The railcars are isolated from the track by a suspension where the vibrational energy is dissipated in friction wedges or other damping devices. Since the energy harvester is placed within the suspension, in the path of the mechanical energy from the side frames to the bolster, it responds to the existing energy and is able to convert some of the mechanical energy that is normally wasted as heat into electrical energy. The magnitude of the forces required by the energy harvester is such that it has no adverse effect on the side frame, axle, or bolster dynamics.

The energy harvester was tested in the laboratory and in heavy axle load service at the Facility for Accelerated Service Testing (FAST) at the Transportation Technology Center (TTC). This *Technology Digest* provides the design concept and results of tests conducted to evaluate its performance and durability.

Prototype Design

The final prototype, shown in Figures 1 and 2, follows previous designs that included a linear generator that proved to be far less efficient than the rotational generation concept used in the final concept. The details of the linear generators are included in past publications by the authors.[4]

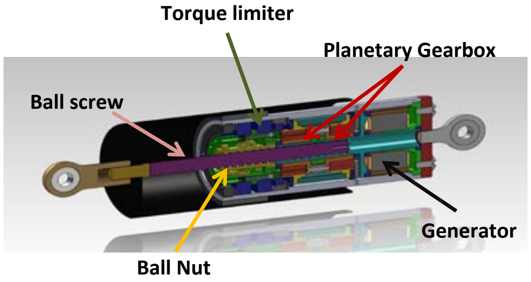

Figure 1. Main Components of the Prototype Energy Harvester for Railroad Applications

Figure 2. Fully Assembled Prototype Energy Harvesters used for On-Track Testing at TTC; (left) without Dust Cover, (right) with Dust Cover

The final design incorporates the results of a study that optimized the performance of both the mechanical and electromagnetic aspects of the energy harvester, as detailed in Reference 5. For instance, unlike the initial rotary design[5] in which the generator's motion corresponds directly to the up or down motion of the ball screw shaft, the final design incorporates a clutch bearing (also called a one-way bearing) that allows the transmission of forces in only one direction, like a freewheel on a bicycle. Therefore, irrespective of the ball screw's direction of motion (up or down), the generator is always driven in the same direction in order to take advantage of the moment of rotation of the generator's rotor. This significantly increases the efficiency of the harvester, since the harvested energy is directly proportional to the speed of rotation. Thus, the higher the speed of rotation, the larger the harvested energy.

The generator shown in Figure 1 takes advantage of off-the-shelf motors used by hobbyists for remote controlled devices. The motor's winding was customized to adapt it to the much slower rotations in the generator, as compared to the faster speeds of the motor's intended applications. An elaborate electromagnetic analysis was used to optimize the electromagnetic circuit of the generator, using the software package FEMM. The custom winding and the design optimization of the electromagnetic components improved the efficiency of the generator by nearly 500 percent as compared with the original motor for the rotational speeds at which the energy harvester operates.[5]

The working principle of the prototype energy harvester is such that the linear motion across the suspension is transformed into a rotational motion, using a ball screw. A set of clutch bearings and gears converts the reciprocating rotation (i.e., clockwise and counterclockwise) of the ball nut into a rotational motion that is always in the same direction, using the clutch bearings described earlier. A permanent magnet brushless direct current generator (motor) transforms the rotational mechanical energy into electrical power. A torque limiter is used to avoid binding the rotary components; it enables the energy harvester to withstand high velocity impact dynamics that may occur at the suspension during the normal operation of the railcar.

The harvester is sized such that it can fit inside of a freight railcar's D5 truck spring with inside diameter of 3.59 inches, a free length of 10.25 inches, and a solid length of 6.56 inches (total stroke=3.69 inches). The prototype harvester in Figure 2 has an outside diameter of 3 inches and a free height of 6.5 inches with 5 inches of stroke, making it suitable for packaging inside of a D5 spring.

Characterization Tests

Once assembled, the prototype energy harvester was tested in a suspension dynamometer that enabled controlling the velocity and displacement across the harvester. The setup allowed for accurate measurement of the generated power, as well as the force required to move the harvester. Additionally, the harvester could be moved using a combination of different amplitudes and frequencies, resulting in various speeds across the suspension, which is the main dynamic element that influences the power output. The higher velocities across the suspension correspond to larger kinetic energy at the suspension, and the ability to harvest more electrical energy, as is shown in Figure 3, which shows the root mean square (RMS) voltage (V_{rms}) and average power (W) while displacing the harvester at 1 Hz at different peak-to-peak amplitudes. The higher amplitudes correspond to higher velocities across the suspension. At higher amplitudes, both the V_{rms} and W increase substantially. It is important to note that the harvested energy (W) is also inversely proportional to the resistive load across the harvester. The smaller the resistive load, the higher the output current and power, since $W = Ri^2$, where R is the resistance across the harvester and i is the resulting current.

The test results in Figure 3 show that as much as 84 watts of power can be generated at amplitudes of 0.75 inch with 5 ohms of resistive loading. In practice, the suspension amplitudes are only a fraction of this amount, and the resistive loading across the suspension is much larger, resulting in substantially smaller power, as will be discussed later.

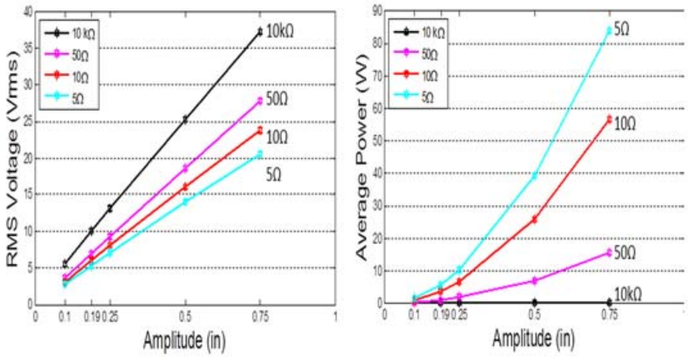

Figure 3. RMS Voltage and Average Power for Laboratory Tests with 1 Hz Sinusoidal Input at Various Suspension Displacements (Travel)

Graphs similar to Figure 3 were produced using field-measured suspension displacements, such as those measured on the High Tonnage Loop (HTL) at FAST shown in Figure 4. Figure 4 shows the suspension displacement (travel) on the left and right sides of the truck. Note that the suspensions on the two sides do not necessarily move by the same amount or in synch with each other due to the difference that may exist between the running surfaces on each side. The suspension travel on track is random, with a dominant peak at 2 Hz that coincides with the natural frequency of the suspension. There are large peaks at some locations, but at most places the suspension travel is very small, which poses a particular challenge for vibration-based energy harvesters that rely on large suspension travels to generate sufficiently large velocities needed for harvesting enough energy to keep a battery charged or to run onboard electronics.

Figure 5 represents the voltage and power output for a single lap on the HTL, and it shows the suspension travel causes large variations in energy harvester power output. “Regulated” power that is periodic or constant is desired, as opposed to the large range unregulated power profile illustrated in Figure 5. It is, however, possible to use power conditioning methods to regulate the power and make it usable by electronic devices or for storage.

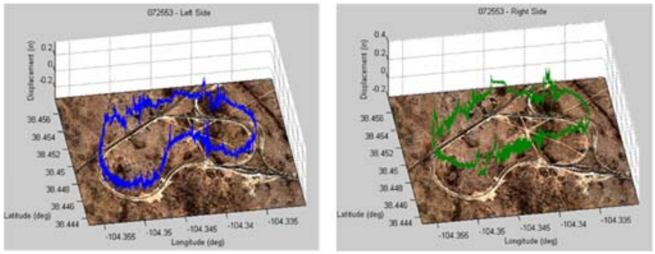

Figure 4. Measured Suspension Displacement (Travel) on the HTL Superimposed on Track Maps

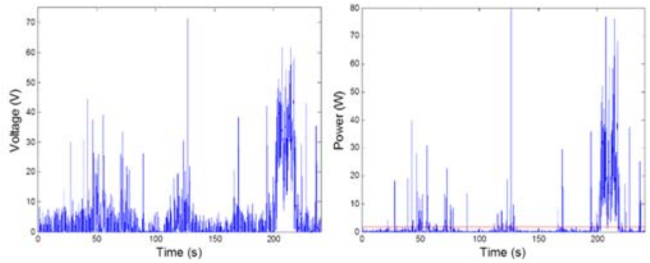

Figure 5. Voltage and Power Output for One Lap on HTL for a Resistive Loading of 50 ohms across the Energy Harvester

Figure 6 shows the results of the energy harvester testing in a shock dynamometer over a long span of time, with the track-measured suspension displacements used as input. The gaps in the data indicate the times that no data was collected. As Figure 6 shows, the harvested energy on the HTL is approximately 6 watts for a resistive loading of 50 ohms and approximately twice as much (13.5 watts) for a smaller resistive loading of 20 ohms. In both cases, the voltage output is maintained sufficiently high (17.5 volts) to charge a 12-volt battery. For most practical applications, the combination of sufficiently high voltage and power are needed. Test results indicate the voltage must remain above 12 volts and the average power be kept in the range of 3 to 6 watts for low-power devices (e.g., GPS units, transducers, data loggers, and signal conditioners) used on freight railcars.

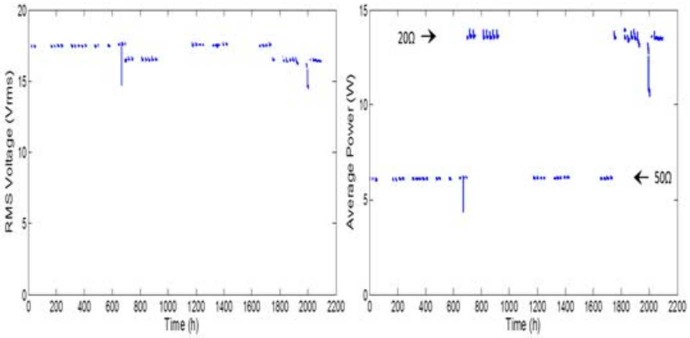

Figure 6. RMS Voltage and Average Power for Laboratory Tests simulating Suspension Displacement Measured on the HTL

On-track Evaluation

In order to determine the viability of the energy harvester for use in field applications, it was tested on board TTCI's Instrumented Freight Car (IFC) for multiple months. Figure 7 shows an energy harvester installed on the left side of the IFC, with an identical one installed on the right side. Before on-track testing at FAST, the energy harvester was dynamically tested in the laboratory with sinusoidal and track-measured inputs for multiple millions of cycles, to represent extended field usage. The on-track tests evaluated the performance of the energy harvesters in conditions more representative of revenue service usage than what can be simulated in the laboratory.

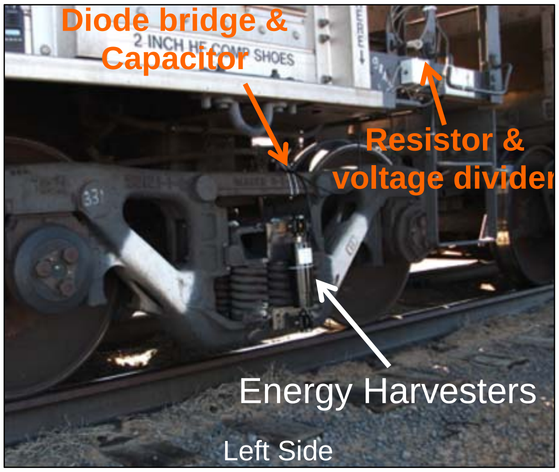

Figure 7. Energy Harvester Installation on TTCI's IFC

On-track tests were not intended to harvest energy, but to monitor how much energy could be generated and to evaluate how well the energy harvesters were able to withstand the on-track dynamic and environmental conditions. The tests were successful in that they highlighted a mode of failure that had not occurred during the laboratory testing, and they also indicated that in the absence of that mode of failure the energy harvesters can perform well for many months.

One energy harvester was removed from the IFC after approximately 5 months and 8,900 miles of operations, because it stopped generating power. Although it did not show any external damage, it had experienced an internal failure. The source of failure was determined to be excessive slip at the clutch bearing due to excessive tolerance stack-up among some of the components. The prototype design was changed to prevent such occurrence in the future.

The other energy harvester was tested for more than 9 months (approximately 13,100 miles of operations). It was still functioning when removed during a track and vehicle maintenance shutdown at FAST. Virginia Tech researchers performed a teardown inspection to determine the extent of wear on the internal components. The energy harvester exhibited normal wear on its internal components; it has been used for additional tests conducted to further improve the electrical components of the harvesters, most notably the power conditioning circuit and means of storing the harvested power.

CONCLUSION

The laboratory tests indicate that under certain conditions the energy harvester can generate several tens of watts of electrical energy, in direct relationship with the relative velocity across the unit. Field testing results at FAST show the harvested energy is in the range of 1 to 2 watts, because of significantly smaller velocities at the suspension. Because of the relatively small amount of force that is needed to operate the energy harvester, the energy generated when the railcar is loaded or empty is equal. The harvested energy, however, is directly proportional to the relative velocity across the suspension, which is influenced by the suspension motion, track condition, and vehicle component conditions. Additionally, on-track testing revealed a failure mode that has been mitigated by a small design change to the energy harvester.

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