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Research Results

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Regenerative Power for Track-Health Monitoring

SUMMARY

The growing availability of low-power sensors, microprocessors, and transmitters makes it increasingly attractive to use distributed sensor networks for track-health monitoring. Widespread implementation of these networks will require robust and low-maintenance methods for powering the electronics. This research investigates two principal methods of harvesting mechanical power from passing railcars in order to supply electrical power to remote networks of sensors.

The research team first considered an electromagnetic device (a simple electric generator) directly driven by vertical rail displacement (Figure 1a). The team then considered a piezoelectric device (a crystalline material in which strain induces voltage) that is attached to the bottom of the rail and is driven by the longitudinal strain produced by passing railcars (Figure 1b). It was demonstrated that each of these techniques can generate electrical power on the order of milliwatts (mW) per device when loaded, which should be sufficient to operate simple sensors.

The focus of this research is to quantify the electrical power that can be generated using these methods under typical rail operating conditions, with the goal of ultimately being able to develop a system that uses regenerative techniques to supply power for track-health monitoring sensor networks.

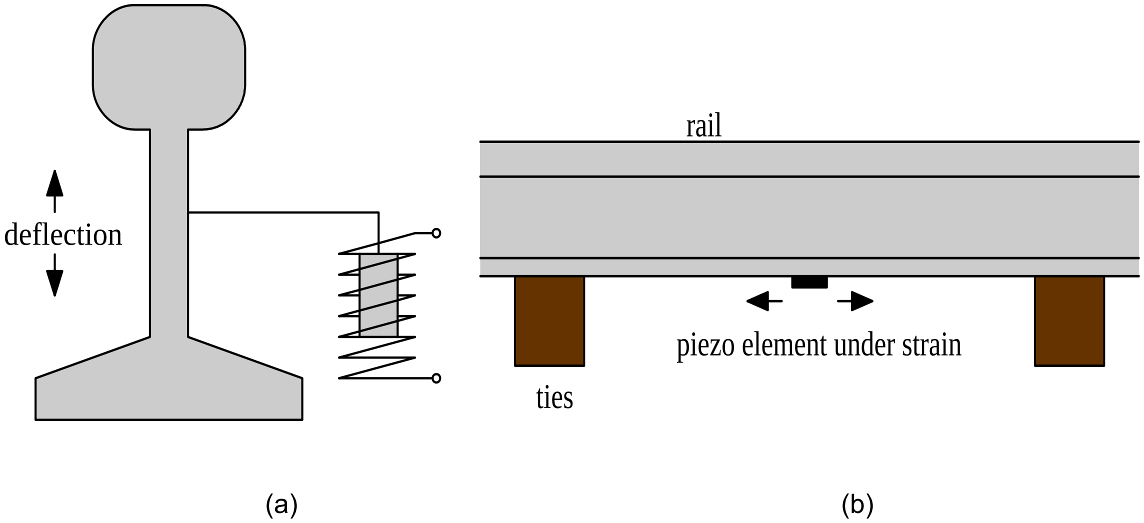

Figure 1. In a loaded section of rail: (a) vertical rail deflection induces a voltage in an electromagnetic induction device; (b) piezoelectric element produces a voltage due to strain along its length

BACKGROUND

Railroad safety is highly dependent on track quality, which makes track-health monitoring a critical issue. The increased availability of low-power sensors, microprocessors, and transmitters is making the use of remote and distributed sensor networks to accomplish this monitoring more attractive. The most limiting factor for these sensor networks, however, is the lack of a long-term, low-maintenance power supply. All such existing systems still require a change of battery, and the remote location and low frequency of maintenance can limit their practical deployment.

Examples of the types of sensors that can be useful in monitoring track health include strain gauges, temperature sensors, and accelerometers. While earlier generations of such devices required power on the order of hundreds of mWs, new devices are not only capable of supporting multiple types of sensors but also serve as wireless transmitters, all while requiring power on the order of a few mWs [1,2]. These advances in sensing technologies make it possible to consider converting from conventional battery power to regenerative power sources that can be implemented without interrupting train or maintenance operations, while also allowing zero-maintenance, indefinite operation of sensors.

THE PROPOSED APPROACHES

Researchers investigated two power scavenging approaches. The first method is based on Faraday's law of electromagnetic induction [3], which states that moving a conductor through a magnetic field produces a voltage. For a coil of wire moving perpendicularly to a uniform magnetic field, the output voltage scales linearly with the length of the wire or, equivalently, with the number of coils used. As illustrated in Figure 1(a), vertical deflection of a rail due to passing trains can be used to create relative velocity between a coil and a permanent magnetic field. The induced voltage in the coil can then be used to power sensors directly, or the electrical energy can be stored in a capacitor or battery. The second method of power scavenging uses a piezoelectric device. When subjected to a strain, piezoelectric materials develop an electrical potential due to shifts in the crystalline atomic structure [4]. If a piezoelectric element is mounted to the bottom of a rail, the longitudinal strain developed within the rail due to passing trains will be converted to electrical energy, as shown schematically in Figure 1(b). For this device, the output voltage scales linearly with the applied strain.

MODELS AND SIMULATIONS

In order to identify viable hardware and system designs before field testing, it is necessary to understand the interaction between the railcar and track deflection, as well as between deflection and output power. To accomplish this, the research team adopted an analytical model of vertical track deflection for simulation purposes.

The track model used is referred to as the Winkler model [5]. This model linearly relates rail deflection to a single applied point load and has a nonlinear relationship to track stiffness. Rail deflection for each track under a railcar is calculated using the superposition of four point loads, one at each wheel contact point.

By using the analytical model of vertical track deflection, it is possible to integrate knowledge of track loading conditions with theoretical models of the electromagnetic induction effect and piezoelectric behavior into numerical simulations. These simulations are used to predict electrical output levels as a function of input mechanical conditions. They are also used to identify the optimal load impedance such that it maximizes power output for given operating conditions.

A commercially available voice coil actuator was used for the inductive power scavenging approach. Using manufacturer-supplied data for this device, along with Winkler model parameters approximated from data available in the literature, the response of this device was simulated in MATLAB under the assumptions of a loaded coal train traveling over the device at 13 mph. As shown in Figure 2, this simulation predicted an average power output of 0.16 mW, with peak values near 0.6 mW, into a 7.5 Ω resistive load.

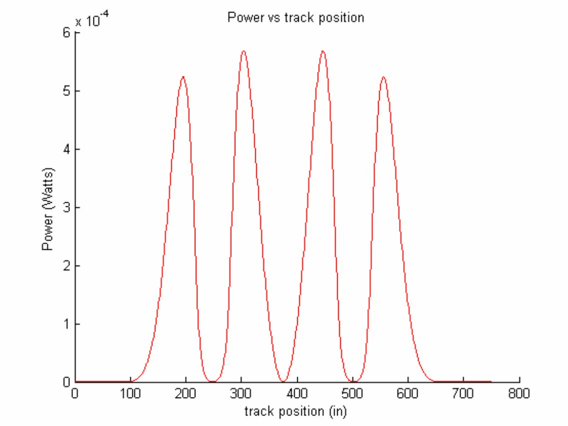

Figure 2. Predicted inductive power output

For the piezoelectric power scavenging approach, the research team selected a commercially available element that develops a voltage when loaded in transverse extension. Simulations of this device, shown in Figure 4, indicated an expected average power output of approximately 1.1 mW into a matched load resistor near 350 kΩ.

LAB AND FIELD TESTS

Researchers conducted lab tests to verify the simulation results for the inductive power scavenging approach. (Lab tests to verify the piezoelectric simulations were not feasible due to the required loading conditions.)

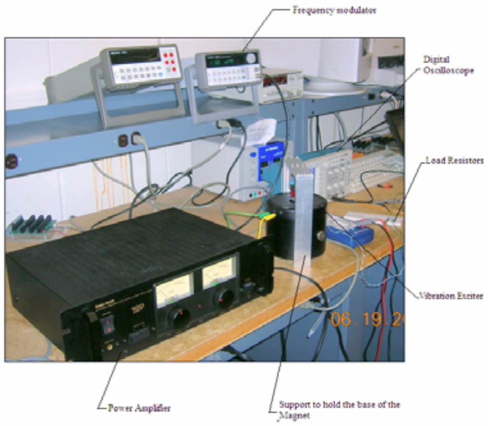

Figure 3. Lab setup for inductive device testing

The inductive lab test system, shown in Figure 3, consists of the voice coil device mounted on a vibratory exciter. A series of resistors was connected to the output leads of the voice coil, and the voltage across the resistors was recorded on an oscilloscope.

The waveform and magnitude of the vertical displacement of the exciter are controlled using a signal generator and a power amplifier. As shown in Figure 4, the results of these tests indicate that maximum output is obtained with a load resistor of 7.5 Ω, which is near the voice coil's internal resistance value of 7.7 Ω. Under low-amplitude, 10-Hz sinusoidal excitation, the system produces an average power of 0.146 mW into this load.

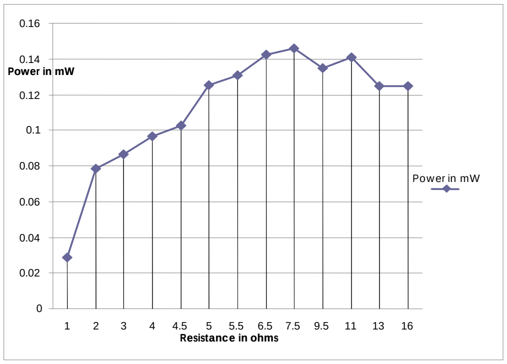

Figure 4. Actual inductive power output

Figure 5 shows the field test setup for the piezoelectric element. This setup consists of a small piezoelectric element glued to the underside of the rail. A series of resistors was connected to the output leads of the element, and voltage across the resistors was digitally sampled and recorded using a computer-based data acquisition board and a Labview control program.

Figure 5. Field test setup of piezoelectric device (orange clamps held device during glue up)

The train monitored during this test consisted of 4 locomotives with 2 on each end, pulling 120 unloaded (~65 kips) coal cars of standard size. Train speed ranged from a full stop to roughly 15 mph. Figure 6 shows the typical data obtained.

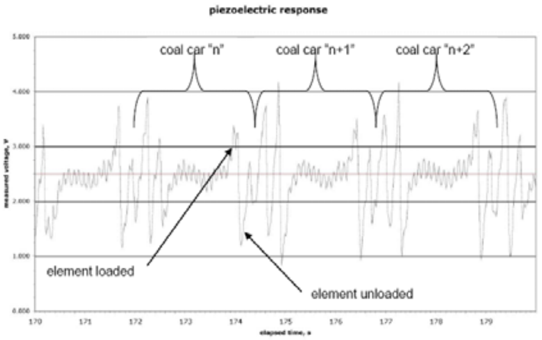

Figure 6. Typical piezoelectric element response under train load

Figure 7 shows the actual and predicted power as a function of load resistance. Peak average power of approximately 0.053 mW was obtained with a load resistance of 387 kΩ. Scaling this result for loaded trains yields an expected average power output of 1.1 mW, in excellent agreement with the numerical simulations.

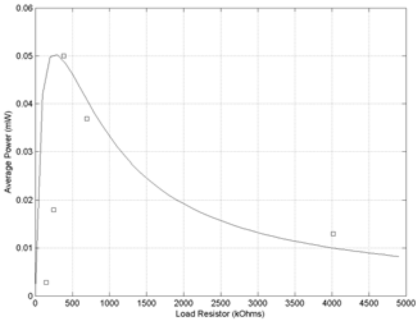

Figure 7. Simulated (curve) and actual (squares) piezoelectric power output as a function of resistive load

For both approaches, these tests show that simple devices can scavenge power near the desired level of 1 mW. Averaging power production between loaded and unloaded trains of the requisite number of the devices would result in adequate power for multiple sensors and wireless data transmission. For the inductive device, mechanical amplification of the vertical displacement is also an option using an intermediate spring to produce sympathetic harmonic excitation, thus increasing amplitude and power production.

CONCLUSIONS

A comparative study was conducted to evaluate the feasibility of using inductive and piezoelectric devices for scavenging power from passing Railcars. The basic concepts are explained, and results of numerical simulations and laboratory and field tests are presented. These results suggest that simple inductive and piezoelectric devices can be used to indefinitely power distributed networks of track-health monitoring sensors at low-power levels. Future work will include prototype development and investigation of increased power scavenging levels.

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REFERENCES

[1] SG-Link wireless strain node, www.microstrain.com, accessed 7/17/07.
[2] Park, C., Chou, P.H. "Eco: Ultra-Wearable and Expandable Wireless Sensor Platform," 3rd International Workshop on Body Sensor Networks, April 2006, pp. 162-165.
[3] Halliday, D., Resnick, R., Walker, J., 1996. *Fundamentals of Physics*, 5th edition, Wiley.
[4] Cady, W.G., 1964. *Piezoelectricity: An Introduction to the Theory and Applications of Electromechanical Phenomena in Crystals*, Vols. 1 & 2, Dover Publications, New York.
[5] Norman, C., "Measurement of Railroad Track Modulus from a Moving Railcar," Masters Thesis, Department of Mechanical Engineering, University of Nebraska, May 2004.

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KEYWORDS

Power scavenging, distributed sensor networks, railroad maintenance, inductive and piezoelectric devices