

# Development of Kinetic Energy Harvesting Systems for Vehicle Applications

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**Abstract**—This work demonstrates the implementation of a functional kinetic energy harvester designed to power wireless sensor electronics used in vehicular applications. The design, fabrication, and experimental characterization of a complete electrodynamic (magnetic) energy harvesting system capable of delivering in excess of 10 mW from 100 milli-g's of acceleration is presented. Unlike previous energy harvesting research, which typically focuses on individual components for proof-of-concept testing, the system implemented for this work includes the integration of a low-frequency transducer, power electronics circuitry, and a rechargeable storage element, all of which are required for a functional system. The design trade-offs, which result from the integration of these system components are examined and design rules for maximizing efficiency are given. Finally, field testing is presented, which demonstrates the ability of the system to operate over a range of different vehicle speeds.

## I. INTRODUCTION AND MOTIVATION

For wireless sensors and sensor networks, the functional lifetime is typically dictated by the finite amount of energy stored in chemical batteries. In embedded applications, where battery replacement and standard recharging techniques cannot be used, harvesting kinetic energy in the form of ambient mechanical vibrations provides a means to extend the operational lifetime of these systems. Over the past decade, a wide array of electrodynamic transducers have been proposed to harvest mechanical vibrations and convert this energy into usable electrical energy [1]–[3]. Electrodynamic energy harvesters, often referred to as magnetic in much of the energy harvesting literature, operate on the principle of electromagnetic induction, whereby electrical energy is converted from mechanical energy by the relative motion between a permanent magnet and a coil [4].

One of the biggest design trade-offs in the implementation of a kinetic energy harvester (KEH) involves the compromise between the system size and the total harvested power. In a *design for size* methodology, the goal is to minimize the overall system size while placing less emphasis on achieving a particular power budget. A *design for power* methodology, on the other hand, is constrained by the need to generate a specific minimum amount of power, and minimizing the size becomes secondary to the power requirements. For harvesting scenarios where the source of the vibration energy is large, such as in buildings and vehicles, and the generation of a particular power level is critical to mission success, a design for power approach should be employed.

In addition to an electrodynamic transducer, a functional energy harvesting system must also include power conditioning circuitry and a storage element; typically this is comprised of a capacitor or rechargeable battery. The power conditioning required for electrodynamic harvesters must provide rectification of the harvested energy as well the means to efficiently deliver it to the storage element and load. Additionally, the power overhead of the conditioning circuitry should be designed to have a minimal impact on the power requirements of the end applications. In this work, the design and characterization of a self-contained and functional energy harvesting system for vehicular applications is presented. Based on current transmission technology, power on the order of mW's is typically needed for a wireless system to significantly increase operational lifetime. Therefore, a power goal of 10 mW (delivered to the load/battery) was chosen. In Section II the basic structure and operation of the transducer and power electronic circuitry is described. In Section III laboratory calibration of the system is presented, and in Section IV the in-situ operation of the designed energy harvesting system is demonstrated. Finally, Section V presents conclusions and future work.

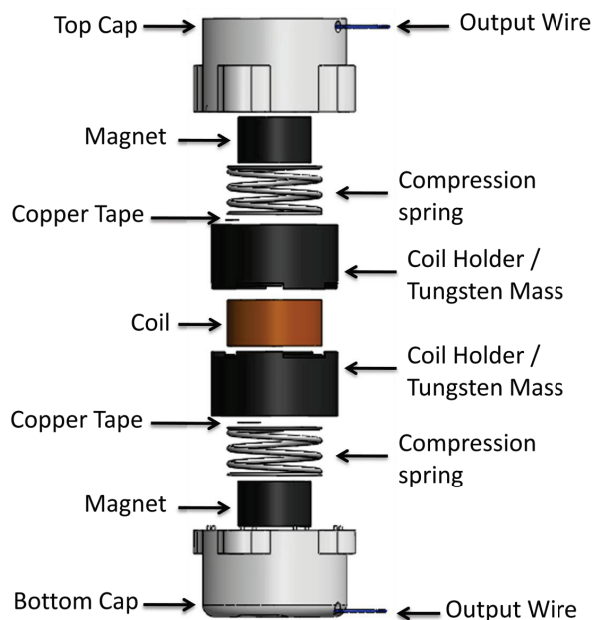


Fig. 1. Exploded schematic of the KEH transducer.

## II. ENERGY HARVESTER SYSTEM OVERVIEW

The energy harvesting system presented in this work is comprised of an electrodynamic KEH transducer, power conditioning circuitry, and a battery which is used to store the harvested energy. This section presents the general structure and basic operation of the various system components. First, the physical structure and underlying physics of the electrodynamic transducer is presented. This is followed by an explanation of the power conditioning circuitry and an overview of its operation. The battery used in this work is a standard Li-ion cell. Details on the charging and discharging behavior for this battery chemistry can be found in [5].

### A. Kinetic Energy Harvester

An exploded view of the electrodynamic KEH transducer used in this work is shown in Fig. 1. Rare-earth magnets made of neodymium are positioned at the top and bottom of the transducer in order to create a spatially-varying magnetic field. The magnets are oriented with like poles facing each other in order to create a large flux gradient [2], [6], as shown in Fig. 2. A copper coil is suspended between the two magnets using compression springs and is allowed to move relative to the magnetic field in the presence of applied mechanical vibration. The relative motion of the coil within the magnetic field causes a change in the incident flux through the coil, and therefore induces a voltage according to Faraday's law

$$V_{emf} = -N \frac{d\phi}{dt}, \quad (1)$$

where  $N$  is the number of turns in the coil and  $\phi$  is the magnetic flux density. In order to generate an induced voltage high enough to overcome the forward voltage drops of diodes in a standard rectification circuit, several thousand turns of copper wire are used to create the moving coil. The presence of the large magnetic flux gradient allows the transducer to harvest electrical energy from very small mechanical displacements.

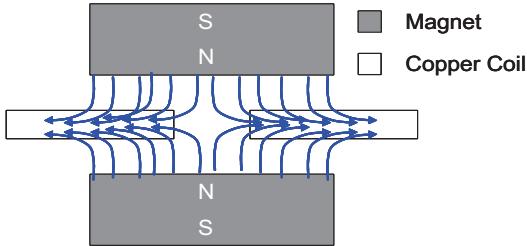


Fig. 2. KEH magnet configuration.

The mechanical behavior of the KEH transducer can be approximated as a second order mass-spring-damper system [7], [8], where the resonant frequency is a function of the mass and the spring constant. The transducer acts as an effective mechanical filter, only responding to vibration signals with a bandwidth near the resonant frequency. As the damping is decreased, which is desirable for increasing the amount of harvested energy, the response bandwidth of the harvesting system narrows. In order to harvest energy efficiently, it is

necessary to ensure that the transducer bandwidth coincides with the vibration energy spectra to be harvested.

Experimental vehicle data showing characteristic acceleration spectra as a function of frequency is shown in Fig. 3 at four different vehicle speeds. At each speed, the peak acceleration levels occur at frequencies near 13 Hz. In order to implement a KEH transducer capable of harvesting energy at these low frequencies, additional mass is added to the moving coil in the form of tungsten epoxy. The added mass also increases the inertial energy present in the transducer and allows more mechanical energy to be harvested.

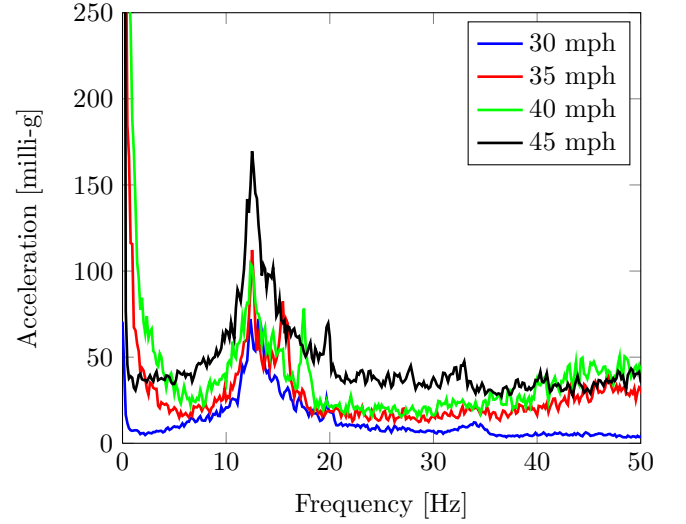


Fig. 3. Characteristic acceleration data as a function of frequency for various vehicle speeds.

### B. Power Conditioning Circuitry

The function of the power conditioning circuitry is to maximize the amount of usable power delivered from the transducer to the battery and electronic load. In theory, the maximum amount of power will be delivered when the transducer is loaded with the complex conjugate of its Thevenin impedance. In practice, however, it is often difficult to implement the complex impedance, and therefore preferable to implement a purely resistive load. Since the battery provides non-linear loading conditions to the transducer, interface electronics in the form of a DC-DC flyback converter are used to emulate a resistive load. The flyback converter is a pulsed width modulated (PWM) DC-DC switching converter operated in discontinuous current mode [9].

A schematic view of the KEH connected to the rectification circuitry and the flyback converter is shown in Fig. 4. The rectification circuitry used in this work is a full-wave bridge rectifier composed of 4 diodes,  $D_1 - D_4$ , and a rectifying capacitor,  $C_{Rect}$ . The flyback converter is comprised of the flyback transformer,  $XRf_1$ , a transistor switch,  $M_1$ , and the free-wheeling diode,  $D_5$ . The input resistance presented by the flyback converter,  $R_{in}$  is given by

$$R_{in} = \frac{2L_{XFR}f_s}{D^2}, \quad (2)$$

where  $L_{XFR}$  is the inductance of the transformer (either side),  $f_s$  is the PWM switching frequency, and  $D$  is the duty cycle of the PWM signal.

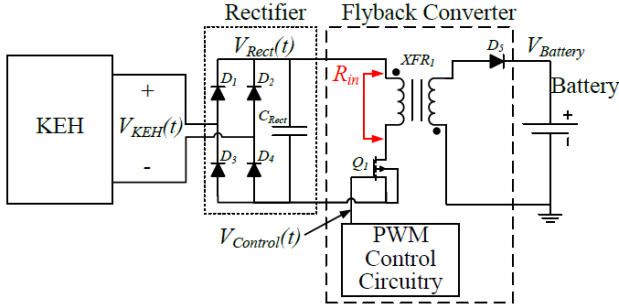


Fig. 4. Schematic diagram of the rectification circuit and flyback converter.

A schematic view of the PWM generation circuitry used to drive the flyback converter is shown in Fig. 5. This circuit is based upon the work by Taylor [10], and uses two comparators to generate the PWM drive signal,  $V_{Control}(t)$ . The first comparator,  $COMP_1$ , creates a triangle waveform,  $V_{Ramp}(t)$ , whose frequency is set by the RC time constant in the negative feedback path. The second comparator,  $COMP_2$ , then compares  $V_{Ramp}(t)$  to an adjustable DC voltage  $V_{Adj}(t)$  in order to control the duty cycle of  $V_{Control}(t)$ . Power for this circuit is provided by the battery. Signal waveforms created by the PWM generation block are shown in Fig. 6.

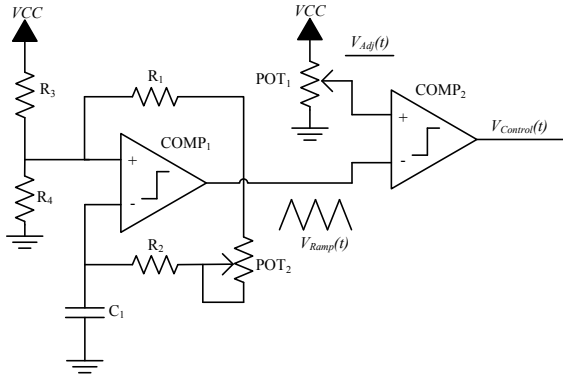


Fig. 5. Flyback converter PWM generation circuitry.

### III. LABORATORY CALIBRATION

Laboratory calibration was first performed before testing the energy harvesting system in the field. Using a shaker table as the acceleration source, the open-circuit resonant frequency of the KEH transducer was tuned to approximately 13 Hz in order to match the vibration spectra shown in Fig. 3. Tuning of the KEH was achieved by adjusting both the tungsten mass around the coil and the spring constant of the compression springs. The final mass of the coil/tungsten was approximately 310 grams.

For the KEH shown in Fig. 1, the optimal resistance was found empirically by connecting discrete resistors across the

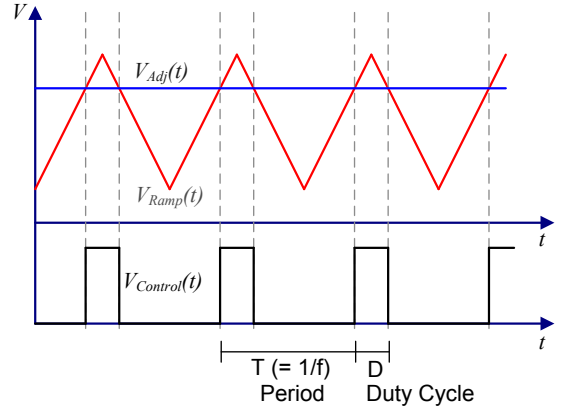


Fig. 6. PWM generation circuitry waveforms.

rectification circuitry and measuring the power delivered to each resistor. For the KEH used in this work, the optimal resistive value was found to be approximately 22 k $\Omega$ , which is higher than many of the other electrodynamic energy harvesters presented in the literature. Unlike many of the presented electrodynamic harvesters, which use coils with relatively low impedance (on the order of a few  $\Omega$ 's for the frequency of interest), the coil used for this KEH is comprised of several thousand windings (16,750) of very thin wire (AWG 38). As a result, the impedance of the coil, and therefore the required optimal load impedance is much higher than for other systems. From Eqn. 2, a flyback converter with the following values was implemented:  $L_{XFR} = 3.3$  mH,  $f_s = 100$  kHz, and  $D = 0.17$ . The power consumption of the PWM generation circuitry in this configuration was approximately 250  $\mu$ W.

### IV. FIELD TESTING

Two sets of field tests using the KEH transducer were performed at different vehicle speeds, one set loaded with a discrete resistor (22 k $\Omega$ ) and the other loaded with the calibrated power conditioning circuitry and battery. For all of the tests, both the KEH and an accelerometer were rigidly fastened to the same location on the test vehicle. Digital multimeters were used to measure the voltage and current delivered to the load, and power was calculated by multiplying the two values.

Spectra of both the input acceleration and the power delivered using the discrete resistor are shown in Fig. 7 and Fig. 8 for vehicle speeds of 35 and 40 mph, respectively. As expected, the harvested power is largest near 13 Hz, at the resonant frequency of the transducer. Integrating over the frequency range, average power levels of 28.1 mW and 26.7 mW were observed for the resistive loads at peak acceleration levels of just over 100 milli-g's. Due to the nonlinear operation of the power conditioning circuitry, spectral data was not taken and only the average power levels were measured. For these cases, power levels of 27.7 mW and 32.5 mW were measured for 35 and 40 mph, respectively. These results are summarized in Table I.

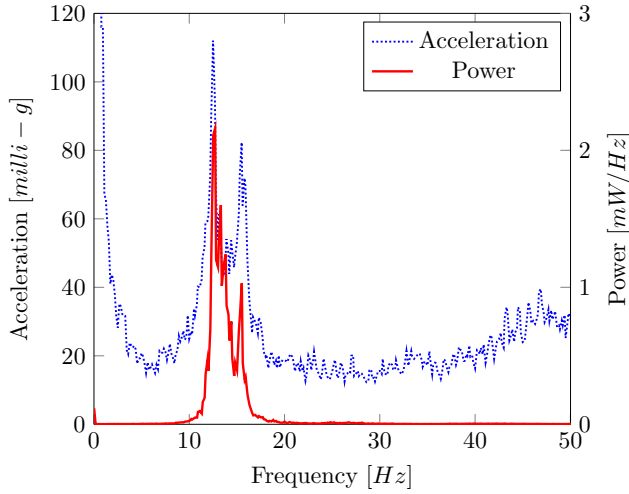


Fig. 7. In-situ experimental results of a fielded system operating at 35 mph with a 22 kΩ resistive load.

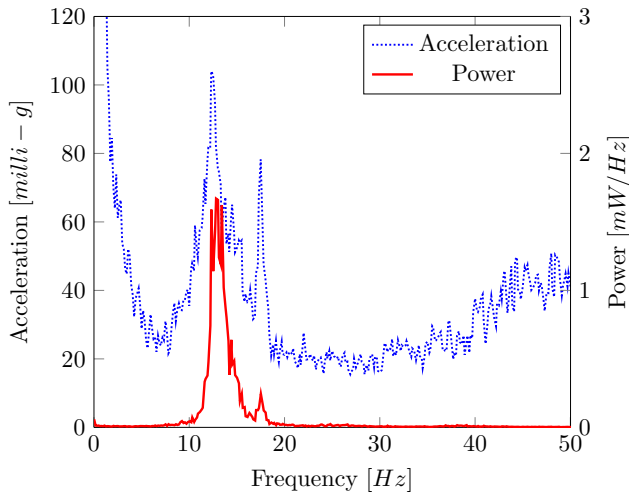


Fig. 8. In-situ experimental results of a fielded system operating at 40 mph with a 22 kΩ resistive load.

At 35 mph the power harvested using a resistive load was greater than that using the power conditioning circuitry. This difference in power can most likely be attributed to the losses associated with the conditioning circuitry and inefficiency in the flyback converter. For the 40 mph testing, however, the power delivered to the resistive load was the smaller of the two. The difference in power in this case most likely stems from the fact that the transducer had to be re-assembled between tests. As a result, the mechanical damping for the case of the resistive load was much higher than with the power conditioning circuitry. Variability of the vibration inputs between individual field tests may also play a role.

## V. CONCLUSION

In this work, SPAWAR Systems Center Pacific has presented a self-powered energy harvesting system for vehicular applications which is capable of delivering more than 20 mW of power from ambient mechanical vibrations. The developed

TABLE I  
SUMMARY OF OUTPUT POWER.

Speed [mph]	Resistor Load [mW]	Flyback Converter [mW]
35	28.1	27.7
40	26.7 <sup>1</sup>	32.5

<sup>1</sup> For the 40 mph testing the KEH transducer had to be re-assembled between tests. The open-circuit mechanical damping of the system when tested with the resistive load was measured to be nearly twice as large as the open-circuit mechanical damping when loaded with the flyback converter.

system includes both a robust transducer, capable of generating voltage levels in excess of 10 Volts, and power conditioning circuitry to efficiently deliver the harvested energy to a battery load. Using discrete, off-the-shelf components, power conditioning circuitry has been realized with an overhead power budget of only 250  $\mu$ W, less than 1% of the harvested power.

Future work for this project includes further reducing the power overhead and increasing the efficiency of the power conditioning circuitry. Due to the high impedance of the KEH, the optimal load resistance which the flyback converter must emulate is also large. Tuning the flyback converter to large values requires either high PWM switching frequency or low duty cycle. For discrete implementations high frequency switching often leads to greater power requirements. Furthermore, the current topology places limits on the minimum duty cycle, especially at high frequency, with a limit of around 14% for a 100 kHz switching frequency.

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