AdaptivEnergy

White Paper

Miniature Portable Ambient Energy Harvesting Modules Powered by RLP® Technology: Joule-Thief ™

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Executive Summary

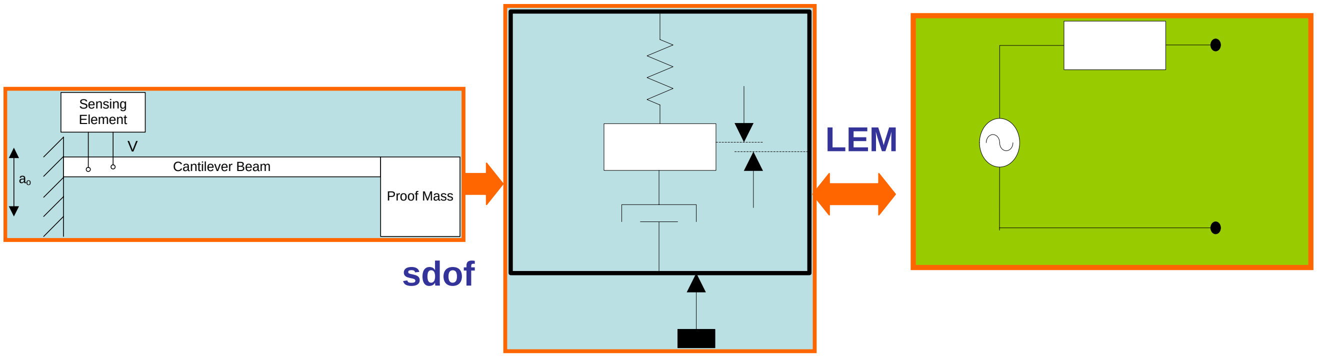
AdaptivEnergy has developed a miniature portable energy harvesting unit powered by its RLP® technology. This energy harvesting module, Joule Thief™, scavenges energy from ambient surroundings and converts it to usable electrical power that can be stored in batteries for further use. It offers significant advantages in size, reliability and cost over conventional energy harvesters. Additionally, it offers higher power outputs and power densities that are better suited for applications such as battery extensions, wireless sensors, condition monitoring etc. The flexibility and robustness of the RLP® technology coupled with Energy Key™ electronics results in a complete stand alone product for energy harvesting solutions. This paper presents an overview of the technology, the general operation and performance of AdaptivEnergy's energy harvester, Joule Thief™. In addition, this paper investigates several issues pertaining to the optimization of performance and finally, some general discussion regarding the applications for vibration based energy harvesters is presented.

Introduction

In the recent past, energy harvesting from the environment (when conventional power is unavailable) has generated a lot of interest for research where many available sources such as thermal, optical, mechanical, fluidic, etc. have been investigated. In addition, it was realized that human movement is a potential source for energy harvesting. AdaptivEnergy's Joule Thief^{TM} is designed to harvest mechanical strain energy, especially using low level vibrations from vehicular, seismic, and industrial environments. Some of the main applications include operating as power source for human wearable electronics, supplement battery storage devices etc. Another key application that is being investigated in great detail is miniature self powered sensors for medical implants for health monitoring and embedded sensors in structures such as bridges, buildings for remote condition monitoring.

AdaptivEnergy's RLP® (Ruggedized Laminated Piezo) actuator has been designed and manufactured such that its core electroactive PZT (lead zirconate titanate) ceramic component is held in compression, thereby relieving tensile failure of the PZT and resulting in a highly reliable, high performance, low form factor device. Powered by AdaptivEnergy's RLP® actuator technology, the Joule Thief has been designed to deliver electrical power at relatively high density (power per unit volume) over competing piezoelectric energy harvesting products.

While there are many converting methods to harness ambient vibration energy into electric power, AdaptivEnergy employs an electromechanical transduction mechanism. With the recent technology advancement in electromechanical transducers, high-performance small piezoelectric actuators can be fabricated in volume with lower cost and higher yield. This provides an opportunity to design and produce miniature instrumentation grade piezoelectric devices with higher reliability and superior performance in large quantities. In the following sections, general discussion of the operation, performance, optimization, and application notes are presented for the Joule Thief^{TM}.



Principle of Operation

Any vibration based energy harvester can be primarily divided into three parts. The first part consists of the *power generator* module which converts the ambient mechanical energy into an electrical equivalent energy. The second part is the *power processor* module that effectively processes the converted energy into a form of DC power. The final module is the *power storage* architecture which stores the generated power into a battery or a capacitor efficiently for application specific end use.

The fundamental concept for piezoelectric energy harvesting involves a piezoelectric layer attached to a vibrating mechanical structure that converts the strain energy into induced electric charge. Joule Thief™ is made up of a composite beam that consists of a cantilever shim with an attached piezoelectric layer and a proof mass at its end. The device when directly attached to a vibrating surface, places the whole structure in an accelerating frame of reference. The proof mass essentially converts the input base acceleration into an effective inertial force at the tip that deflects the beam, thereby inducing mechanical strain in the piezoelectric layer. This strain produces an effective voltage in the layer that is converted into usable power with the help of a power processor.

The cantilever configuration is chosen over other designs such as circular plate/membrane configurations or fixed-fixed plate/beam designs. The primary reason for this choice is based on the goal to maximize the stress/strain in the piezoelectric layer for a given fixed vibration input. Since the ambient surroundings have a definite amount of energy in amplitude and frequencies, the fundamental optimization in the mechanical device would be to generate maximum power for a given source. Consequently, the need to maximize the strain the piezoelectric layer is essential as the voltage generated in the piezoceramic is proportional to the strain induced.

AdaptivEnergy's Joule-Thief™ achieves exactly the same requirement using their core RLP® technology. AdaptivEnergy has spent years of research in developing a lamination technique for producing stress biased piezoelectric composites in various sizes and shapes. The stress biasing technique effectively places the piezoceramic element in the device under compression. Therefore, the operation range and strain limits for failure for the piezoelectric layer is extended further. Consequently, the device exceeds in performance and reliability resulting in a robust product that can survive harsh environments for extended periods of time. This unique feature of RLP® products provides a great advantage over competing technologies in similar applications.

RLP® Energy Harvester: Analytical Electromechanical Model

The Joule Thief^{TM} device consists of a piezoelectric composite cantilever beam with a proof mass at one end that essentially translates the input base acceleration to an effective deflection at the tip relative to the clamp. The induced strain due to the deflection in the device generates a voltage in the piezoelectric layer (using d_{31} mode). A simple schematic of the piezoelectric composite beam energy harvester is shown in Figure 1. In the figure, a_o is the input acceleration, f_{ext} is the excitation frequency of the base vibration and V is the resulting voltage from the piezoceramic.

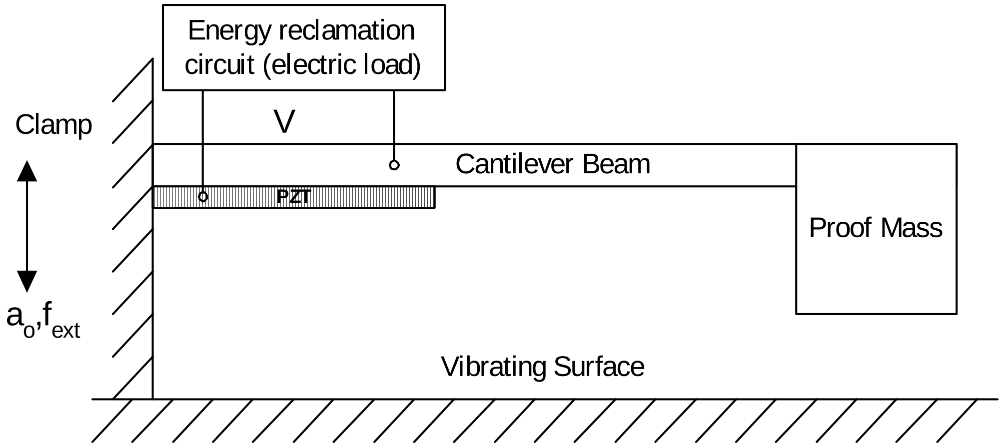


Figure 1: Schematic of a piezoelectric composite beam energy harvester.

The objective of this work was to be able to model an RLP® for energy harvesting, predict the power generated for known sources of vibration and provide an analytical tool for optimization and choice of materials and geometrical dimensions. An analytical electromechanical lumped element model (LEM) was formulated to accurately predict the behavior of the piezoelectric composite beam. This approach is valid in the case of a cantilever beam, until the first resonance. The lumped element modeling technique is useful for analyzing and designing coupled energy domain transducer systems. Here, equivalent circuit elements are used to effectively represent the actual behavior of the structure. These circuit analogies enable efficient modeling of the interaction between different energy domains in a system. Euler-Bernoulli beam theory is implemented to model the piezoelectric composite cantilever beam. The advantage of this circuit model is that it enables complete system simulation along with the energy harvesting circuit in pSpice, Cadence etc. The overall circuit is then represented in its thevenin equivalent to calculate the output voltage and impedance of the device. In this analysis, for simplicity, the output parameters such as voltage, current and power are calculated across a purely resistive load which can be simulated by connecting to the thevenin circuit form.

A piezoelectric composite beam represents an electromechanical system that can be separated primarily into two energy domains consisting of electrical and mechanical parts. These two energy domains interact in the equivalent circuit via a transformer as shown in Figure 2. The circuit is obtained by lumping the distributed energy stored and dissipated in the system into simple circuit elements. An impedance analogy is used to represent the circuit, where all elements sharing a common effort are connected in parallel, and the elements that share a common flow are connected in series. When the composite beam is subject to a mechanical load, the strain induced in the piezoelectric material generates a voltage, which represents the conversion from the mechanical to the electrical domain. Conversely, the composite beam can be driven with an ac voltage that causes it to vibrate due to the piezoelectric effect. This represents a conversion from the electrical to the mechanical domain. This is a very general representation of a piezoelectric transducer to model its behavior as an actuator, sensor and energy harvester.

Figure 2 represents the entire equivalent circuit consisting of mechanical and electrical lumped elements representing the composite beam. All elements are labeled and defined in the figure. In the notation shown in the figure, the first subscript denotes the domain (m for mechanical and e for electric), while the second subscript denotes the condition (s for short circuit and b for blocked). Using the described notation, for example, C_{ms} is defined as short-circuit mechanical compliance, and C_{eb} is the blocked electrical capacitance of the composite beam.

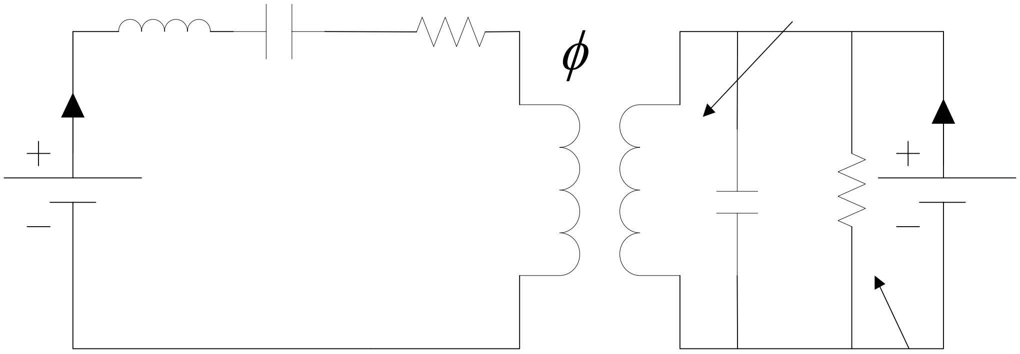


Figure 2: Equivalent electromechanical circuit model for a piezoelectric energy harvester.

F is the effective force applied to the structure that is obtained by the product of input acceleration and effective mass lumped at the tip, U is the resulting tip velocity, V is the voltage, and I is the current generated at the ends of the piezoelectric material. All the parameters are obtained by lumping the energy at the tip using the relative motion of the tip with respect to the base. The beam is represented as a spring-mass-damper system by lumping the energy (kinetic and potential) in the beam to an equivalent mass and compliance. The mechanical mass and compliance of the structure can be equated to an equivalent electrical inductance and capacitance. Similarly, mechanical damping is analogous to electrical resistance. However, mechanical damping cannot be easily estimated from first principles although it is a critical parameter for resonant structures.

Power transfer analysis

Although the overall electromechanical model appears complex, it can be further simplified as a thevenin equivalent circuit as shown in Figure 3. This representation enables easier understanding of the power generator module as an effective voltage source with equivalent impedance called the thevenin impedance. The estimation of thevenin equivalent parameters is a well known concept in circuit analysis. An alternate representation would be a Norton equivalent circuit that represents the RLP® as an effective current source with equivalent parallel impedance. Now, the power processor can be connected to the end of the thevenin circuit for simulations. Here, we assume a power processor that acts as a purely resistive load at the output.

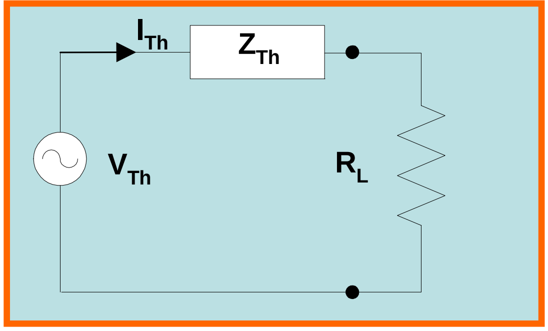


Figure 3: Thevenin equivalent circuit model for a vibration energy harvester.

Substituting the lumped element expressions for the parameters in terms of material properties and device dimensions provides the desired scaling dependence of power and efficiency but results in complex algebraic expressions. Furthermore, these analytical expressions provide a comprehensive model that enable intelligent design for any specific requirement. This analytical model has been previously tested and verified with experiments on macro-scale PZT composite beams (Kasyap et al., 2002, 2006) and FEM wherever applicable. In addition, a non-dimensional analysis was carried out to observe the overall device performance with respect to various dimensions and properties. This procedure aids in material selection and other properties for the device to maximize the extracted power from a vibration. This model is constantly used during design to prevent multiple design cycles to arrive at a final optimized design.

A picture of the RLP® beam is shown in Figure 4 below. The beam used in the Joule-Thief™ module is smaller than 2 inches.

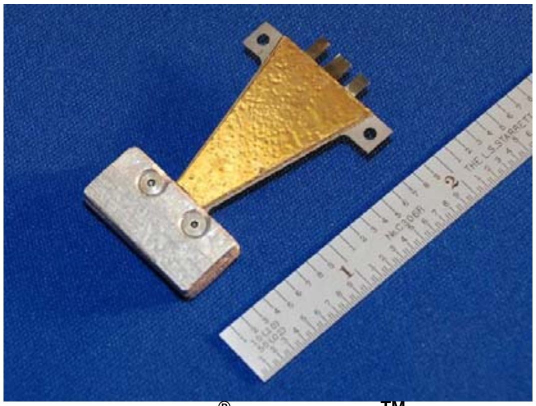


Figure 4: RLP® Joule-Thief™ beam.

Energy flow in a vibration based energy harvester

Next, the energy conversion between various modules of the energy harvester is discussed. First, the ambient mechanical energy is converted to its electrical equivalent using the piezoelectric transduction mechanism discussed earlier. This transfer represents the power generator part of the device. The ac voltage generated at the RLP® is then converted into a DC voltage using the power processor module that is stored in the power storage module to be dissipated across a load. Figure 5 represents the power transfer diagram in the Joule Thief™. The objective of the power converter is to match the impedance of the power generator, RLP® energy harvester for maximizing the power transfer.

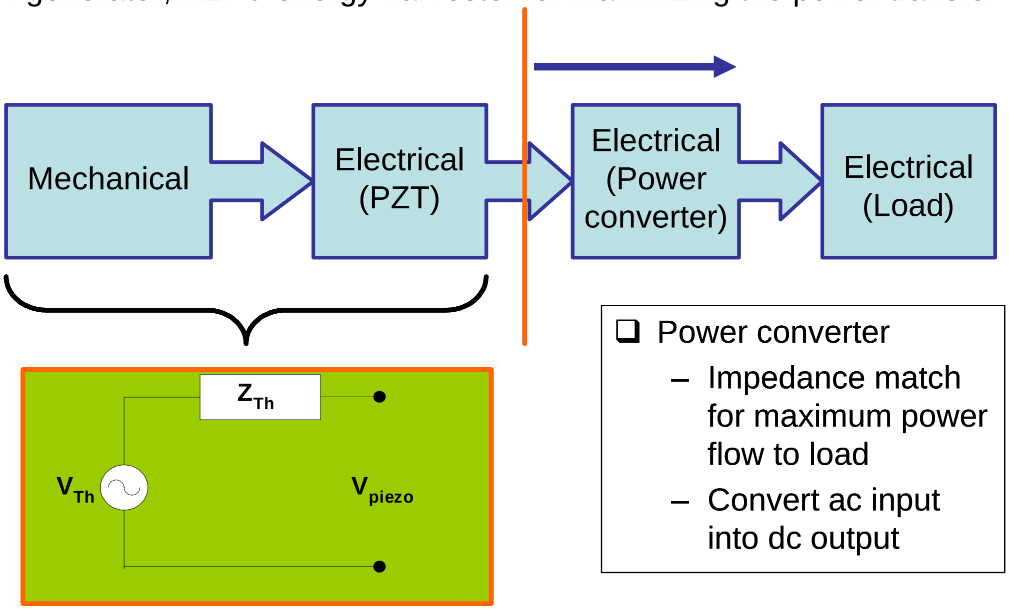


Figure 5: Energy flow in a vibration based energy harvester.

Energy Harvesting Key™

The output of a raw Joule-Thief™ energy harvesting beam consists of a high voltage sinusoidal signal (up to +/- 200 Volts). The devices that need to be powered typically require a low DC voltage (1.8 to 3.6 Volts). Therefore, it is imperative to have circuitry that will reduce the voltage to a more usable level and provide low loss energy storage for the scavenged energy. The energy harvesting key combines both the power processing module and the power storage module described earlier. A block approach was adopted with the design of the energy harvesting circuitry. The blocks thus developed include: (1) an active energy extraction circuit which increases energy harvesting efficiency, (2) an ultra low power switching circuit that diverts energy to a storage capacitor when insufficient energy is available to drive the load and (3) a charging and management circuit for a Li-Ion battery. The complete energy harvesting circuit was modeled using pSpice and verified with experimental data to validate its function and performance. A description of Modules 1, 2 and 3 follow.

Module 1: Active Collection Circuit

Module 1 is an active switching circuit that essentially extracts energy from the RLP® beam at the optimal time to maximize the energy transfer to the storage element. This is accomplished using a low power active circuit to detect the voltage on the RLP® capacitance that triggers the release of energy in the capacitor using a low power MOSFET through an optimal inductor and into a suitable energy storage element when the voltage reaches a peak. Any suitable energy storage component, such as a capacitor, can be used with this circuit. Other energy storage means such as an ultra capacitor or battery can also be used, provided any necessary voltage and current limits for the chosen energy storage element are observed.

Module 2: Energy Extraction and Switching Module

Module 2 is an ultra-low power switching circuit that diverts energy to a storage capacitor when insufficient energy is available to drive the desired load. This is achieved by connecting the onboard storage capacitor to the load when the capacitor voltage reaches 3.6 Volts and disconnecting the load when the capacitor voltage reaches 1.8 Volts using two very unique ultra-low power Field Effect Transistors (FETs). This accomplishes two key requirements: First, to produce a more common and usable 1.8 to 3.6 V DC output to drive the load, and second, the energy is extracted from the RLP® at an optimal voltage that closely corresponds to an impedance match. This feature ensures that maximum power transfer occurs from the RLP® Joule-Thief™ beam. The capacitor initially charges until it reaches approximately 3.6 Volts following which the load is connected, in this case a dead short. The capacitor voltage then drops rapidly to the lower cutoff voltage of approximately 1.8 Volts after which the load is disconnected and the capacitor begins to recharge. The capacitor was chosen to optimally charge and switch for specific low power applications in mind. That value can be changed according to other power requirements for wireless applications.

Module 3: Li-Ion Battery Charging and Management

This module provides the battery charging and protection features for a Li-Ion battery in the Joule-Thief™ EHD modules. The battery charging module uses an ultra-low power battery management chip to provide the battery charging and protection features. This is essential to maintain the voltage levels required to protect the battery from over charging and complete discharge.

A picture of the Joule-Thief™ Energy Harvesting Module is shown in Figure 6. The module contains the RLP® Joule-Thief™ beam, the energy harvesting circuit. Two alternate versions of the circuit are provided, one that includes the battery management part and provision for a Li-Ion battery. The other version is the standard capacitive version that can be used in low power applications directly. It should be noted that both versions are essentially the same, except that the battery version has a battery management chip and a few components to regulate the voltage output to suit battery charge/discharge cycles.

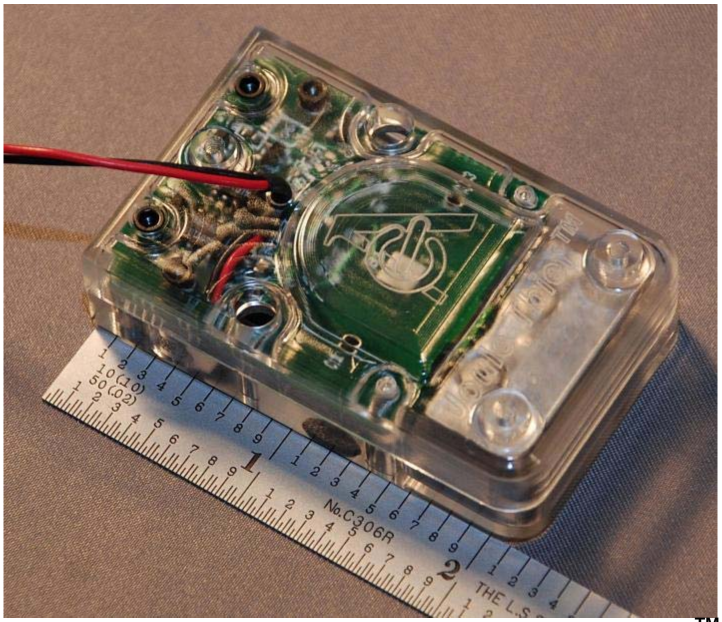


Figure 6: Energy harvesting module for the Joule Thief™

Measured performance of the current circuit achieves twice that of a passive circuit and generates an overall circuit efficiency of 58-63%, depending on the voltage generated at the PZT.

For more technical information about the RLP® beam and Energy Key™ product, readers are referred to its datasheet, which can be downloaded from AdaptivEnergy's website, www.adaptivenergy.com.

Performance Metrics

The Joule Thief EH Development Kits were prototyped, qualified and tested at the AdaptivEnergy facility. While there is no standard performance metric for EHDs, the following was captured as a benchmark for further testing and evaluation by the customer. Application specific engineering support will be provided by AE to the customer if required. The contact for discussion is provided at the end of this document.

The shape of the beam is tapered to effectively obtain a uniform stress state across the length of the PZT. This will strain the PZT equally unlike a rectangular beam that will have a normal stress gradient along the length. As a result, for a rectangular beam, maximum stress occurs at the clamp and will gradually reduce to zero stress at the tip. In such a case, all of the PZT is not strained and utilized efficiently unlike in the tapered beam that produces a constant bending axial stress.

Power output of Joule-Thief^{TM}

Since the power output of a piezo generator is dependent on the load impedance, it is important that the energy harvesting circuit effectively presents optimal load impedance to the device for maximum power transfer. A simple way to determine the optimal load impedance is to measure the power output of the device versus the external load with the specific vibration input that will be used in the particular application. A plot of this data will have a definite peak in the power versus load curve at the value of the optimal load. The optimal load typically corresponds the one-half the open circuit voltage produced by the beam for that vibrational input. However, designing a circuit that acts as a pure resistor is difficult. AdaptivEnergy's Energy harvesting circuit was designed with this feature in context and therefore, maximizes the energy transfer.

Next, the EHD module was completely assembled with the capacitive version of the energy harvesting circuit. Using the battery version will complicate the characterization of the EHD module and therefore was not included here. The voltage accumulated in the circuit is allowed to dissipate across a 100 Ω resistive load. During each cycle, the module dissipates approximately 2 mJ of energy across the load which is sufficient for transmission in many wireless sensor applications. A sinusoidal vibration at 60Hz was used as source for the module. Increasing acceleration levels were used to obtain the energy discharge curves as shown in the following plot.

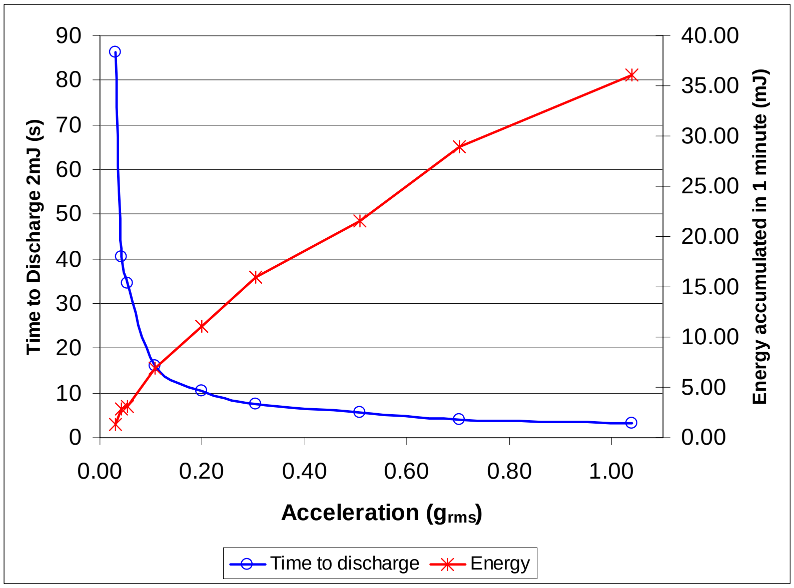


Figure 7: Energy charge/discharge for the Joule Thief EHD module.

As indicated in the plot, the time between discharges exponentially decreases as the source acceleration increases. Additionally, it should be noted that the resonance shifts with magnitude of the vibration and is not considered here. Furthermore, the energy that is generated using the Joule-Thief^{TM} module in 1 minute is also shown in the plot. As much as 35 mJ of usable energy can be generated with a 1g$_{rms}$ input at 60 Hz. Most ambient vibrations are below 0.2 g$_{rms}$ which generate more than 10 mJ of energy using Joule-Thief^{TM} module. Frequency sweeps were also carried out to measure the average real power delivered to the load for various acceleration levels. Figure 8 shows a plot of power as a function of frequency for accelerations varying from 50 mg$_{rms}$ to 1 g$_{rms}$. As expected, the resonance shifts from 58 Hz down to 54 Hz. It should be noted the open circuit resonance will shift lower when a load is connected to the PZT. Depending on the vibration source, bandwidths can be established for the Joule-Thief^{TM} that will enable energy harvesting at multiple frequencies or across a range around the device resonance.

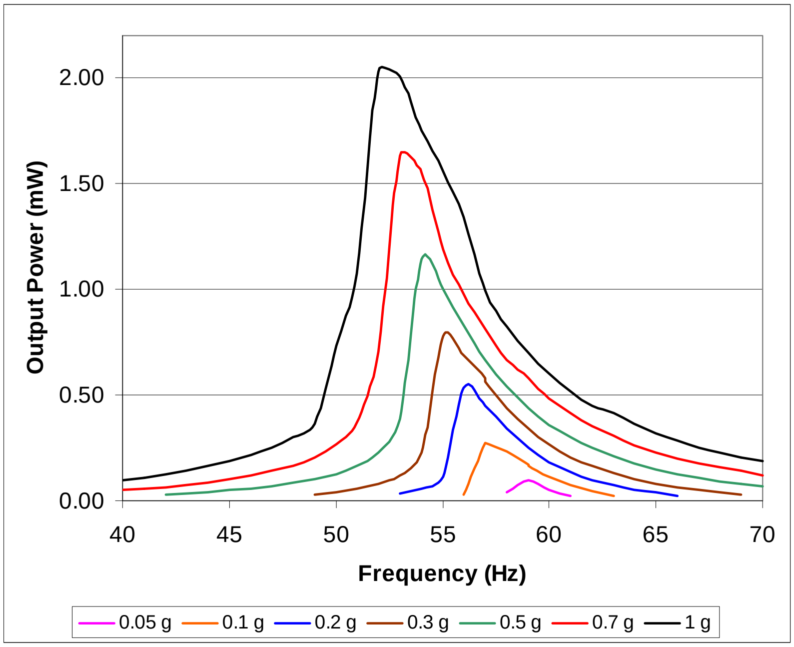


Figure 8: Average power generated by the Joule-Thief^{TM} EHD module.

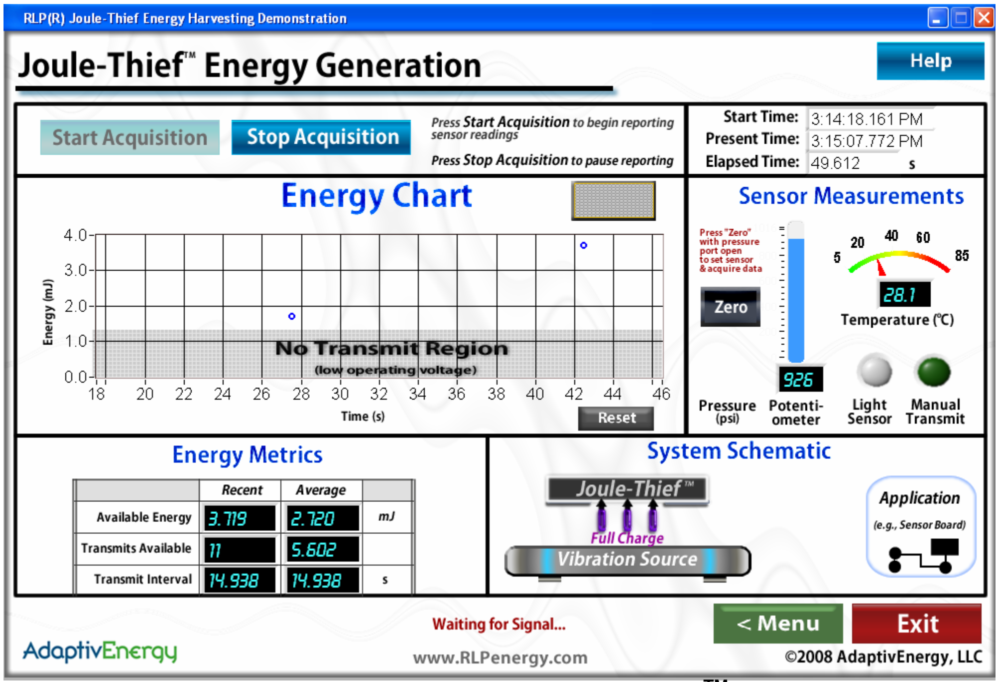
Candidate Application : Powering Wireless sensor nodes/networks

An obvious application for the Joule-Thief^{TM} is serving as a power solution for wireless sensor nodes. Joule-Thief^{TM} already proved that it has significant advantages and superior performance over other competing technologies. In addition, AdaptivEnergy also demonstrated that Joule-Thief^{TM} can easily power multiple wireless sensors and transmit data to a remote sensor located many meters from the wireless node. The reader is referred to www.adaptivenergy.com for more details. A significant feature for Joule-Thief^{TM} is that it presents infinite lifetime compared to other battery solutions. An important advantage therefore is eliminating replacement of batteries that constitute a major part of service and maintenance for customers, both in capital and labor.

The Joule-Thief^{TM} EH demonstration kit currently costs $ 699.00. Figure 9 shows the demonstration kit that is currently shipped by AdaptivEnergy. AdaptivEnergy will engage the customer and provide necessary engineering support if required to implement the kits in their applications. The Joule-Thief^{TM} demonstration kit comes with a standard air pump that serves as the vibration source. The vibration of the pump while running is sufficient to power the array of sensors on the board. Sensors such as pressure sensor, temperature sensor, light sensor, potentiometer are situated on the sensor board module. Energy harvested from the vibration is utilized to power this multitude of sensors and transmit data real-time to a remote wireless receiver for processing. This development kit clearly demonstrates a completely stand alone turn key energy harvesting solution in the area of wireless sensor networks.

Figure 9: Joule-Thief^{TM} Energy Harvesting Demonstration Kit

A snapshot of the data acquisition that shows various sensor measurements transmitted using the energy harvesting kit is in Figure 10. The kit when fully charged contains enough energy to make 10 transmissions without any vibration source attached to it. A provision for manual transmissions is also available on the sensor board for the user.



Press **Start Acquisition** to begin reporting sensor readings

Press **Stop Acquisition** to pause reporting

Start Time: 3:14:18.161 PM
Present Time: 3:15:07.772 PM
Elapsed Time: 49.612 s

Press "Zero" with pressure port open to set sensor & acquire data

Temperature (℃): 28.1
Potentiometer: 926

	Recent	Average	
Available Energy	3.719	2.720	mJ
Transmits Available	11	5.602	
Transmit Interval	14.938	14.938	s

Waiting for Signal...

Figure 10: Data acquisition screenshot of the Joule Thief^{TM} EH Demonstration kit.

The Joule-Thief^{TM} lends itself well even for vehicular applications such as automobiles and trucks. Vibrations on vehicles are more random and occur over a wide frequency range instead of single frequency peak. In addition, the input will vary depending on the type of vehicle and the location of the device on the vehicle. AdaptivEnergy has performed real-time vibration measurements on different locations on base vehicles and recorded the acceleration spectra. However, as a rough baseline for the expected power output from the EHD while mounted to a vehicle a shaker was used to simulate these vehicle input from recorded accelerometer data. Since the input is discontinuous, the power output from the EHD is also not constant. Therefore, the average power was measured over 30 seconds of simulated vehicular vibration. Depending on the vehicle location and type of vehicle the "average" power output from the EHD was sufficient for many transmissions.

Since the power output of a piezo generator is a function of the magnitude of the mechanical input to the device it is useful to determine the power output of the device with the expected input. This device is designed to be directly mounted to any even surface using magnets. Provisions are given for screw mounts for a more rigid attachment. Therefore, the customer is encouraged to investigate the Joule-Thief^{TM} on alternate vibration sources with AE's technical support.

Conclusion

The Joule-Thief^{TM} energy harvesting beam is optimally designed for power generation and collection at very low vibrations (even perceivable to humans) down less than 10milli-g. However, they work reliably well for accelerations in the range of 3g_{rms}. Preliminary tests have been carried out to verify durability at elevated vibrations levels, impact and shocks.

Contact Information

For more information regarding technical support or assistance, contact Anurag Kasyap at (757) 320-4121 (akasyap@rlpenergy.com). For more information regarding the products and services AdaptivEnergy offers, visit www.adaptivenergy.com. AdaptivEnergy is the leading innovator of miniature piezo actuators and generators. Founded in 1997, AdaptivEnergy is a privately held company based in Hampton, Virginia. The core RLP® (Ruggedized Laminated Piezo) technology of AdaptivEnergy's products and services is protected under US 7,191,250 and US 7,191,503 in addition to several foreign patents. US and Foreign Patents Pending.