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Multi-Transducer System for Energy Harvesting

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NOMENCLATURE

a_1	½ the total thickness of the PZT and substrate
a_2	½ the thickness of the substrate
a_3	-½ the thickness of the substrate
D_3	Electric displacement
d, d_{31}	Electromechanical coupling coefficient
E_b	Elastic modulus of the substrate
E_3	Applied electric field
I	Current
P	Power output
R_L	Load resistance
S_1	Axial mechanical strain
s_{11}^E	Mechanical compliance under constant electric field
T_1	Applied axial stress
T_w	Hot side temperature of TEG
T_c	Cold side temperature of TEG
V, V_3	Voltage output by transducer
Y_1^E	Modulus of the PZT under constant field
α	Seebeck coefficient
ε_{33}^T	Permittivity under constant stress
κ	Curvature of the substrate

ABSTRACT

Multi-sensor arrays are an emerging technology to reliably measure the various conditions in civil, aerospace and biomedical applications. One of the major drawbacks in embedded systems is providing power to the individual sensor nodes. In some remote locations supplying power through cables, or using disposable energy sources, is often impractical if not impossible. By using energy harvesting techniques a fully self-sustaining system can be implemented. The purpose of this study is to compare two methods of energy harvesting to determine optimal solutions in terms of power output for a given environment. The techniques analyzed in this study include piezoelectric materials and thermoelectric ceramics. Vibration and thermal measurements are taken from existing structures, and these measurements are then used to perform controlled laboratory experiments to simulate the various environments in which energy harvesting systems can be located. Mathematical models are also developed to predict the power output using the measured excitations. From the results of the models and tests, the best possible operating conditions for each technique of energy generation are determined. By utilizing various sources of ambient energy, a multi-transducer system is designed to optimize energy harvesting across a large structure. Using the energy provided by this multi-transducer approach, a low-power wireless impedance-based sensor node is operated as a proof-of-concept for a fully self-sustained embedded sensing system.

1 INTRODUCTION

Energy harvesting is the method by which ambient energy is extracted from the environment and converted into a form that can be used to accomplish a specific task. While this technique has been used by humans for centuries in the form of water wheels and windmills, recent studies have focused on harvesting vibrations and thermal gradients as a means for powering modern electronics. These sources have traditionally been considered too small to power sensing equipment; however modern advances in low power electronics and wireless communication devices have made it possible to develop highly efficient sensor nodes. Recently a wireless impedance device (WID) has been developed that offers active sensing capabilities, yet operates at power levels that make it amenable to several energy harvesting techniques [1, 2]. In this study both electromechanical and thermoelectric devices are used to harvest mechanical and thermal energy from common everyday sources, storing this energy in a small capacitor which is used to power the wireless impedance device.

1.1 Background

Piezoelectric materials were first introduced into the scientific community in 1880 by the French physicists Pierre and Jacques Curie [3]. Piezoelectric materials have the unique property of producing an electrical charge when undergoing a mechanical strain, known as sensing, and conversely they will produce a mechanical strain when an electrical potential is applied, known as actuation [4]. Since the discovery of these original materials there have been numerous attempts to fabricate new substances with improved mechanical and piezoelectric properties. These studies have led to the development of the most common piezoelectric materials used today: lead metaniobate (PMN), lead zirconate titanate (PZT) and polyvinylidene fluoride film (PVDF) [1]. Since their discovery piezoelectric substances have had a wide variety of uses including sonar sensors, microphone pickups, radio transducers, and acceleration/force gages.

Piezoelectric materials receive the most amount of research attention due to their high voltage output, ease of implementation, and their availability. In most energy harvesting applications piezoceramic materials are bonded to a cantilever beam which has natural frequencies tuned to the expected excitation frequencies. The resulting bending stress induced in the beam due to ambient vibration is transformed into electrical energy by the Piezoceramic patches. A method of energy harvesting utilizing piezopolymer strips includes attaching one end of the strip to a structure while the other end is attached to a mass. The stress induced by this single degree-of-freedom mass-spring system is then transformed into electrical energy by the piezopolymer [5].

Aside from using mechanical vibrations to produce energy, the conversion of thermal gradients into useable electrical energy is also an area of interest for energy harvesting research. Devices that perform this energy conversion are known as thermoelectrics and work on the principles of the Peltier-Seebeck effect. Peltier described the temperature gradient that is produced when a set of dissimilar metals is introduced to an electrical current. Conversely, Seebeck noted that an electrical current is produced when two dissimilar metals are introduced to a temperature gradient. This Seebeck effect is the main focus of energy harvesting because a large temperature gradient can produce a relatively large amount of energy. Thermoelectrics have received considerable interest in the automotive industry, where the exhaust from engines has been used to produce electrical power. As a demonstration of the potential power output from exhaust heat, a thermoelectric recovery unit placed on a diesel truck produced 1kW of power, enough energy to bypass the alternator completely [6]. The largest downfall to thermoelectric energy conversion is when the temperature gradient is not significantly large which results in very low conversion efficiencies and power outputs.

The final obstacle in energy harvesting techniques is the conditioning and storage of the harvested electrical power. Passive bridge rectifiers have long been used to convert incoming AC signals into DC signals, which in turn are stored directly to a capacitor; however, this is not ideal because there is no way to monitor or control the amount of power being transferred. Also, when using thermoelectric generators (TEG) the DC voltage produced by the TEG may not be high enough to obtain the voltage level needed to power some electrical components. As a result of these problems there has been a strong push for research in the field of low-power, high efficiency rectifying and power conversion circuits [7].

1.2 Motivation

The accelerated demand for self sustaining electronics, such as wireless sensors, has fostered a new found interest in energy harvesting systems. Given their nature, wireless sensors require a self-sustained power supply.

This issue has been addressed previously by using conventional electro-chemical batteries; however, for some applications using such a power source is impractical due to their finite lifespan. Furthermore, some applications place these sensors in remote locations (i.e. bridges – SHM, animals – GPS as tracking devices, structures with embedded sensors, etc.), where retrieval of the hardware is troublesome and in many cases the cost of maintaining a sensor is more than that of the sensor itself. Due to the fact that energy is ever-present in the surroundings (i.e. vibrations, heat, radiation and many others); extracting and storing this energy into capacitors or rechargeable batteries becomes technically and economically beneficial. By designing wireless sensor networks to rely on ambient power sources alone some of the detrimental effects of using nonrenewable power sources are mitigated. Previous efforts in powering wireless sensor nodes have been focused on using a power harvesting device focusing on converting one source of ambient energy. This approach seems practical when the host structure is under a single constant excitation for which a transducer has been designed. However, if the host structure is not under constant excitation then sensors at some locations will not be provided with adequate power. Given this problem, a systematic approach for designing multiple power harvesting devices is employed to draw out energy from several of the available surrounding sources, providing a relatively constant power source.

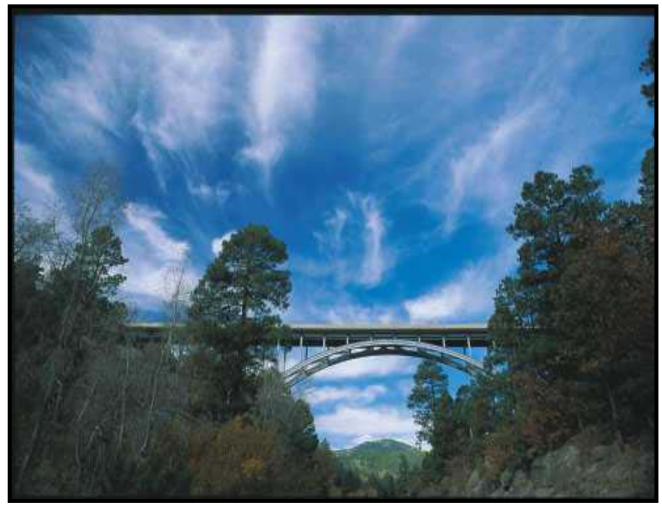

Figure 1: Vibration and temperature measurements were taken along the Omega bridge in Los Alamos, NM in July 2008.

1.3 Purpose

The purpose of this project was to develop a multi-transducer system that could harvest electricity from the vibrations and thermal gradients associated with common pieces of equipment or infrastructure. Three sources were considered for this investigation, including a small vehicle engine, a compressor motor, and a local highway bridge. Due to time constraints, the bridge data was selected as the primary excitation source, and an electromagnetic shaker and a thermal fixture were used to replicate the data in the laboratory. Piezoelectric and thermoelectric materials were used to convert each form of energy into an electric signal which was used to charge a 0.1F capacitor. This capacitor was selected so that we could estimate the charging profile expected with the WID sensor node. Each transducer was first characterized independently and then they were combined to provide an integrated harvester that could be used to successfully operate one of the wireless impedance-based sensor nodes.

This paper is organized into six sections beginning with the introduction which presents background information and the motivation behind this work. The various sources of excitation are discussed in Section 2, with some detailed examples of the vibration and thermal environments measured for the bridge structure. Section 3 presents a discussion on the piezoelectric materials used in this study, along with an analytical model and some validation results. Section 4 provides a similar discussion of the thermoelectric materials, comparing the analytical model with some experimental results. The energy harvesting properties of each of these materials are brought together in Section 5, first examining each independently, then combining the energy harvesters to operate the wireless impedance device. In the final section a short discussion is presented of the overall study, and several conclusions are presented regarding the suitability of this multi-transducer technique in powering small sensor systems.

2 SOURCES OF EXCITATION

The first stage in this study was to collect environmental data from several mechanical and thermal sources that are commonly found on structures. Three distinct sources were considered in this stage: a small vehicle engine, a pneumatic compressor, and a highway bridge located near the research facility. Acceleration and temperature data was collected for each of the systems, however due to time constraints only the data taken from the Omega

Bridge in Los Alamos, NM (Figure 1) was used as part of the energy harvesting study. Vibration measurements were taken at several locations along the outer steel girder on the western side of the bridge. PCB Model 352A24 accelerometers were placed 3m from the southern bridge abutment, and time histories were captured as normal traffic excited the bridge. The resulting data was collected using a LDS-Dactron Photon II data acquisition system. Temperature measurements were made hourly at several locations along the concrete deck of the bridge throughout the day using a handheld Fluke Model 62 infrared thermometer. These results were compared to ambient air measurements to estimate the thermal gradients that would develop at different times of the day.

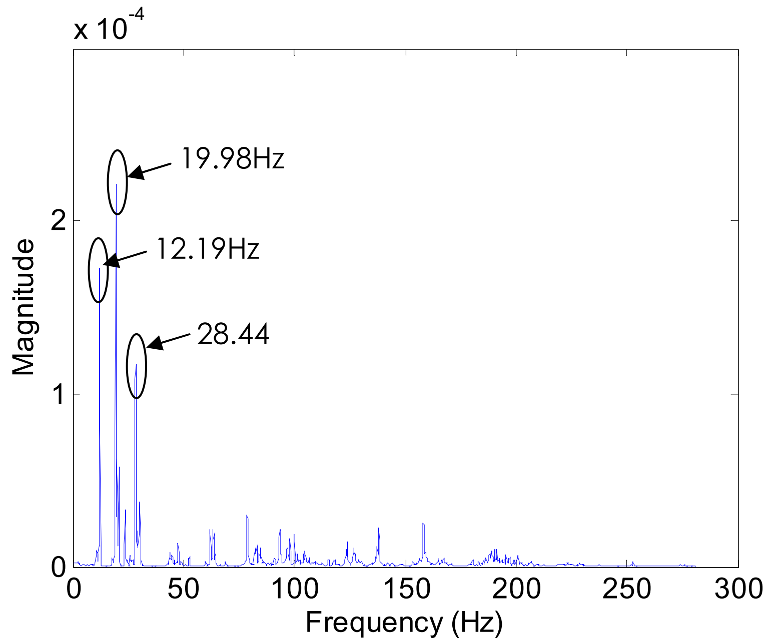

Figure 2: Autospectrum of the acceleration data measured on the Omega Bridge in Los Alamos, NM.

The purpose of collecting the vibration data was to identify the fundamental frequencies of different sections of the bridge. One example of the resulting data is shown in Figure 2, corresponding to the transverse motion of the webbing in one of the steel I-beams supporting the southern-most span of the bridge. Using this frequency data, cantilever beams could be designed to resonate at the same frequencies as those found on the test structure, yielding the maximum potential harvested energy. The frequency response data was obtained by conducting a Fast Fourier Transform (FFT) on the data and constructing the autospectrum as shown in Figure 2. The results of this spectral analysis were also used to develop excitation signals that would be used to drive the cantilevered energy harvesters in a manner that would emulate the operating environment of the bridge.

Similarly, temperature measurements were taken along the length of the bridge, as indicated in Figure 3. These measurements were subsequently compared with the ambient air temperatures to develop the thermal gradient one would expect for a thermoelectric transducer mounted on the bridge deck. These thermal gradients are presented in Figure 4 for three positions along the bridge. It is seen from this chart that the thermoelectric would be ineffective in the morning as the bridge

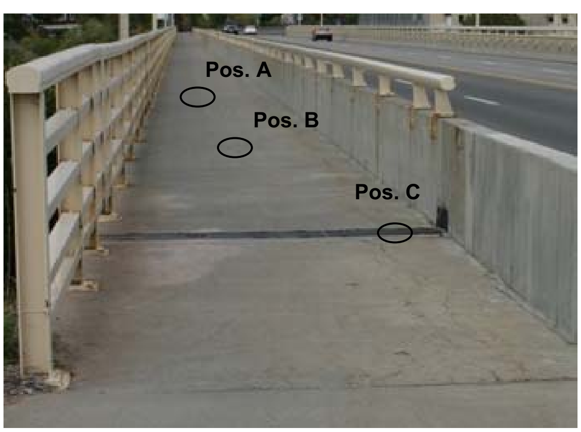

Figure 3: Temperature measurement locations along the Omega Bridge.

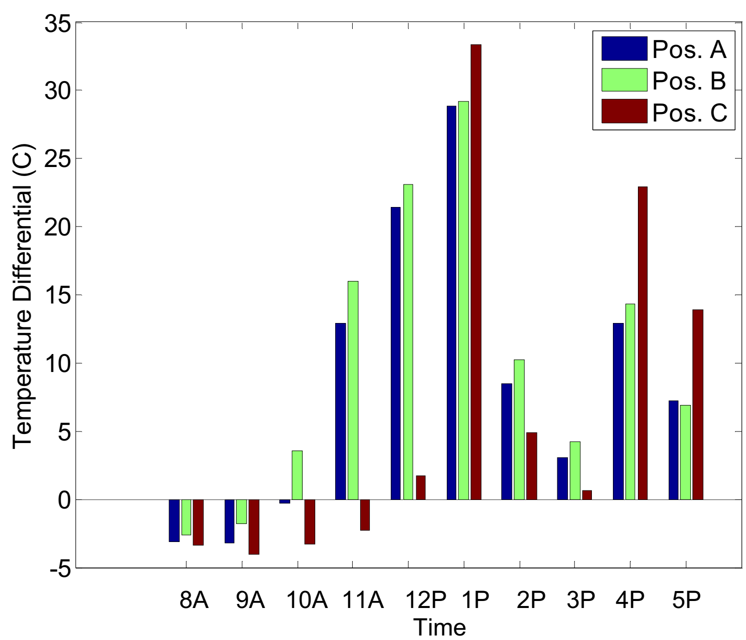

Figure 4: Temperature difference between concrete deck of the Omega Bridge and the ambient air temperature.

began warming, however it should become highly effective at midday as temperature differentials reached as high as 33°C. In the early afternoon heavy cloud cover set in and the thermal gradient dropped significantly, however they were seen to increase later in the afternoon as the cloud cover dissipated. Position C corresponds to the expansion joint of the bridge shown in Figure 3, and was seen to be the most responsive location to thermal variations. This location was predominantly in the shade during the morning; however the surface temperature was seen to rise rapidly after 12PM when it was exposed to full sun.

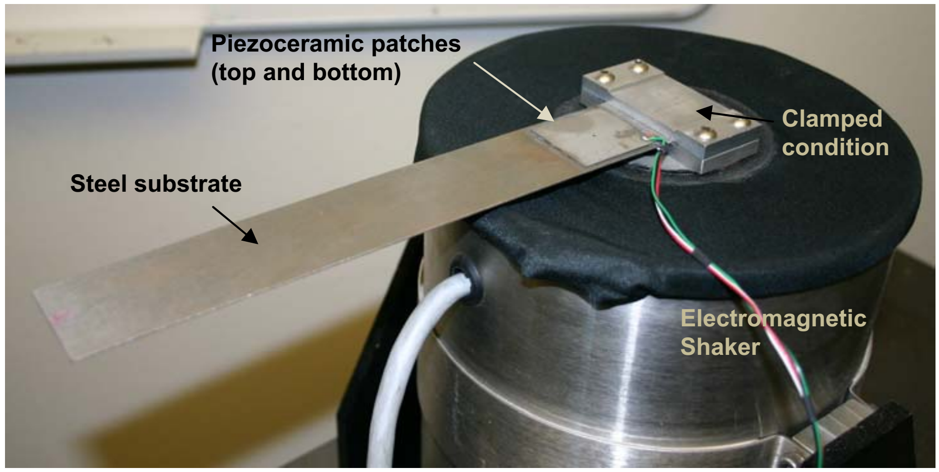

Figure 5: Cantilevered beam with piezoceramic patches mounted in a bimorph configuration, subjected to base excitations.

3 PIEZOELECTRIC MATERIALS

The piezoceramic lead zirconate titanate (PZT) was used as the electromechanical transducer in this study. The intrinsic properties of the piezoelectric materials enable them to convert energy between the mechanical and electrical domains, allowing them to sense, or harvest, electrical signals when they are subjected to a mechanical strain. In each of the energy harvesting experiments PZTs where mounted in a bimorph configuration on thin aluminum or steel substrate beams which were cantilevered from a test fixture that provided a base excitation for the sample as seen in Figure 5. The length of the substrate was used to tune the energy harvester's natural frequency to match one of the fundamental frequencies observed in the vibration response of the Omega Bridge. Once the energy harvesters had been tuned they were characterized with harmonic and multi-frequency base excitations through the electromagnetic shaker shown in Figure 5. The multi-frequency source was a filtered form of the bridge data that had been scaled by the shaker's inherent transfer function. The remainder of this section presents an analytical model used to position the transducers and to provide estimates of the peak strain/ peak power, as well as a set of experiments used to validate the model.

3.1 Analytical Model

A bimorph configuration was chosen to increase the output power of the energy harvester by scavenging both compressive and tensile loads that alternate between the upper and lower surfaces of the substrate. When mounted in this configuration the PZT responds to a change in length due to the curvature of the substrate material. The transducer material used in this study was the PSI 5A4E piezoceramic from Piezo Systems, Inc. and all simulations were conducted using the manufacturer's material specifications. An analytical FEM modal model was developed for the composite bimorph beam using 2-D beam elements. The clamped condition was modeled with no rotational degrees of freedom, and a prescribed displacement in the vertical direction. The resultant modeshapes are used to estimate the maximum curvature for each resonant frequency. This data was then used as an input into an Euler-Bernoulli model used by Inman and Cudney [3] to estimate the voltage generated by the PZT patches. The process models the mechanical response of the composite beam and relates it to the electric displacement through the linear constitutive equations,

$$\begin{aligned} S_1(t) &= s_{11}^E T_1(t) + d_{31} E_3(t) \\ D_3(t) &= d_{31} T_1(t) + \varepsilon_{33}^T E_3(t) \end{aligned} \quad . \tag{1}$$

Following the example of Inman and Cudney the electric displacement D_3 can be written as,

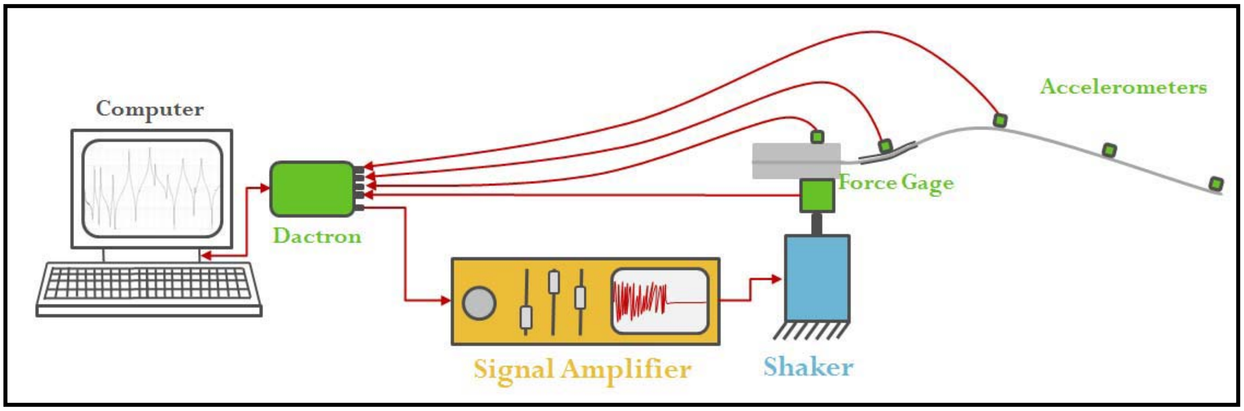

Figure 6: Diagram of the Modal Characterization Test for a PZT Cantilever Energy Harvester.

$$D_3 = \frac{d_{31}\kappa\left[E_b\left(a_2^{\,3} - a_3^{\,3}\right) - 2Y_1^{\,E}\left(a_1^{\,3} - a_2^{\,3}\right)\right]}{3\left(a_1^{\,3} - a_2^{\,3}\right)}, \tag{2}$$

where d_{31} is the coupling coefficient, κ is the curvature of the beam, E_b and Y_1^E are the Young's modulus of the substrate and piezoceramic materials, a_1 is the ½ the total thickness of the PZT and substrate, a_2 is ½ the substrate thickness, and a_3 is $-a_2$. From this the voltage can be solved for using field relationships, such that the voltage out V_3 would be,

$$V_3 = \frac{2(a_1 - a_2)D_3}{\varepsilon_{33}^{\;T}}, \tag{3}$$

where ε_{33}^T is the permittivity of the piezoceramic material. With this relationship it is possible to estimate the voltage response of the PZT.

3.2 Experimental Validation

Validation tests were performed to determine the accuracy of the analytical models ability to predict power output from the various energy harvesting devices. Controlled laboratory experiments were conducted incorporating the collected environmental data in order to simulate real vibrational and thermal situations. The first step for validating the piezoceramic generator model was to perform a modal characterization on a prototype beam. A beam was first constructed using a rectangular bar of aluminum 0.16cm thick by 3.85cm wide, cut to a length of 25cm. Two piezoceramic patches were then bonded to the aluminum beam in a bimorph configuration, similar to the configuration that will be used in practice. The beam was then clamped in aluminum grips and the whole assembly was attached to a force gage, which in turn was connected to a shaker. A total of 5 accelerometers were placed along the length of the beam at approximately 5cm increments to provide a rough mesh of the cantilever, Figure 6. The shaker was used to provide a 60% burst random base excitation and the accelerometers measured response signals along the length of the beam. Transfer functions were calculated using the force measurement as the reference, and the functions were curve fit to provide a modal characterization of the prototype cantilever. The results from this experiment were used to compare and update the Finite Element Model (FEM) developed to predict the mode shapes and frequencies of a bimorph piezoelectric cantilever energy harvester.

After validating the FEM, an experiment was performed to determine the power output of the piezoelectric cantilever prototype under typical operating conditions. A similar setup as the modal validation was used with the exception that the accelerometers and force gage were removed. In the power output test, the artificial acceleration signals obtained from spectral analysis were used as the input into the shaker, and the voltage and current outputs from the piezoceramic patches were measured using a data acquisition (DAQ) board. The results from this experiment were compared to the predictions from the analytical electro-mechanical model. After validation, the Finite Element and Electro-Mechanical models were used to design and predict the optimal dimensions for piezoelectric generators under various operating conditions.

4 THERMOELECTRICS

The second energy harvesting device considered in this study is the thermoelectric generator (TEG) which uses a thermal gradient to generate electricity. The TEG device is composed of p-type and n-type junctions that are arranged thermally in parallel and electrically in series to convert energy between the thermal and electrical domains. The devices rely on the Seebeck effect, shown in Figure 7, which describes the current that results from the junction of two dissimilar p- and n-type metals when subjected to a thermal gradient. As in the previous section this discussion of the thermoelectric device is separated into an analytical study and an experimental validation section.

4.1 Analytical Model

The voltage output from the thermoelectric generator is defined as a combination of the Seebeck effect and Ohm's law,

$$V = (T_w - T_c)\alpha - IR \,, \quad (4)$$

where T_w and T_c are the temperatures corresponding to the hot and cold sides of the TEG, respectively, the α variable denotes the Seebeck coefficient for the junction, I represents the current flow and R_l represents the load resistance. Using general power relationships, the output power for a TEG module as shown in Figure 7 would be

$$P_m = VI = \alpha(T_w - T_c)I_m - I_m{}^2 R_L \,. \quad (6)$$

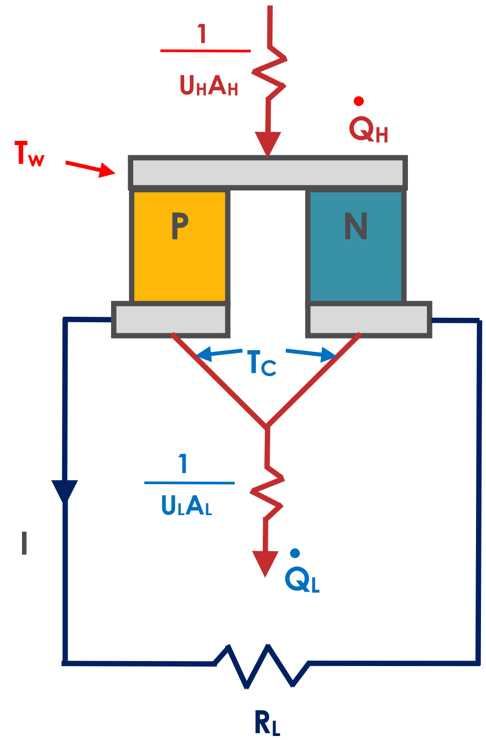

Figure 7: Schematic of the P-N Junction Model of the Thermoelectric Generator

4.2 Experimental Validation

In order to investigate the energy harvesting capacity of the TEG's (Tellurex Corporation model C1-1.4-127-1.65) in a realistic environment, temperature measurements from common heat sources such as car engines, rotating machinery, steam pipes, boilers, and concrete exposed to sun radiation are needed. These are environments were a TEG could take advantage of the temperature differential between the surface and the surrounding environment and produce appreciable power levels. For the purpose of this study, measurements at random surface locations and from the surrounding environment of the Omega Bridge were taken using a Fluke Model 62 infrared thermometer. Once the collected data was analyzed to determine the operating temperature ranges, a heat plate (Barnstead International model HP130915) was employed to simulate each studied environment. To control the temperature of the plate, TEG, and the environment, thermocouples (Cooper Atkins, model 49138-K) were placed on the surface of the heat plate, on top of the TEG module and above the module. Then the thermocouples were linked to a LabView interface through a National Instruments PXI-1042Q DAQ to continuously measure the temperature output of the thermocouples and the electrical output of the TEG.

Different configurations of the test were designed to determine the feasibility of using a rectangular fin heat sink in a natural convection environment. For these tests the environment conditions of the Omega Bridge where simulated and maintained constant through the complete testing. For the first configuration, the TEG module is placed directly on the heat plate without the heat sink, and then temperature data is measured to determine the heat transfer from the heat plate through TEG module to the environment. The second and third configurations consists of the TEG module coupled with the heat sink to measure the heat transfer from the heat plate through the TEG module to the heat sink to the environment for the second configuration. Finally for the third configuration the heat sink is placed directly over the heat plate to measure the heat transfer from the heat plate through the heat sink to the TEG module then to the environment.

In the experimental characterization shown in Figure 8 of the Tellurex G1-1.4-127-1.65 TEG two conditions were considered, first without a passive heatsink, and one with a passive heatsink. Figure 8 presents the results of these experiments, plotting power output versus temperature differential ΔT. The first test considered the TEG without a heatsink, and the results are presented as red squares in the figure. An analytical model of the bare TEG is also presented as blue diamonds, which agree very well with the experimental data. Following this initial test a passive heatsink was attached to the thermoelectric module and the tests were rerun, with the data plotted as yellow triangles. This data demonstrates the feasibility of using the passive heatsink to increase power output as it provides a 15-20% increase in performance.

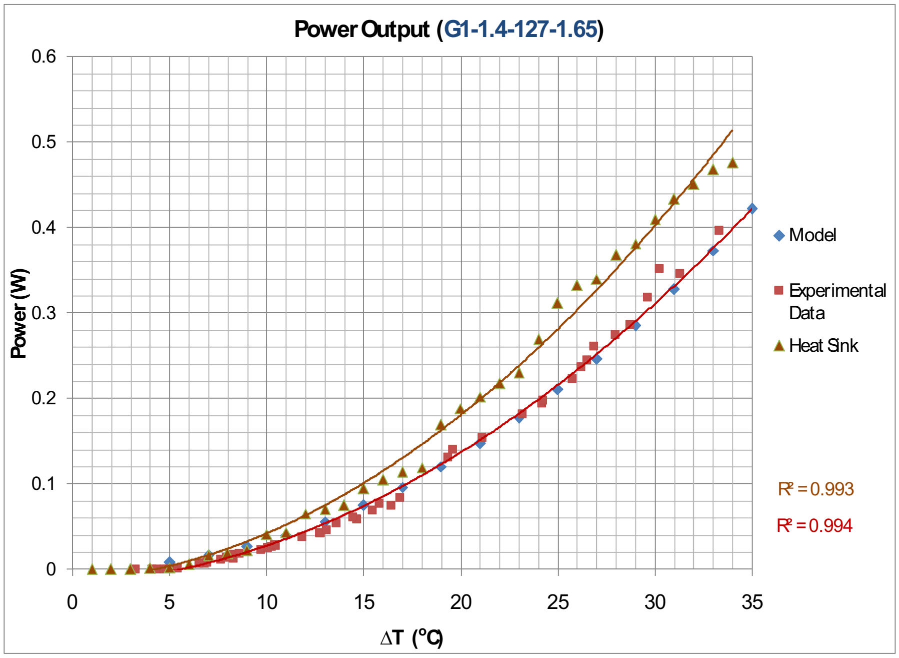

Figure 8: Power output for the G1-1.4-127-1.65 thermoelectric (theoretical and experimental) as a function of the change in temperature ΔT.

5 CHARGING STUDIES

Once each of the energy harvesters had been fully characterized, the next step in this study was to begin obtaining charging profiles for each. Several 33mF and 47mF capacitors were examined initially. Following success with these smaller capacitors, focus was shifted to a larger 0.1F Aerogel supercapacitor that possessed the energy density needed to power one of the wireless impedance devices shown in Figure 9. The WID3 requires between 2.7V and 3.5V to operate the microcontroller, approximately 60 mW of power to perform measurements, and 75mW to wirelessly transmit data through the telemetry chip. The WID3 is equipped with a power conditioning circuit that allows an onboard capacitor to store power until it reaches an internal voltage of 3.5V, at which point it releases the energy to the microcontroller and powering the unit.

Several charging experiments were considered in this study, evaluating the performance of each energy harvester, as well as several conditioning circuits. Since the PZT based energy harvester produces an oscillating voltage a rectifying circuit is needed to produce a DC signal which can be used to charge the capacitor. Three separate circuits were examined with the PZT energy harvester, a simple full bridge rectifier made from Schottky diodes, a commercially available EHE001C circuit from MIDE. and the EPAD EH300A energy harvesting module from Advanced Linear Devices, Inc. A simple harmonic excitation was used to evaluate each of these circuits, with their charging profiles shown in Figure 10. From this it is seen that the MIDE rectifying circuit provides the quickest charging time, reaching 3V within 235 seconds. The simple rectifying circuit required a longer charge time, taking 323 seconds to charge, while the ALD circuit required the longest charge time of 378 seconds. While the ALD circuit was seen to take the longest time to charge the 0.1F capacitor to 3V, it did have some features that were amenable to the multi-transducer technique. Specifically, the ALD circuit can accept input voltages of +/-500V, providing a controlled output voltage of 1.8 or 3.6V.

Figure 9: The wireless impedance device (WID3) developed at the Engineering Institute.

The advantage of this circuit is that it can accept voltage from either the piezoelectric or the thermoelectric generator, and the output from several circuits can be combined to provide a multi-transducer energy source for systems such as the WID3.

Due to the advantages of the ALD circuit, it was selected for each of the subsequent experiments. In the initial characterization of each power conditioning circuit, the PZT energy harvester was excited using a harmonic excitation at the cantilevered beam's 1st natural frequency. The second charging study examined the effectiveness of using the acceleration data obtained from the Omega Bridge to charge the 0.1F supercapacitor. Figure 12Figure 11 presents the charge response obtained by a purely harmonic excitation, and the response based upon data from the Omega Bridge. From this figure it is seen that the charge time associated with the acceleration data increases considerably from 378 seconds to 2230 seconds; however it is apparent from this result that the ambient excitation is sufficient to power a small sensor node such as the WID3.

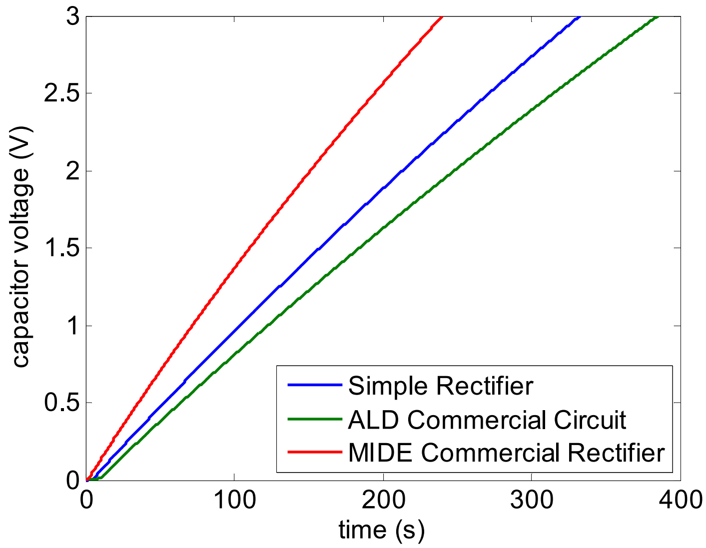

Figure 10: A comparison of the charge time using three different rectifying circuits.

Thus, the next step in this investigation was to couple the PZT based energy harvester with the thermoelectric generator, and used this coupled system to charge the low power sensor node. For this experiment two ALD energy harvesting modules were used to precondition the voltage response from the PZT and TEG units. The ALD circuits were connected electrically in series to increase the voltage out, and to improve the charge time. Figure 12 presents the charge response of the onboard 0.1F supercapacitor used to power the WID3. Both the thermal and the vibration sources were initiated at time t=0 in this figure. Thus, the voltage out of the TEG was predominantly governed by the warming rate of the heat source. Over the first 208 seconds the TEG adds to the charge response, until the voltage reaches 1.18V which was the maximum output of the TEGs used in this experiment. Beyond this point the PZT harvester is responsible for building voltage within the capacitor. Once the voltage level reaches 3.5V, the energy is released to the WID3 which powers on and monitors the electrical impedance of three sensors used to monitor bolt preload. The sensor node performs a 100 point measurement on each sensor, computes the maximum impedance, and stores this data to the onboard flash memory. This operation is initiated after 912 seconds of charging and requires 2 seconds to perform the prescribed tasks. The voltage response during the WID3 operation is shown in the exploded view in the lower right of Figure 12. The initial voltage drop in this exploded view is associated with the measurement cycle, while the second discharge is due to data processing and writing to file operations. Following the measurement and storage operations, the WID3 continues to perform low level operations from 914 to 915.5 seconds to further deplete energy from the onboard capacitor. Once the voltage drops to 2.7V the WID3 automatically removes power from the microcontroller, preventing components of the WID3 from consuming additional power once the voltage has dropped below the levels needed for stable operation of the microcontroller. At this point the energy harvester begins to recharge the WID3, and will repeat the measurement cycle once the voltage reaches 3.5V. These results indicate that

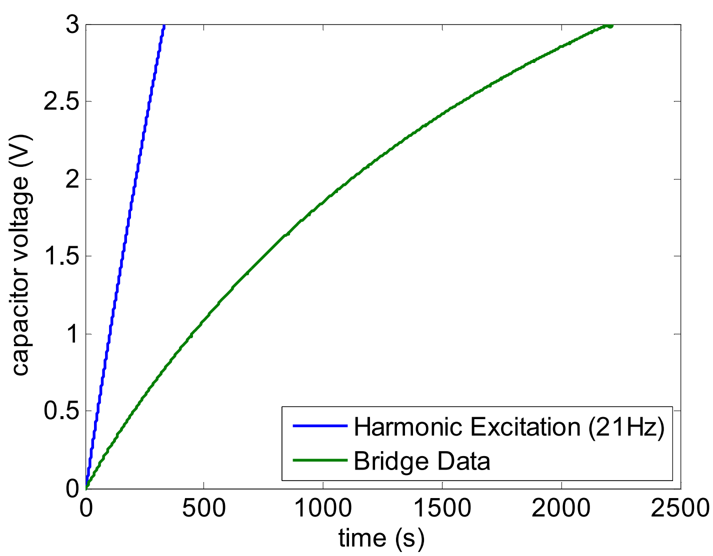

Figure 11: Charging profiles using a harmonic excitation at 1st resonance, and using ambient vibrations collected from the Omega Bridge.

the multi-transducer system is capable of powering a piece of hardware that is capable of interrogating the structural health of a number of different systems.

5 DISCUSSION AND CONCLUSIONS

The ultimate goal of many sensing networks is to develop a system that can operate long term with minimal need for maintenance. One aspect of this goal is to have a robust power source that can meet the needs of the network for its operational lifespan, through either advanced battery technologies or energy harvesting techniques. This study has focused on the use of a multi-transducer system to power a small wireless impedance device. Using data collected from a local highway bridge, an electromagnetic shaker and a thermal environment were used to excite the coupled energy harvesting system. The results demonstrate that the coupled system is capable of powering a sensor node capable of being deployed for structural health monitoring applications. While the system took many minutes to charge, it was able to build up enough energy to power the sensor node, and could be used in numerous applications where a random interrogation method would be desirable such as in many structural health monitoring applications. If further refined, this technology can potentially be integrated into sensor networks to provide a truly self-sustaining energy solution that will aid in the long-term deployment of systems for structural or security applications.

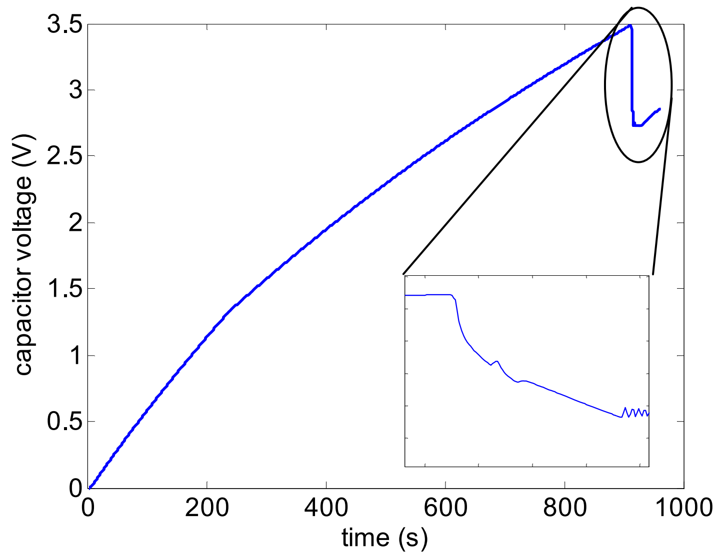

Figure 12: Voltage profile for the onboard 0.1F capacitor used to power the WID3 sensor node.

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