Energy Harvesting with Coupled Magnetostrictive Resonators
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ABSTRACT
We report the investigation of an energy harvesting system composed of coupled resonators with the magnetostrictive material Galfenol (FeGa). A coupled system of meso-scale (1-10 cm) cantilever beams for harvesting vibration energy is described for powering and aiding the performance of low-power wireless sensor nodes. Galfenol is chosen in this work for its durability, compared to the brittleness often encountered with piezoelectric materials, and high magneto-mechanical coupling. A lumped model, which captures both the mechanical and electrical behavior of the individual transducers, is first developed. The values of the lumped element parameters are then derived empirically from fabricated beams in order to compare the model to experimental measurements. The governing equations of the coupled system lead to a system of differential equations with all-to-all coupling between transducers. An analysis of the system equations reveals different patterns of collective oscillations. Among the many different patterns, a synchronous state appears to yield the maximum energy that can be harvested by the system. Experiments on coupled system shows that the coupled system exhibits synchronization and an increment in the output power. Discussion of the required power converters is also included.


1. INTRODUCTION
At meso-scale (1 cm-10 cm), the dominant transduction mechanisms are electromagnetic and piezoelectric. The electromagnetic technique includes suspended magnets in a coil or a suspended coil in a magnet array which oscillates as it is excited with vibrational motion. These devices' performance rely heavily on the proximity of the magnets with the coil, strength of magnets, and coil windings. For piezoelectric energy harvesting, materials that can integrate into standard processes have low coupling coefficients and more strongly coupled materials (e.g. PZT) have lead in their fabrication process which is an environmental risk. Another major issue with standard energy harvesting techniques is that most transducers behave as second order systems and are designed to have strong resonant behavior (i.e. high Q) to create more displacement. However, the amount of electrical energy produced is small for these devices when there is a mismatch between the resonant frequency of the device and the excitation frequency. The mismatch can be addressed by devices with nonlinear resonance. Devices with nonlinear springs can possibly perform better than a linear device resulting in larger bandwidth under broadband random vibrations. Additionally, coupled systems of nonlinear oscillators have been shown to improve the performance of sensors by increasing sensitivity [1]. This concept can be utilized to harvest more energy by synchronization of individual energy harvesters in the coupled system.

As shown in Figure 1, the coupled composite beams consisting of Aluminum as substrate, Galfenol (FeGa) as the magnetostrictive material and magnet wire as coil are used to convert the mechanical vibrations into electrical voltage. The ac signal then is fed into rectifier and related power converter circuit that stores the dc voltage in a thin film battery. The battery is used to power low power transmitter to transmit the sensor data intermittently and/or as the sensing event takes place. The energy harvester system can be used to power and/or aid the performance of a low power wireless sensor node.
Galfenol is a ferromagnetic material with a typical composition of Fe$_{83}$Ga$_{17}$. It is a magnetostrictive material and exhibits large magnetostrictive affect: 200-300 ppm strain at low applied magnetic field [2]. It has high power generation and efficiency (~20mW/cm$^3$). Additionally, it exhibits low output impedance, which is good for matching, small hysteresis and low coercivity [3]. Ceramic material like PZT tends to develop fatigue during its cycles whereas Galfenol does not have that issue because it behaves like metal. Its transduction efficiency is comparable to piezoelectric materials like PZT [3].

2. BEAM MODEL

In this section, we show the single beam model based on the experimental data. The Galfenol samples were obtained from Etrema, Inc. These samples were non-stress-annealed and non-magnetic field-annealed.

2.1 Linear transducer model

The test equipment involved laser displacement sensors, dynamical signal analyzer, and shaker system. A schematic of the magnetostrictive, meso-scale transducer explored in this work is shown in Figure 2. The transducer is comprised of Galfenol sample mounted onto a thin aluminum shim. This entire structure, both the shim and the Galfenol, is then wrapped with insulated magnet wire to form the coil. As the base of the transducer is vibrated in the z-direction, inertial forces cause a relative displacement between the base and tip of the beam. The result of this displacement is a strain induced in the Galfenol in the x-direction, which generates a magnetic field (mainly in x-direction) due to the magnetostrictive effect. Oscillations of the beam lead to a time-varying magnetic field within the coil, which produces a time-varying electrical current as a result of electromagnetic induction.

![Figure 2. Composite Cantilever beam with magnetostrictive energy harvesting transducer](image-url)

The linear transducer model used in this work is based on the principles of lumped element modeling, whereby the potential and kinetic energy distributed throughout the transducer beam is “lumped” together and assumed to occur at the tip of the beam. In this manner, the transducer can be modeled as a second order mechanical system coupled to the electrical domain via the magnetostrictive effect and the electrical coil. The mechanical domain of the transducer is represented by a second order mass-spring-damper system, as shown in Figure 3(a), where $M_m$ represents the lumped mass, $k_m$ is the lumped spring constant, and $R_m$ is the lumped damping parameter. The effort variable is force $F_m$, and the flow variable is velocity $\dot{x}$. Since the transducer operates in both the electrical and mechanical domains, a more intuitive representation for this system is to use circuit elements to represent the lumped parameters, as shown in Figure 3(b).
The electrical domain of the transducer is comprised of the coil inductance $L_c$ and its resistance $R_c$, shown in Figure 3(b). The transduction between the two domains is modeled as a gyrator and shown in Figure 3(b) as a complete multiple domain model. Unlike the transformers commonly used in electrodynamic modeling, a gyrator assumes a linear relationship between the effort and flow variables of the two domains. A linear relationship is assumed between the force in the mechanical domain and the current $i$ in the electrical domain and vice versa between voltage in electrical domain and velocity $\dot{z}$. The gyrator transduction factor $G$ lumps all of the energy transduction mechanisms (mechanical to magnetic to electrical) into a single term. The derivation of this term from first principles is not trivial, and has been derived empirically for this work.

2.1.1 Extraction of the linear transducer parameters

In order to verify the accuracy of the linear model, various composite beams with Galfenol as the main material and aluminum as the substrate were wrapped with 35 gauge magnet wire for the coil. The beams were fitted to the test apparatus on top of the shaker using plastic clamp bars to avoid interaction with the shaker magnet. The shaker was driven by amplifier which was connected to the source of the dynamic signal analyzer. Various base clamping configurations and beam clamping methods were tried and an appropriate setup was created. Figure 4 shows the measured frequency response curves with sinusoidal excitation. Here, base displacement and tip displacement were measured with laser sensors and the output of the sensor was converted to the actual displacement values. The beam clearly shows soft-spring response as opposed to the linear response (as indicated by blue arrow). The resonance frequency shifts to the left as the vibration is increased. Here, the resonance peak shifts from 46.25 Hz to 36.8 Hz. Nonlinear (soft-spring) response occurs due to the material compression-tension and the alignment of the magnetic poles while the beam is being vibrated. The nonlinear behavior is crucial for the coupled system in which the nonlinear behavior contributes to the synchronization of the individual beams and can potentially increase the output power. The load resistance was matched to coil resistance and the maximum power was observed as 12 $\mu$W at 1g acceleration. Note that this value depends on the shaker vibration, the material, the base clamp configuration and beam structure. Additionally, the magnetic domains in Galfenol may be somewhat randomized which can reduce the output voltage.

Figure 4. Frequency response curves of the composite fixed-free beam: normalized frequency response with tip displacement divided by base acceleration divided by Earth’s gravity vs excitation frequency
It was also observed that adding the coil on top of the sample creates an imbalanced lumped mass which can contribute to the lowering of the effective mass. The coil also spreads the frequency response and lowers the Q (based on the mechanical displacement amplitude vs. excitation frequency curve). As expected, when the frequency was swept up and down, a hysteresis was developed for a large excitation amplitude. The width of the hysteresis enlarges as the vibration amplitude increases. It is important to note that as the excitation amplitude is increased beyond a certain value, non-ideal acceleration of the base impinging on the tip of the beam can contribute to additional vibration modes thereby reducing the tip displacement response and output power.

Experiments were carried out for the spring constant, mechanical to electrical transduction, and damping. The measured data of one of the beams was used to develop the linear and nonlinear transducer model. Here, the shaker was vibrated at low amplitude to confine the vibration within linear regime and the frequency response curves for the tip displacement and base displacement were used to determine the relative tip displacement (Tip\_disp − Base\_disp) over the base acceleration. The spring constant was measured using weight vs. displacement measurements and the resonance frequency was measured as 46.25 Hz. Using these values, the value of effective mass m or beam inductance L_m was determined. Using this value of effective mass as an approximation, the damping parameter b or beam resistance R_m was derived by Levenberg–Marquardt algorithm. The parameters for the coil were measured on the LCR meter. Table 1 enlists the parameters mentioned in Figure 3 based on the estimation method as described above.

Table 1. Measured and derived parameters for the model shown in Figure 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
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<tr>
<td>Beam Resonance</td>
<td>f_o</td>
<td>46.25</td>
<td>Hz</td>
</tr>
<tr>
<td>Frequency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam Capacitance</td>
<td>C_m</td>
<td>0.001758</td>
<td>F</td>
</tr>
<tr>
<td>Beam Inductance</td>
<td>L_m</td>
<td>0.006734</td>
<td>H</td>
</tr>
<tr>
<td>Beam Resistance</td>
<td>R_m</td>
<td>0.24</td>
<td>Ω</td>
</tr>
<tr>
<td>Transduction Factor</td>
<td>G</td>
<td>0.1448</td>
<td>N/A or V/(m/s)</td>
</tr>
<tr>
<td>Coil Resistance</td>
<td>R_e</td>
<td>198.58</td>
<td>Ω</td>
</tr>
<tr>
<td>Coil Inductance</td>
<td>L_e</td>
<td>47.16</td>
<td>mH</td>
</tr>
<tr>
<td>Load</td>
<td>R_l</td>
<td>180</td>
<td>Ω</td>
</tr>
</tbody>
</table>

The value of transduction factor G was determined by two methods: from the mechanical side and from the electrical side. For the mechanical side measurement, the current output of the coil across 10 MΩ resistor (open circuit) was measured for a given shaker vibration amplitude and corresponding tip velocity. Here, G becomes the ratio of coil output voltage over tip velocity [V/(m/s)]. Conversely for the electrical side measurement, the coil was connected to the voltage source and the output vibration was measured which was then converted to corresponding force. Here, G becomes tip force over input current [F/A]. The two values were close to each other and an average value was derived.

2.2 Nonlinear transducer model

Nonlinear transducer model is important for the simulation of the coupled system. By utilizing the experimental data, simulations were performed to derive the nonlinear spring constant using the dynamical equations (as shown in the next section). Ideally, the soft potential behavior of the magnetic material can be estimated from the hysteresis during up-sweep and down-sweep in the experiment. However increasing the base excitation to a higher amplitude (so that nonlinearity is more prominent than damping) can break the beams. As noted before, both the measured and simulated responses show a distinct shift of the resonant frequency to the left and eventually a hysteresis is exhibited while increasing the excitation amplitude. The experimental and simulated values of the nonlinear spring constant were matched qualitatively by fitting the simulated hysteresis to the measured hysteresis. Nonlinear spring can be represented as charge (displacement) controlled voltage (force) source with cubic nonlinearity in the lumped electrical model. Here the investigation and characterization of the nonlinear resonance is carried out to assess (a) the widening of the excitation frequency range of a single beam and (b) the properties of synchronization of coupled beams.
3. NUMERICAL SIMULATION OF COUPLED SYSTEM

In this section, we briefly show the results of numerical simulation of the coupled system with three resonators.

3.1 Coupling constant

Experiments on the coupled beams were carried out in order to approximate the coupling constants. Two types of coupling can exist between the beams: (1) vibrational coupling through the base and (2) mutual inductance between the beams through read-out coils. Here vibrational coupling can be estimated as the average of the proportional displacements of the two beams while being uncoupled and coupled. Vibrational coupling depends on position of the beams on the base, the clamp holes and clamp screw strengths (which relates to damping), and the mass/coil variation between the beams. Mutual inductance was not observable in the experiment. This may be due to the small amplitude of the magnetic field being generated in the beams. It should be noted that the mutual inductance value will depend on the vibrational coupling between the beams as well as the distance between the beams. To simplify the coupling mechanism, we assume vibrational coupling only. Here, we treat the coupling constant in its dimensional less form as the bifurcation parameter.

3.2 All-to-all coupled system

Research conducted by the team members in the area of coupled systems of nonlinear resonators/oscillators has shown that the sensitivity of the system increases greatly at the bifurcation boundary [1]-[4]. Here we would exploit this property to explore and enhance energy harvesting property of the coupled system. Two types of coupled system are being investigated: (a) chain (b) ring. While the chain configuration may represent a specific case of the ring configuration, our research will be focused on analyzing and maximizing the power output of the coupled system of Galfenol beams regardless of the type of configuration.

For N number of resonators in a ring configuration with resistive-capacitive load, the dynamical equations of jth resonator can be written as follows:

\[ m \ddot{z}_j(t) + b \dot{z}_j(t) + k_1 z_j(t) + k_3 z_j(t)^3 + G \dot{z}_j + \lambda \Omega_j = A_d \cos(\omega_d t) \] \hspace{1cm} (1)
\[ L_c C_s \dot{V}_j(t) = G \dot{z}_j(t) - C_s (R_L + R_C) \dot{V}_j(t) - V_j(t) \] \hspace{1cm} (2)

Where, \( m \) = mass of the resonator [kg] \( = L_m \) in Table 01, \( b \) = damping parameter [N*s/m] \( = R_m \) in Table 01, \( k_1 \) = linear spring constant [N/m] \( = 1/C_m \) in Table 1, \( k_3 \) = nonlinear spring constant [N/m^3], \( G \) = transduction factor [N/A], \( \lambda \) = vibrational coupling constant [N/m], \( \Omega \) = coupling function \( = z_1 + z_2 + z_3 \) = all-to-all coupling or sum [m] with \( S_i \) symmetry [5], \( A_j \) = excitation amplitude [N], \( \omega_d \) = excitation frequency [rad], \( L_c \) = read-out coil inductance [H], \( C_s \) = load capacitance [F], \( R_L \) = load resistance [Ohm], \( V \) = output voltage [V], and \( Z \) = displacement in z-direction [m].

After substituting \( \tau = \omega_o z_j(t) \) \( = \sqrt{\frac{k_1}{|k_3|}} x_j(\tau), \frac{d}{dt} (z_j(t)) = \omega_o \frac{k_1}{|k_3|} \frac{d}{d\tau} (x_j(\tau)) \) \( = \frac{d^2}{d\tau^2} (z_j(\tau)) \) and letting \( \dot{V}_j(t) = \frac{k_1}{C_s \omega_o G} \sqrt{\frac{k_1}{|k_3|}} U_j(\tau), \frac{d}{dt} (V_j(t)) = \frac{k_1}{C_s G} \sqrt{\frac{k_1}{|k_3|}} d\tau (U_j(\tau)), \frac{d^2}{d\tau^2} (V_j(t)) = \) \( \frac{k_1}{C_s G} \sqrt{\frac{k_1}{|k_3|}} d\tau^2 (U_j(\tau)) \), and noting that \( (') \) and \( (\prime) \) denote first and second derivatives with respect to \( \tau \), we re-write the Equations (1) and (2) in dimensionless form as follows:

\[ x_j''(\tau) + \frac{1}{\gamma} x_j(\tau) + x_j(\tau) + \gamma x_j(\tau)^3 + U_j'(\tau) + \lambda \omega_r \Omega_{\tau j} = F_r \cos(\omega_r \tau) \] \hspace{1cm} (3)
\[ U_j''(\tau) = k_2 x_j'(\tau) - \frac{1}{\alpha} U_j'(\tau) - \frac{1}{L_c C_s \omega_o} U_j(\tau) \] \hspace{1cm} (4)

where, \( \lambda \) = \( \frac{\lambda}{k_3} \), \( k^2 = \frac{G^2}{L_c k_1} \), \( \gamma = sgn(k_3) \), \( F_r = \sqrt{\frac{|k_3|}{G^{3/2}}} A_d \), \( \omega_r = \frac{\omega_d}{\omega_o} \), \( \alpha = \frac{L_c \omega_o}{(R_L + R_C)} \).
Here, we assume that the coil generates sufficient current through the magnetostrictive property of Galfenol to charge the load capacitor. Also, note that the dimensionless equations (3) and (4) are valid for the coupled system at meso-scale as well as micro-scale.

3.1 Bifurcations

Bifurcation diagrams for three energy harvesters in ring configuration were obtained using software package AUTO. Here we focus in two coupling regimes: weak and strong. As a convention, solid/dashed lines and filled/empty circles correspond to stable/unstable equilibrium points and stable/unstable periodic solutions, respectively in the bifurcations diagram shown below.

![Bifurcation Diagrams](image)

Figure 5. Bifurcation diagrams for one of the resonators within N=3 coupled system with the dimensionless coupling constant \( \lambda_r \) as the bifurcation parameter: (a) no forcing with \( F_r=0 \) and (b) periodic forcing with \( F_r=0.1 \). Here the solid lines and filled dots represent stable fixed points and stable periodic solutions, respectively. Note that \( \omega_r = 0.9, Q=100, \alpha=1, k^2=0.2, \gamma=-1, 1 / (L_c C_s \omega_o^2 )=0.1 \).

As shown in Figure 5(a), the resonator exhibits pitchfork bifurcation when it is not forced. Here for coupling constant values less than a critical value (shown by rectangular box) the system shows unstable fixed point after which one stable fixed and two unstable fixed points appear through pitchfork bifurcation. As shown in Figure 5(b), the system first exhibits unstable solutions as coupling constant is swept from -1 to 1. These solutions form stable solutions at a certain \( \lambda_r \), where the resonators exhibit travelling wave pattern with zero mean and two resonators completely synchronize with each other. These regions are indicated by branch 2 and 3 in Figure 5(b). Here, it is interesting to note that for both weak and strong coupling constant values, the system exhibits full synchronization which is indicated by branch 1 in Figure 5(b). It is evident that the system shows rich dynamical behavior and multiple bifurcations occur through which system enters partial and fully synchronized states. We are currently investigating several cases including (a) the role of mutual coupling along with the vibrational coupling, (b) bidirectional coupling, and (c) the effect of the broadband excitation signal.

4. EXPERIMENTAL RESULTS OF COUPLED SYSTEM

In this section, we describe the characterization of coupled system in two different configurations: (a) chain and (b) ring.
4.1 Chain Topology

Figure 6. Experimental results of the coupled system with n=3 in chain configuration: from left to right, the source excitation frequencies. For example, beam 2 in uncoupled state, outputs 0.89 uW at 1 g acceleration and excitation frequency of 305 Hz when the source amplifier is set to 500 mV. The same beam, while being actuated in coupled state, outputs 10.5 uW at 1 g acceleration and excitation frequency of 305 Hz when the source amplifier is set to 500 mV. The same beam, while being actuated in coupled state, outputs 10.5 uW at 1 g acceleration and excitation frequency of 305 Hz with the same source amplifier setting. It can be seen that the coupled system does not synchronize at lower excitation amplitude; however all three beams show synchronization at higher excitation amplitude. The time-series of the coupled beams show all three beams in phase which is important for power conversion. All three resonators synchronize at 305 Hz. We denote increment factor at the synchronized frequency as the ratio of the peak power of a given beam in the coupled state vs. the one in the uncoupled state at that frequency. Here, the increment factors at the synchronized frequency are 3.1, 11.7, and 4.25 for beam 1, beam 2, and beam 3, respectively.

4.2 Ring Topology

For the ring topology, same three beams were fixed on a plastic disk in a triangular pattern as shown in Figure 7. Here, we uncover the same phenomena where the three resonator synchronize at higher excitation amplitude at 314 Hz in frequency domain. The synchronized pattern in time domain showed two resonators in phase and one resonators out of phase which requires additional modification in the power converter circuit. Here, the increment factors at the frequency of synchronization are 51.9, 29.76, and 30.49 for beam 1, beam 2, and beam 3, respectively.
Figure 7. Experimental results of the coupled system with n=3 in ring configuration: from left to right, the source amplitude=100mV, 300 mV, and 500 mV. The top row and bottom row correspond to uncoupled responses and coupled responses, respectively. Note the increase in power when the peaks align themselves at a single frequency.

It is possible that the disk facilitates weaker coupling than the bars. The coupled system on the bars may exhibit nearest neighbor coupling whereas the coupled system on the disk may exhibit all-to-all coupling. This change may contribute to the higher incremental factors and the change in the synchronizing patterns in time-domain.

5. DESIGN OF POWER CONVERTERS

In this section, we describe the design of power converters including magnetic pulsed resonator converter and fly-back converter. We analyze magnetic pulsed resonant converter in detail.

5.1 Magnetic pulsed resonant converter (M-PRC)

Figure 8. A pulsed resonant converter for inductive loads.
The magnetic pulsed resonant converter (M-PRC) is a non-linear power converter topology which falls into the class of synchronous charge extraction (SCE) converters. SCE converters were first demonstrated for piezoelectric energy harvesting applications [8, 9], and were shown to have a 4X increase in harvested energy when compared to an optimal resistive load [10]. Unlike other classes of power converters where there is a constant transfer of energy from the source transducer to the load, an SCE circuit operates by harvesting energy from the source in short bursts only when the instantaneous energy on the source is maximized. For the magnetostriective energy harvesting system presented in this work, the M-PRC circuit operates by keeping the magnetostriective transducer short circuited for most of its operation. Harvested energy is only transferred from the transducer to the load when the current on \( L_C \) reaches a peak.

The M-PRC transfers energy from the transducer to the load using the 4 active switches, \( SW_1, SW_2, SW_3, \) and \( SW_4 \) and its operation can be logically divided into 4 phases as shown in Figure 8. For the majority of the energy harvesting process, the M-PRC operates in Phase I, where \( SW_1 \) short circuits the output of the transducer and the rest of the switches are open. When the current flowing through the \( L_C \) reaches a peak value, Phase II operation begins. During Phase II, \( SW_1 \) opens and \( SW_2 \) closes, and the current stored on \( L_C \) flows into the capacitor, \( C_{PRC} \). Assuming that the parasitic losses of this energy transfer are negligible, all of the energy stored on \( L_C \) will be transferred to \( C_{PRC} \). In this case, the voltage across \( C_{PRC} \) will reach a peak value at exactly the same time that the current through \( L_C \) falls to zero [11]. The value of \( C_{PRC} \) should be chosen so that the LC time constant of this resonant power transfer is much faster than the period of the mechanical vibrations being harvested.

Once the harvested energy has been transferred to \( C_{PRC} \), the operation of the M-PRC follows that of the pulsed resonant converter used for piezoelectric energy harvesting. A detailed analysis of this operation is presented in [11]. As the voltage on \( C_{PRC} \) reaches a maximum the M-PRC enters Phase III operation. During this phase, \( SW_2 \) is opened and \( SW_3 \) is closed, creating a resonant power transfer between \( C_{PRC} \) and the inductor, \( L_{PRC} \) (similar to Phase II operation). Assuming again that the energy lost in the resonant transfer is negligible; the voltage across \( C_{PRC} \) will fall to zero as the current through \( L_{PRC} \) rises to a peak. In reality, voltage drops across the diodes and conductive losses within the diodes and \( L_{PRC} \) reduce the amount of energy transferred. When the current through \( L_{PRC} \) has reached a maximum value, Phase IV begins with \( SW_3 \) opening and \( SW_4 \) closing. The energy stored on \( L_{PRC} \) during Phase III is transferred to the load, shown in Figure 8 as a battery, and the energy process is complete. Phase IV ends with \( SW_4 \) opening and \( SW_1 \) closing to again short-circuit the transducer, and the circuit returns to Phase I.

In order to verify the operation of the M-PRC circuit shown in Figure 8, simulations were performed using LTSPICE IV, a circuit simulation program developed by Linear Technologies. For these simulations, all of the switches and diodes were modeled as ideal components, and the switching signals were optimized for maximum power transfer. The values of the transducer and M-PRC components are given in Table 2. The input acceleration for this simulation was set to 1 m/s², the oscillation frequency was set to 46.25 Hz, and the coil resistance was set to 1 Ω.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>( L_C )</td>
<td>Coil Inductance</td>
<td>47.2 mH</td>
</tr>
<tr>
<td>( R_C )</td>
<td>Coil Resistance</td>
<td>1 Ω</td>
</tr>
<tr>
<td>( C_{PRC} )</td>
<td>M-PRC Capacitor</td>
<td>10.0 nF</td>
</tr>
<tr>
<td>( L_{PRC} )</td>
<td>M-PRC Inductor</td>
<td>800.0 nH</td>
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</table>

Results of the M-PRC simulations are shown in Figure 9, along with simulated results for an optimal resistive load with a rectifier and large filter capacitor 200 μF. Measuring the power delivered to an optimal resistive load is a typical way to characterize the performance of the transducer in an energy harvesting system. The transducer properties were identical to the M-PRC simulations and were performed under identical acceleration conditions. For the optimal resistive load, a resistance value of 15 Ω delivered 308 nW of power. For the M-PRC simulations, a voltage load was used to emulate a battery, and 447 nW of power were delivered with the same input acceleration conditions as the optimal resistive load. The battery voltage was varied over a range of 2.0 V to 5.0 V and produced approximately 451 nW at all voltages.
In order to make a more accurate comparison between the M-PRC and rectifier-capacitor circuit, simulations were performed where the optimal resistor was replaced with a voltage load. However, due to the low input power levels, the transducer voltage was never high enough to forward bias the rectifier diodes, and zero power was delivered. A major advantage of the M-PRC architecture is its ability to charge voltage loads (batteries) from low input levels. And while the power delivered to the load using the M-PRC did not meet the 4X levels predicted for piezoelectric systems there is a significant improvement in power delivered over the optimal resistive loading; a factor of \( \sim 1.46 \).

It should be noted that the value of \( R_C \) used in these simulations was lower than the value extracted from fabricated beams. Based on the work done by Ngo et al for the PRC with piezoelectric beams [10], the power extracted using PRC circuits is greater than optimal resistive loads for circuits when the time constant (RC for piezoelectric and RL for magnetostrictive) is low. The value of \( R_C \) in the simulation was lowered to demonstrate the potential advantages of the PRC circuit if used with a properly designed beam, i.e. by increasing the coil wire diameter or reducing number of turns.

![Figure 9. Simulated results of the M-PRC circuit compared to an optimal resistive load. Note that the M-PRC circuit improves the power by 1.46 when compared to optimal load condition.](image)

5.2 Flyback power converter

We are also analyzing and performing experiments on the energy harvester system using the flyback power converter. With a stack of four samples (1.5 cm wide x 7.5 cm long x 0.5 mm thick) with bias magnets and low permeability yoke, the maximum observed power out of the transducer was 1.7 mW and 1.1 mW out of the power converter with 1g acceleration at 100 Hz using 10 kΩ load. Here we observed average efficiency of 60% using different load values. In order to test the Galfenol transducers and power conditioning circuits, Silicon Labs Wireless sensor evaluation board was used. The supplemental power provided by the Galfenol transducer, conditioned through the flyback converter, is sufficient in helping the battery to maintain a constant voltage. For a detailed discussion on this design, the reader is referred to [14].

6. CONCLUSIONS

This section concludes the key points of the paper and entails the direction of the future work.

6.1 Conclusions

Development of linear and nonlinear transducer models based on experimental data was carried out. Experiments on various types of beams and coupling topology are ongoing. The beams were comprised of Galfenol sample and
Aluminum substrate and wrapped with a thin and small gage wire. Three single transducer beams with one Galfenol sample each were assembled in chain and ring configurations in which they exhibit synchronization and an increment in measured power. For low input power levels, we show the benefit of using magnetic pulsed power converter circuit that can increase the output power by 1.46 when compared to an optimal load condition.

6.2 Future Work

Future work will entail further developments to improve the efficiency of the power conditioning circuitry and reducing the parasitic power demand of the control electronics. Along with improvements to the power electronics, we aim to achieve greater power density in the Galfenol transducers as we modify the design and construction. In the end we plan to perform long term testing on the complete system (Galfenol transducer, power conditioning circuits, storage element, and wireless sensor node) in a real world environment to demonstrate the true potential of using Galfenol as a source for energy harvesting in a vibration-based environment whereby the life, range, and number of transmissions of the sensor node can be enhanced. We are also investigating micro-scale coupled energy harvesters on silicon nitride substrate with thin film Galfenol. The micro-scale harvesters can be integrated with wireless sensors to power them and/or aid their performance. This will allow the miniaturization of the system and efficient autonomous monitoring of various signals and events in an unattended sensor network.

7. REFERENCES