MULTIFUNCTIONAL SELF-CHARGING STRUCTURES FOR ENERGY HARVESTING IN UNMANNED AERIAL VEHICLES

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Abstract

This paper presents the investigation of a novel concept involving the combination of piezoelectric and new thin-film battery technology to form multifunctional self-charging, load-bearing energy harvesting devices. The proposed self-charging structures contain both power generation and energy storage capabilities in a multilayered, composite platform consisting of active piezoceramic layers for scavenging energy, thin-film battery layers for storing scavenged energy, and a central metallic substrate layer. Such multifunctional devices can find use in applications where mass loading is critical. An application of interest involves multifunctional energy harvesting in small unmanned aerial vehicles (UAVs). Several aspects of the design, modeling, fabrication, and evaluation of self-charging structures are reviewed.

Keywords: energy harvesting, self-charging, multifunctional, unmanned aerial vehicles, piezoelectric

Introduction

With recent growth in the development of low-power electronic devices such as portable consumer electronics and wireless sensor nodes, the topic of energy harvesting has received much attention in the research community. Several modes of energy harvesting exist including conversion of solar, thermal, vibration, and wind energy to electrical energy. Among these schemes, piezoelectric vibration-based harvesting has been most heavily researched. Previous studies have investigated the modeling, circuitry, and various applications of vibration energy harvesting using piezoelectric devices. An interesting application of piezoelectric harvesting lies in scavenging vibration energy during flight of unmanned aerial vehicles (UAVs). A recent focus has been established on creating more efficient UAVs that can be carried and deployed by soldiers in the field. In this work, the authors investigate a novel multifunctional approach to piezoelectric energy harvesting in which additional functionality is achieved in a composite harvesting device, in an effort to improve the efficiency of small UAVs.

Traditional piezoelectric energy harvesting systems consist of an active harvesting element, conditioning circuitry, and a storage medium, and the sole function of the entire system is to convert ambient mechanical energy into usable electrical energy. Furthermore, conventional systems are designed as add-on components to a host structure, often causing undesirable mass loading effects. The performance and efficiency of UAV systems are highly dependent on the mass and aerodynamics of the aircraft. Considering the importance of reducing the total mass addition of energy harvesting systems in UAVs, a multifunctional approach is considered in which a single device can generate and store electrical energy and also carry structural loads. The proposed self-charging structures, shown in Figure 1(a), contain both power generation and energy storage capabilities in a multilayered, composite platform consisting of active piezoceramic layers for scavenging energy, thin-film battery layers for storing scavenged energy, and a central metallic substrate layer. The operational principle behind the device involves simultaneous generation of electrical energy when subjected to external dynamic loads causing deformations in the structure, as well as energy storage in the thin-film battery layers. Energy is transferred directly from the piezoceramic layers through appropriate conditioning circuitry to the thin-film battery layers, thus a single device is capable of both generating and storing electrical energy. Additionally, the self-charging structures are capable of carrying loads as structural members due to the flexibility of the piezoceramic and battery layers. The ability of the device to harvest energy, store energy, and support structural loads provides true multifunctionality. Figure 1(b) provides an example of the integration of self-charging structures into the wing spar of a UAV.
The fruition of the self-charging structure concept is mainly due to the development of novel thin-film battery technology which allows for the creation of thin, flexible batteries. Conventional energy storage devices, such as capacitors and traditional rechargeable batteries, are not suitable for direct integration into the active element of an energy harvesting device as their mass and stiffness would hinder the ability to harvest energy. Additionally, they may fail under the loads applied to the harvester. Thin-film lithium-based batteries provide a viable solution with flexible devices that have thicknesses on the order of less than a millimeter, masses of around 0.5 grams, and capacities in the milliamp-hour range. Combined with an appropriate piezoelectric element and substrate layer, thin-film batteries can be used to create multifunctional self-charging structures.

This paper focuses on the development and evaluation of self-charging structures. Details on the fabrication of the devices are presented. Both analytical and experimental analyses are carried out in order to prove the concept of self-charging structures. Lastly, the strength of the fabricated self-charging structures is investigated both statically through conventional three-point bending tests and dynamically by exciting the device at resonance under various excitation levels and monitoring for failures.

**Performance Evaluation of Thin-Film Batteries**

Thinergy® MEC101-7SES thin film lithium rechargeable batteries manufactured by Infinite Power Solutions, Inc. (Littleton, CO) are investigated in this research (Figure 2(a)). The all solid-state energy cells utilize a ceramic electrolyte composed of lithium phosphorous oxynitride (LiPON), developed at the Oak Ridge National Laboratory, which eliminates any liquid components. The batteries consist of a lithium anode, LiPON electrolyte, and lithium cobalt dioxide cathode encapsulated in a metal foil casing. Typical battery dimensions are 25.40 mm x 25.40 mm with a thickness of 178 μm and a mass around 0.46 grams. The nominal voltage of the cells is 4.1 V and their capacities are around 0.7 mAh.

Prior to combining the thin film batteries with the piezoelectric devices to create self-charging structures, the performance of the batteries is evaluated experimentally. The batteries are charged using an HP 6825A power supply/amplifier and discharged through standard carbon film resistors. During charging and discharging, the battery voltage and the current flowing in/out of the battery are monitored and recorded using a National Instruments data acquisition system. The current measurements can be used to quantify the amount of energy flowing through the battery. Batteries capacities are rated in milliamp-hours (mAh), which describes charge over time. The capacity achieved during charging and discharging can be calculated by performing numerical integration of the current measurement over time as follows:

\[ C = \int i \, dt \]  

Typical voltage and current measurements during charging and discharging of the Thinergy® batteries are shown in Figure 2(b) and Figure 2(c), respectively. Charging is performed using a constant voltage charging method as recommended by the manufacturer by supplying 4.1 V to the battery using a power supply until only about 35 μA of current is sourced by the battery. Discharge performance is obtained by applying a resistive load of 2749Ω across the battery in order to draw roughly 2C of current (2 times the rated 0.7 mAh capacity, i.e. 1.4 mA) until a voltage of 3.0V is reached. Carrying out the capacity calculation given in Equation (1), the capacity in charging is calculated as 0.741 mAh, and the capacity in discharging is 0.749 mAh. It is expected that these capacities be reasonably close to...
one another, as is the case, and in both charging and discharging, the full 0.7 mAh capacity can be obtained.

Fabrication of Self-Charging Structures

The components used to fabricate the self-charging structures used in this study consist of an 1100-O aluminum alloy substrate layer (colored blue on one face), QuickPack QP10N piezoelectric ceramic layers (Midé Technology Corp.), and Thinergy® thin-film batteries described in the previous section. The QuickPack devices consist of a central monolithic piezoceramic (PZT-5A) layer bracketed by 0.0635 mm thick Kapton layers to protect the active element and provide some robustness. The relevant physical parameters of the various components used to construct the self-charging structures are given in Table 1.

Fabrication of the self-charging structures is performed by separately bonding each layer using a vacuum bagging procedure, shown in Figure 3(a), to achieve thin, uniform bonding layers. 3M ScotchWeld™ DP460 2-part epoxy is chosen for the bonding layer due to its high shear strength (4000 psi when bonded to Aluminum) and high volume resistivity (2.4 x 10¹⁴ ohm-cm). Bonding is achieved by applying a thin layer of epoxy between two structural layers, placing the device in vacuum, and allowing it to cure for 6 hours. After curing, any excess epoxy is removed from the edges of the device and the process is repeated until the self-charging structure is complete.

With all of the self-charging structure layers bonded, the final step in fabrication involves attaching electrical leads to both the piezoceramic layers and battery layers. The QuickPack devices contain an electrical connector, however, it is removed to reduce the length and mass of the piezoceramic layer. With the connector removed, a small area of the flat electrodes is exposed by removing the Kapton coating with a razor blade. 22-gauge insulated and stranded wire is then soldered to the exposed electrodes to create an electrical connection. The entire faces of the Thinergy® batteries serve as electrodes, and there is a slight overlap on one of the sides of the battery such that both positive and negative electrodes are accessible from a single side of the battery. Electrical leads are attached to the batteries by directly soldering the same 22-gauge wire to the electrode surfaces. A very small amount of solder is used as to not short the device when attaching the lead to the overlapping electrode, therefore, an additional epoxy coating is placed over the electrode connections to provide mechanical strength as well as electrical

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Aluminum Substrate</th>
<th>QP10N Device</th>
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<td>Mass (g)</td>
<td>0.530</td>
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Figure 2. (a) Photograph of Thinergy® thin-film battery and typical (a) charge and (b) discharge curves of the battery.
Electromechanical Modeling

Cantilevers used as piezoelectric energy harvesters are typically excited by the motion of their host structure (base excitation). Distributed-parameter analytical solutions for cantilevered unimorph \(^4\), bimorph \(^10\), and multi-morph \(^11\) energy harvester beams have been presented in the recent literature. Convergence of the electromechanical Rayleigh-Ritz formulation \(^12\) to the analytical solution given by Erturk and Inman \(^4\) for sufficient number of kinematically admissible functions was reported in the literature \(^3\). Since the Rayleigh-Ritz formulation is an efficient way of handling structures with non-uniform geometric and material properties, the two-segment self-charging structures developed in this work are modeled using this technique. The following is a summary of the derivation (based on the Euler-Bernoulli beam theory) and details can be found in Hagood et al \(^12\), Elvin and Elvin \(^3\) or duToit et al \(^13\) among others. The cantilevered beam structure is assumed to be sufficiently thin so that the shear strain and rotary inertia effects are negligible for the practical modes of interest (the fundamental mode is of particular interest in energy harvesting). The electrode pairs (of negligible thickness) covering the opposite faces of each piezoceramic layer are assumed to be perfectly conductive so that a single electric potential difference (voltage) can be defined across them.

The governing equations of a piezoelectric generator can be obtained from Hamilton’s principle for electromechanical media as

\[
\mathbf{M}\ddot{\mathbf{r}}(t) + \mathbf{C}\dot{\mathbf{r}}(t) + \mathbf{K}\mathbf{r}(t) - \mathbf{\Theta}v(t) = -\mathbf{M}^*a_B(t) \tag{1}
\]

\[
C_p\dot{v}(t) + \frac{v(t)}{R_i} + \mathbf{\Theta}^T\mathbf{r}(t) = 0 \tag{2}
\]

where \(\mathbf{M}\), \(\mathbf{C}\), and \(\mathbf{K}\) are the mass, damping, and stiffness matrices, \(\mathbf{\Theta}\) is the electromechanical coupling vector, \(\mathbf{M}^*\) is the effective forcing vector, \(C_p\) is the equivalent capacitance, \(R_i\) is the external load resistance, \(\mathbf{r}(t)\) is the modal mechanical response, \(v(t)\) is the voltage response across the load resistance, \(a_B\) is the base acceleration of the harvester, and an over-dot represents differentiation with respect to time. Here, proportional damping is assumed so that standard modal analysis can be used with mathematical convenience (i.e., the damping matrix has the form \(\mathbf{C} = \alpha\mathbf{M} + \beta\mathbf{K}\) where \(\alpha\) and \(\beta\) are constants of proportionality). Expressions for the elements of the mass, stiffness, damping, effective forcing, electromechanical coupling matrices, and vectors can be found in the literature \(^3, 12, 13\).

The physical vibration response of the beam relative to its vibrating base is

\[
w(x,t) = \sum_{i=1}^{N}\phi_i(x)r_i(t) = \mathbf{\Phi}^T(x)\mathbf{r}(t) \tag{3}
\]

where \(\mathbf{\Phi}(x)\) is the vector of admissible functions and \(N\) is the total number of mechanical modes used in the expansion. A simple admissible function that satisfies the essential boundary conditions of a clamped-free beam is \(^3\)

Figure 3. (a) Vacuum bagging setup, (b) complete self-charging structure.
\[ \phi_i(x) = 1 - \cos \left( \frac{(2i-1)\pi x}{2L} \right) \]  

(4)

where \( i \) is the modal index. Note that one should use sufficient number of admissible functions for convergence of the natural frequencies of interest to the exact values.

If the base acceleration is assumed to be harmonic of the form \( a_B(t) = \bar{a}_B e^{j\omega t} \) (where \( \omega \) is the excitation frequency and \( j \) is the unit imaginary number), the steady-state voltage response and the vibration response can be obtained from

\[
v(t) = j\omega \left( \frac{1}{R_i} + j\omega C_p \right)^{-1} \Theta^T \times \left( K - \omega^2 M - j\omega C + j\omega \left( \frac{1}{R_i} + j\omega C_p \right) \right)^{-1} \ldots
\]

(5)

\[
\Theta \Theta^T \right)^{-1} \times M^* \bar{a}_B e^{j\omega t} \\
w(x,t) = -\Theta^T (x) \times \left( K - \omega^2 M - j\omega C + j\omega \left( \frac{1}{R_i} + j\omega C_p \right) \right)^{-1} \ldots
\]

(6)

Here, the voltage output – to – base acceleration and the vibration response – to – base acceleration FRFs (frequency response functions) can be extracted as \( v(t)/\bar{a}_B e^{j\omega t} \) and \( w(x,t)/\bar{a}_B e^{j\omega t} \), respectively.

**Experimental Performance of Self-Charging Structures**

The performance of the fabricated self-charging structure shown in Figure 3(b) is evaluated experimentally by mounting the device in a cantilever fashion and subjecting it to base excitations. The self-charging structure is clamped to a small LDS electrodynamic shaker with an overhang length of 43.7 mm (Figure 4(b)). In order to determine the resonant frequency and optimal load resistance of the clamped device, experiments are conducted to obtain the electromechanical FRFs of the self-charging structure for a set of resistive electrical loads (ranging from 100 \( \Omega \) to 1 M\( \Omega \)). SigLab data acquisition hardware is used for all FRF measurements. The input acceleration is measured using a PCB U352C67 accelerometer, the tip displacement is measured using a Polytec OFV303 laser Doppler vibrometer, and the voltage output of the device is measured directly with the data acquisition system. The overall test setup is shown in Figure 4(a). For the series connection of the piezoceramic layers (to obtain larger voltage output), the voltage output – to – base acceleration FRFs and the tip velocity response – to – base acceleration FRFs of the symmetric multilayer generator are shown in Figure 5(a) and Figure 5(b), respectively (where the base acceleration is given in terms of the gravitational acceleration, \( g = 9.81 \) m/s\(^2\)).

To verify the electromechanical model developed for the prediction of the output of the self-charging
structure, the voltage output and the vibration response FRFs are predicted using Equation (5) and Equation (6), respectively, and plotted over the experimental results in Figure 5. 20 modes are used in the Rayleigh-Ritz formulation \((N = 20)\) to ensure the convergence of the fundamental natural frequency using the admissible functions given by Equation (4). As the load resistance is increased from 100Ω to 1 MΩ, the experimental value of the fundamental resonance frequency moves from 204.0 Hz (close to short-circuit conditions) to 211.1 Hz (close to open-circuit conditions). These two frequencies are called the short-circuit and the open-circuit resonance frequencies \(N, 10\) and they are predicted by the electromechanical model as 204.1 Hz and 211.0 Hz, respectively. The amplitude-wise model predictions are also in agreement with the experimental measurements. It is worth mentioning that the maximum voltage output is obtained for the largest load resistance for excitation at the open-circuit resonance frequency as 34 V/g (peak amplitude). The optimal electrical loads for excitations at 204.0 Hz and 211.1 Hz are identified as 9.8 kΩ and 91.0 kΩ (among the resistors used), respectively, which yield similar peak power outputs of 2.8 mW/g² and 3.1 mW/g², respectively. These voltage and power output values given in terms of base acceleration are, however, frequency response-based linear estimates obtained from low-amplitude chirp excitation and they are not necessarily accurate for large-amplitude excitations with nonlinear response characteristics.

After the preliminary analysis for the resistive load case, the piezoceramic and thin-film battery layers are connected to the input and output of a simple linear voltage regulator circuit (consisting of a full bridge rectifier, smoothing capacitor, and voltage regulator), respectively. The electrical boundary conditions of the piezoceramic layers then become more sophisticated. The tip velocity FRF is measured for this case as well and plotted in Figure 5(b). It appears from the figure that the case with the largest resistive load (1 MΩ, close to open-circuit conditions) successfully represents the vibration response of the self-charging structure when connected to the circuit, which exhibits resonance around 210.0 Hz. With the resonant frequency of the self-charging structure connected to the circuit obtained, the energy harvesting performance of the device can be experimentally evaluated. Using an experimental setup similar to that shown in Figure 4, the self-charging structure is excited at 210.0 Hz and the output of the piezoelectric layers is fed into the harvesting circuit and used to charge the thin-film battery layers. For this experimentation, the two piezoelectric layers are connected in series for increased voltage output and used to charge a single battery layer. The input base acceleration amplitude is set to ±1.0 g, which is considered a reasonable acceleration level. The device is excited for 1 hour and the battery voltage and current into the battery are measured throughout the test. Once the test is complete, the battery is discharged using a 2749 Ω resistor (drawing 2C of current out of the battery). Results from both the charging and discharging tests are shown in Figure 6. From Figure 6(a), it can be seen that the piezoelectric layers are able to supply an average of about 0.08 mA of current into the battery. The battery voltage remains constant throughout the test at about 3.9V. Using Equation (1), the capacity during charging is found to be 0.0781 mAh. During discharging, the voltage on the battery is maintained around 3.9 V and the current output is held at 1.4 mA for 150 seconds. A capacity of 0.0663 mAh is found by integrating the current over time. There is a slight difference between the capacity calculated in

**Figure 5.** The (a) voltage-to-base acceleration and (b) tip velocity-to-base acceleration FRFs of the self-charging structure for a set of resistances.
charging and that calculated in discharging. It is likely
that this is a leakage effect where some of the energy
during charging is dissipated in the battery, thus there is
a small decrease in capacity when discharging.

The charge/discharge results presented in Figure 6
prove the ability of the self-charging structures to both
generate and store electrical energy in a multifunctional
manner. The current of 0.0781 mA during charging is a
reasonable number for piezoelectric energy harvesting.
The average power into the battery during charging is
around 0.306 mW.

**Failure Testing**

It has been proposed that the self-charging structures
developed in this work be directly integrated into host
structures in a multifunctional manner. Inherent in this
proposal is the fact that the self-charging structures
must act as load bearing members. Both static and
dynamic testing is carried out in order to determine the
strength of the self-charging structures. Results of the
strength testing can be used as a design tool in the
development of embedded self-charging structure systems.

*Static Failure Analysis and Testing*

Classical 3-point bend tests are performed in order to
experimentally evaluate the strength of the various
components of the self-charging structures as well as
the complete assembly. The bending strength of a
simple beam placed under 3-point bend loading is
defined from Euler-Bernoulli beam theory as

\[ \sigma_b = \frac{3L}{2bh^2} P_f \]  (7)

where \( P_f \) is the failure load, \( L \) is the support span, \( b \) is
the sample width, and \( h \) is the sample thickness. The
failure load, \( P_f \), is taken as the maximum load observed
during testing for the materials exhibiting classic brittle
failure, and as the load corresponding to a transition
from elastic to plastic behavior for ductile materials.

The bending strength of a multilayer composite device,
such as the complete self-charging structure assembly,
can be defined for each device layer as

\[ \sigma_{b}^{\text{max}} = \frac{Y_k h_{kn} L}{4Y T} P_f \]  (8)

where \( \sigma_{b}^{\text{max}} \) is the maximum stress of a layer at a given
failure load of the device, \( Y_k \) is the elastic modulus of
the layer of interest (layer \( k \)), \( h_{kn} \) is the distance from
the neutral axis to the outer surface of the \( k^{th} \) layer, \( L \)
is the support span, and \( Y T \) is the overall bending
stiffness of the multilayer beam. In order to obtain the
value of \( Y T \) of a multilayer beam, a cross-section
transformation (as described by Erturk and Inman) can
be used. It is worth mentioning that the maximum
stress of a layer for the failure load of the assembly may
be lower than its individual failure strength. For
instance, for the failure load that results in fracture of a
piezoceramic layer in a multi-layer assembly, the
maximum stress in the metallic layer could be lower
than its individual failure strength. Nevertheless, the
overall structure is considered to be failed when it starts
exhibiting brittle or ductile failure behavior.

Experimental testing is performed using an Instron
4204 universal test frame equipped with a 1000 N load
cell and a small three-point bend fixture with adjustable

![Figure 6. Experimental curves for self-charging structures in (a) charging and (b) discharging.](image-url)
supports, shown in Figure 7. Each specimen rests on the two lower support pins, which are spaced 20 mm apart, and the central pin is lowered using the machine at a rate of 0.3 mm/min until a prescribed displacement is reached. In each case, the specimens fail before the maximum displacement is achieved.

Three individual samples are tested for the aluminum substrate, QP10N piezoceramic, and Thinergy® battery layers. Aluminum specimens are cut to 25.4 mm x 25.4 mm, and the QuickPack samples are cut in half (resulting in about 25.4 mm x 25.4 mm) to fit in the test fixture. A single self-charging structure is tested and cut in half such that each section can be tested separately. The load and crosshead displacement are recorded throughout each test, and typical load-deflection curves for the complete structure are shown in Figure 8. From the results, it can be seen that the root section of the self-charging structure experiences brittle failure, where the tip section exhibits simultaneous ductile and brittle failure signatures. This phenomenon is likely due to failure occurring in the piezoceramic (brittle) and battery (ductile) layers for nearly the same force.

Based on the failure loads observed during testing, Equations (7) and (8) are used to obtain the bending stress values for each sample tested. Bending strength results are presented in Table 2. From the results, it can be seen that failure in the root section of the self-charging structure is due to failure of the piezoceramic layers. At the point of failure, the maximum stress in the aluminum layer is much less than the failure stress observed in a single aluminum layer. The failure stress in the QuickPack is about half of the failure stress obtained for a single layer, however, it is on the same order of magnitude. Although there is a significant difference between the failure stress of the single layer and composite device, it is typical in brittle failure to observe a wide range of failure loads (thus stresses) for a single material. The results for the tip section of the self-charging structure show failure in both the piezoceramic and battery layers with stresses similar to the failure stress of the individual layers in both cases. This result is confirmed by the simultaneous brittle and ductile failure observed in Figure 8. Overall, it can be concluded that the piezoceramic and battery layers are the critical layers in three-point bending failure.

**Dynamic Failure Analysis and Testing**

To gain an understanding of the dynamic loading that can be withstood by the self-charging structures without failure, a series of dynamic tests are conducted using the same experimental setup show in Figure 4. Dynamic failure testing is conducted by subjecting the cantilevered harvester to resonant base excitations

![Figure 7. Three-point bend fixture setup.](image)

![Figure 8. Typical load-displacement curves observed during 3-point bend testing.](image)

<table>
<thead>
<tr>
<th>Table 2. Maximum stress at failure for various samples.</th>
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<tr>
<td>Individual Layers</td>
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<tr>
<td>Self-Charging Structure - Root</td>
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<td>Self-Charging Structure - Tip</td>
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(previously found to be 210.0 Hz) of increasing amplitude until electrical failure is observed. Electrical failure is defined as a 10% decrease in either the charge or discharge behavior of the device as compared to baseline charge/discharge curves. Once clamped to the shaker, the device is not disturbed for the duration of testing.

An initial baseline charge/discharge measurement is obtained for the device (using the same procedure to calculate capacity as described previously when evaluating the performance of the self-charging structures) and all future measurements are compared to this baseline. Once the baseline is obtained, the device is first excited at resonance at an initial acceleration input level of ±0.2 g for 1 hour. During the test, the piezoceramic layers are connected in series to the harvesting circuit and used to charge a single thin-film battery (which is initially fully discharged to 3.0 V). The battery voltage and current are monitored and recorded. After 1 hour, the excitation is ceased and a discharge test is performed on the battery. The self-charging structure is then allowed to sit for 24 hours before testing is resumed. The following day, the thin-film battery is charged using the power supply and then discharged. This data is compared to the baseline charge/discharge curves, and significant changes indicate device failure (caused by the excitation the previous day). Finally, the acceleration amplitude is increased and the process is repeated. Complete results from the dynamic failure testing for the power supply charge/discharge are given in Figure 9(a) for base acceleration values from 0.2 g to 7.0 g. Additionally, the complete charge/discharge results with the piezoceramic layers charging the battery are given in Figure 9(b).

From the dynamic failure testing results presented in Figure 9(a), it can be seen that as the excitation amplitude is increased from 0.2 g to 7.0 g, there is no significant change in the power supply charge or discharge behavior. In each case, the charge amplitude is slightly higher than the discharge amplitude, likely due to leakage in the battery. The power supply charge after 5.5 g excitation is abnormally high, thus the battery initially appears damaged, but continuation of testing at higher excitation levels shows that the battery still functions properly. This phenomenon may be due to experimental errors. Although it was expected that electrical failure would occur in the batteries at the acceleration levels tested, no electrical failure was observed. Testing is stopped at an excitation level of 7.0 g in order to protect the device from any mechanical failure.

The piezoceramic charge/discharge results presented in Figure 9(b) show that the piezoceramic layers are able to partially charge the thin-film battery. As the excitation amplitude is increased, the total charge capacity monotonically increases. This is expected as more vibration energy is available for harvesting at higher excitation levels. Accordingly, the discharge capacity also increases with the excitation amplitude. There is, however, a difference in the charge and discharge capacities for each test. This variability is likely due to leakage in the battery as the current input from the piezoceramic layers is quite low. Overall, these results are in agreement with the power supply results in that no electrical failure is observed for any of the excitation levels tested.

**Summary and Conclusions**

This paper provides details on the development and evaluation of the self-charging structure concept. Thin-film lithium-based batteries are investigated for use in self-charging structures and found to perform well in both charging and discharging. Fabrication of the self-charging structures is outlined and proven successful by using epoxy cured under vacuum as the bonding layer material. Experimental testing of the frequency response behavior has shown the natural frequency of the first bending mode of the self-charging structure to
be 210.0 Hz. When excited at the first bending mode with ± 1.0 g base acceleration input, the device is able to generate an average of 0.306 mW of continuous power, supplying 0.0781 mAh of capacity to the thin film battery layer over a 1 hour period. Upon discharging, 0.0663 mAh of capacity is drawn from the battery. This difference is attributed to leakage losses in the battery during charging. These results have proven the concept of self-charging structures offering multifunctionality in piezoelectric energy harvesting. Finally, the strength of the self-charging structures has been tested both statically and dynamically. It is found that the piezoceramic and battery layers are critical in static bending tests. Dynamic testing results show that no electrical failure of the device is observed up to an acceleration of 7.0 g of excitation. Overall, the results of this research have proven the concept of self-charging structures. The devices are able to simultaneously harvest and store electrical energy, while maintaining robustness under dynamic excitation.

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