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Energy Harvesting from Wood Floor Vibration Using a Piezoelectric Generator

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Abstract

Vibration can occur in wood floor systems as a consequence of a variety of human activities, ranging from common daily movements associated with individuals living in homes to high-intensity activities associated with sporting events that are held in large sports arenas. For example, the potential for harvesting energy from a wooden floor system in public buildings during daily rush hours could be substantial. In this pilot study, an energy harvesting system was developed to investigate the feasibility of harvesting energy from a vibrating wooden floor system. The purpose of this publication is to provide a summary of the experimental technique we developed and to present data obtained from its use.

Keywords: energy harvesting, piezoelectric property, vibration, wood floor systems

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Energy Harvesting from Wood Floor Vibration Using a Piezoelectric Generator

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Introduction

The Beijing Forestry University and USDA Forest Service, Forest Products Laboratory (FPL) are investigating various methods and technologies surrounding energy usage in wood structures. Investigations on the use of various insulation methods and other energy saving techniques are ongoing. One of the areas proposed for investigation is the concept of capturing, or harvesting, mechanical energy generated by appliances and occupants as they live and work in wood structures. A significant amount of research has been conducted to investigate energy harvesting for a wide range of applications—from harvesting energy from the boots of soldiers to power their portable electronic field equipment to using harvesting technologies to provide power for in-service sensors for monitoring transportation structures.

Wood floor systems are widely used in residential and commercial buildings, as well as in large public facilities. Movement can occur in wood floor systems as a consequence of various human activities ranging from walking to intense sports activities (Saidi and others 2006). For example, the walking pace of a human is generally between 0.9 and 16 steps per second (Braune and Fischer 1987). For a 68-kg man walking at 2 steps per second, the available power that can be generated by the fall of his heel is 67 W (Starner 1996; Starner and Paradiso 2004).

The use of piezoelectric generators to harvest energy from the movement of humans has been extensively studied. Individual human motion, in general, can be characterized as being of relatively low frequency and large amplitude. The theoretical limits of piezoelectric energy harvesting on human applications have suggested that 1.27 W could be obtained from walking by using a piezoelectric generator (Gonzalez and others 2001). One of the earliest examples of a shoe-mounted generator incorporated a hydraulic system coupled to cylindrical lead zirconatetitanate (PZT) stacks.

The hydraulic system amplifies the force on the piezoelectric stack while decreasing the stroke. A 1/17th scale model was built and tested and was found to generate $5.7 \pm 2.2 \text{ mW kg}^{-1}$ during walking, which suggested that 6.2 W could be generated with a full-size generator on a 75-kg subject (Antaki and others 1995).

Scientists have also developed a generator using polyvinylidene fluoride (PVDF) inserted in a sports training shoe in which the bending movement of the sole strained the PVDF stacks, producing a charge from the d_{31} mode (Kymissis and others 1998). At a foot fall frequency of 0.9 Hz, this generator produced an average power of 1.3 mW into a 250-k Ω load. Shenck and Paradiso (2001) tested a piezoelectric generator using a compressible dimorph that was located in the heel of a work boot. Under excitation of 0.9 Hz, the generator produced an average of 8.4 mW into a 500-k Ω load.

Also, piezoelectric crystals embedded in the heel of a shoe have been demonstrated by the Electric Shoe Company (Drake 2001). This generator could recharge a mobile phone after 5 days of walking. Yoon and others (2005) used a simply supported curved piezoelectric unimorph, similar to a piezoelectric bimorph, to verify the analytical model of the curved PZT unimorph. They found that it is more effective to increase the width of the unimorph rather than the length. The height at the center and the thickness of the substrate material should be maximized within the capacity of the manufacturing process and the available compressing force.

In an analytical study on PVDF inserts, Mateu and Moll (2005) compared homogeneous (two layers of PVDF bonded together) and heterogeneous beams (PVDF bimorph) with different boundary conditions in both rectangular and triangular shapes. The overall conclusion was that the best PVDF structure was a simply supported asymmetric bimorph beam under a distributed load, with a large ratio of substrate to PVDF thickness being preferable.

Almost all energy generators introduced in previous research were used on wearable computing electronic systems or implanted sensor nodes for a specific purpose. No information has been reported on the use of piezoelectric generators in wood floor systems to extract energy from floor vibration.

The objective of this pilot study was to investigate the feasibility of using a piezoelectric generator to harvest vibration energy from a wood floor system.

Fundamentals of Piezoelectric Material

Piezoelectric materials have been used for many years to convert mechanical energy into electrical energy. The piezoelectric effect was discovered by Jacques and Pierre Curie in 1880 (APC International Ltd. 2002). They found that if certain crystals were subjected to mechanical strain, they became electrically polarized, and the degree of polarization was proportional to the applied strain. This is called direct piezoelectric effect. Conversely, these materials deform when exposed to an electric field. This is called converse piezoelectric effect. The direct piezoelectric effect is responsible for the material's ability to function as a sensor or generator. The converse piezoelectric effect is accountable for its ability to function as an actuator. A material is deemed piezoelectric when it has this ability to transform mechanical strain energy into electrical energy and likewise transform electrical energy to mechanical strain energy.

The mechanical and electrical behavior of a piezoelectric material can be modeled by two linear constitutive equations (Riemer and Shapiro 2011). These equations

contain two mechanical and two electrical variables:

$$\{D\} = [d]\{T\} + [\epsilon^T]\{E\} \quad (1)$$

$$\{S\} = [S^E]\{T\} + [d]^t\{E\} \quad (2)$$

where $\{D\}$ is the three-dimensional electric displacement vector; $\{T\}$ is the stress vector; $[\epsilon^T]$ is the dielectric permittivity matrix at constant mechanical stress; $[S^E]$ is the 6-by-6 matrix of compliance coefficients at constant electric field strength; $\{S\}$ is the six-dimensional strain vector; $[d]$ is the 3-by-6 matrix of the piezoelectric constant; and $\{E\}$ is the electric field vector. The superscript t denotes transposition of a matrix. Equation (1) is for direct piezoelectric effect, and Equation (2) is for converse piezoelectric effect:

When the material is deformed or stressed, an electric voltage can be recovered along any surface of the material (via electrodes). Therefore, piezoelectric properties must contain a sign convention to facilitate this ability to recover electric potential in three directions. The piezoelectric material can be generalized for two mode operations. The first is the stack configuration that operates in the 33 mode, and the second is the bender that operates in the 13 mode. The sign convention assumes that the poling direction is always in direction 3.

In the 33 mode as shown in Figure 1, the electric voltage is recovered in direction 3 and the material is strained in the poling direction, or direction 3. In the 13 mode as shown in Figure 2, the electric voltage is measured in direction 3 and the material is strained in direction 1, or perpendicular to the poling direction. These two modes of operation are particularly important when defining the piezoelectric constants.

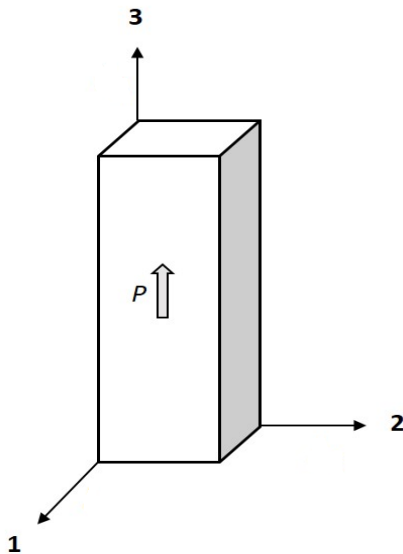


Figure 1—The 33 mode of the piezoelectric effect described in an orthogonal system. P is the direction of polarization.

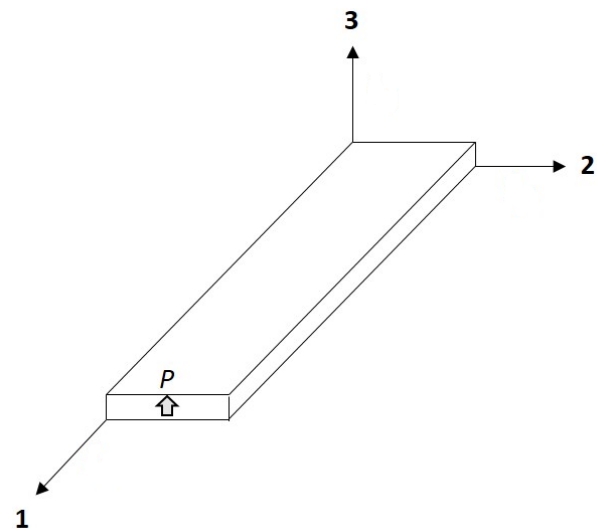


Figure 2—The 13 mode of the piezoelectric effect described in an orthogonal system. P is the direction of polarization.

The piezoelectric charge constant α is defined as the electric polarization generated in a material per unit mechanical stress applied to it. Alternatively, it is the mechanical strain experienced by the material per unit electric field applied to it. For example, α_{31} is the induced polarization in direction 3 per unit stress applied in direction 1. Also, it is the mechanical strain induced in the material in direction 1 per unit electric field applied in direction 3.

The piezoelectric voltage constant g is defined as the electric field generated in a material per unit mechanical stress applied to it. Alternatively, it is the mechanical strain experienced by the material per unit electric displacement applied to it. For example, g_{31} is the induced electric field in direction 3 per unit stress applied in direction 1. Also, it is the mechanical strain induced in the material in direction 1 per unit electric displacement applied in direction 3.

Another important constant for piezoelectric material is the coupling factor k_{eff} , which is a measure of the effectiveness with which electrical energy is converted into mechanical energy and vice versa. At frequencies well below the resonant frequency of the piezoelectric body, k_{eff} is given by

$$k_{\text{eff}}^2 = \frac{\text{energy converted}}{\text{energy input}} \quad (3)$$

This expression holds for both electro-mechanical and mechano-electrical conversions. As with other piezoelectric constants, coupling factors carry subscripts. k_{33} , for instance, is the coupling factor for longitudinal vibrations of a very long, slender rod (in theory infinitely long, in practice with a length/diameter ratio >10) under the influence of a longitudinal electrical field. k_{31} is the coupling factor for longitudinal vibrations of long rod under the influence of a transverse electric field. The real efficiency is the ratio of the converted useful energy to the energy taken up by the transducer. A tuned and well-adjusted transducer working in its resonance region could be more than 90% efficient. If it is outside its resonance region, however, its efficiency could be very low.

Piezoelectric materials are widely available in many forms including single crystal (quartz), piezoceramic (PZT), thin film (sputtered zinc oxide), screen-printable thick films based on piezoceramic powders (Baudry 1987; White and Turner 1997), barium titanate (BaTiO_3), and polymeric materials such as PVDF. The piezoelectric constants of common materials are given in Table 1.

Materials and Methods

Wood Floor System

The wood floor system used in this pilot study was constructed of nine 40- by 225-mm Douglas-fir joists spaced 380 mm on center, with a span of 3.65 m (Fig. 3).

Table 1—Constants of common piezoelectric materials

Property	PZT-5H ^a	PZT-5A	BaTiO ₃ ^b	PVDF ^c
d_{33} (10^{-12} CN ⁻¹)	593	374	149	-33
d_{31} (10^{-12} CN ⁻¹)	-274	-171	78	23
g_{33} (10^{-3} VmN ⁻¹)	19.7	24.8	14.1	330
g_{31} (10^{-3} VmN ⁻¹)	-9.1	-11.4	5	216
k_{33}	0.75	0.71	0.48	0.15
k_{31}	0.39	0.31	0.21	0.12
Relative permittivity (ϵ/ϵ^0)	3400	1700	1700	12
Curie temperature (°C)	195	365	120	110

^aPZT, cylindrical lead zirconatetitanate.

^bBarium titanate.

^cPVDF, polyvinylidene fluoride.

The floor deck was 20-mm-thick plywood panels, which were fastened to the joists with drywall screws. The floor system was rigidly supported on both ends by portable concrete barriers (Fig. 3).

Energy Harvesting System

Figure 4 shows the energy harvesting system used in this study. The experimental setup consisted of a beam-type piezoelectric generator, an energy harvesting electrical interface, a digitizer (NI-USB-5132, National Instruments, Austin, TX), and a personal computer with signal-recording software developed by the authors. The conversion chain starts with a mechanical energy source: floor vibration resulting from human motions. The vibration energy is converted into electrical energy via a piezoelectric generator installed in the floor. The produced electricity is thereafter regulated by electrical interface before being stored in a storage system or powering the load (electrical device).

Piezoelectric Generator

A bending type piezoelectric generator (D220-A4-503YB, PiezoSystems Inc., Woburn, MA) was selected for this



Figure 3—The laboratory-constructed wood floor system used for energy harvesting experiments.

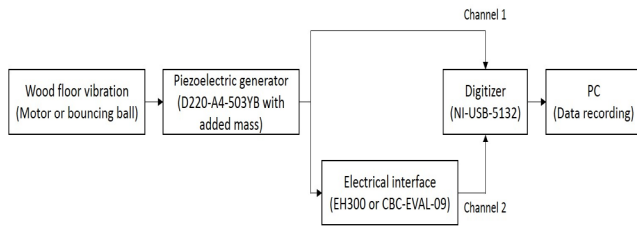


Figure 4—The energy harvesting system using a piezoelectric generator applied to a wood floor structure.

experiment and mounted underneath the floor deck. The piezoelectric generator was constructed of PZT material deposited on both sides of a brass substrate (Fig. 5).

Excitation

Two excitation sources were used to generate the floor movement. One excitation source consisted of a small electric motor whose rotational frequency was continuously adjustable up to 30 Hz. This excitation source was used to simulate walking. An inflatable ball dribbled continuously was also used, to simulate what a sports floor might be subjected to.

Electrical Interface

Two electrical interfaces were used in the experiments. One was an EH 300 energy harvesting module (Advanced Linear Devices, Inc., Sunnyvale, CA) with two 3300 pF parallel-connected capacitors for low power intermittent duty and long storage time applications. The other is a universal energy harvesting evaluation kit (CBC-EVAL-09, Cymbet Corporation, Elk River, MN) with an energy processor (EnerChip EP CBNC915-ACA, Cymbet Corporation) and a solid state battery module (EnerChip CBC51100 100 μ Ah, Cymbet Corporation). Under each excitation condition, the two electrical interfaces were used respectively to regulate and store the energy harvested from the vibration. The effect of the electrical interfaces on the output power of the energy harvesting system was evaluated based on the experimental results.

Experimental Procedures

Energy harvesting experiments were conducted with four different combinations of electrical interfaces and excitation sources: (1) EH 300 energy harvesting module with motor excitation; (2) EH 300 energy harvesting module with

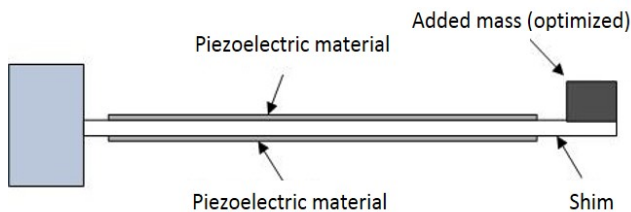


Figure 5—Beam-type piezoelectric generator.

bouncing ball excitation; (3) CBC-EVAL-09 universal energy harvesting evaluation kit with motor excitation; and (4) CBC-EVAL-09 universal energy harvesting evaluation kit with bouncing ball excitation.

In the cases of motor excitation, the wood floor was excited by an electric motor with the rotational frequency that produced the maximum output voltage of piezoelectric. In the cases of bouncing ball excitation, the wood floor was excited by repeated impact from a basketball when a person constantly bounced the ball while walking on the floor. The maximal output voltage of the beam-type piezoelectric generator and the voltage of the capacitor or battery of the electrical interface were recorded once every 30 s by the digitizer and recorded by the signal-recording software.

Data Analysis

To model the electrical behavior of a vibrating piezoelectric generator, we consider the following: (1) the generator is excited around its resonance frequency; and (2) the displacement of the vibration movement remains in the linear range. Then, the structure with piezoelectric elements can be modeled by a mass + piezoelectric element + spring + damper (Roundy and Wright 2004). The resonant frequency is conversely proportional to the squared root of mass M . Adding the proof mass can decrease its resonant frequency to about 10 Hz, which is in the main-energy frequency range. Therefore, in this study, the piezoelectric generator was excited around its natural frequency. In this case, the harvested power varied with different electrical load and reached a maximum harvested power for an optimal load (Minazara and others 2007).

The energy stored in the capacitors harvested from the wood floor vibration was calculated as

$$\Delta E = \frac{1}{2} C (U_2^2 - U_1^2) \quad (4)$$

where U_1 represents the initial voltage across the capacitors, U_2 is the voltage across the capacitors after being charged, C is the capacitance, and ΔE represents the energy stored in the capacitors.

The average power (P) from the piezoelectric generator was calculated by dividing the stored energy by charging time (T_c).

The average charging current I_c was determined by

$$I_c = \frac{(U_2 - U_1) \times C}{T_c} \quad (5)$$

Results and Discussion

The vibration levels observed were different for different excitation methods. The maximal vibration amplitude was observed when the bouncing ball was used to generate

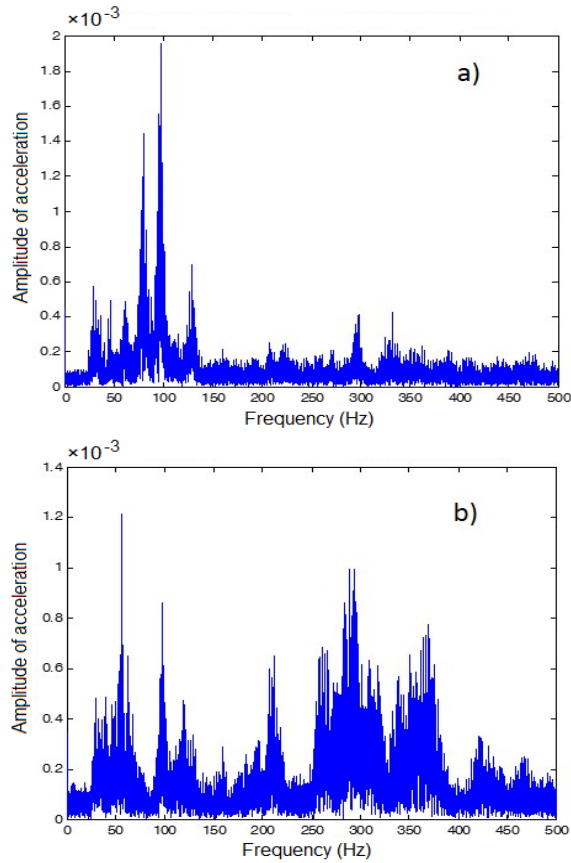


Figure 6—Single-sided amplitude spectrum of vibration signals captured from the wood floor system (a) in deck, (b) in joist.

vibrations on the floor. The measured vibration levels for walking simulated by motor excitation were relatively low.

Figure 6a shows the frequency spectrum of the vibration signal obtained from the floor deck, and Figure 6b shows the frequency spectrum of the vibration signal obtained from the floor joist. The vibration energy of the floor deck was concentrated in the frequency range of 0–130 Hz, whereas the vibration energy of the floor joist was concentrated in the frequency range of 0–420 Hz. The peaks corresponded to the main frequencies of the wood floor system and human motions. The peaks observed were less than 420 Hz, regardless of the speed of the bouncing ball and the weight of the person walking on the wood floor. The interesting frequency band to harvest energy, where 90% of the energy of the vibrations induced by human motions was concentrated, was approximately between 0 and 420 Hz (Figs. 6 and 7). It is therefore essential to select and tune a piezoelectric generator that resonates in the frequency range of 0 to 420 Hz, where 90% of vibration energy is available. To harvest the maximum energy, the piezoelectric generator should be tuned to the resonant mode of the floor structure.

Table 2 shows the average power harvested from the wood floor vibration by the piezoelectric generator with an EH

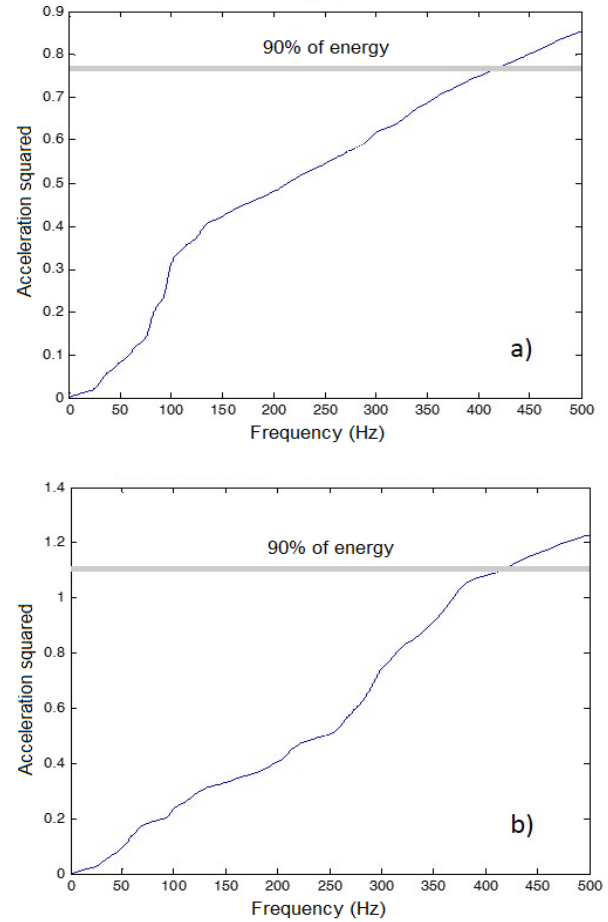


Figure 7—Cumulative sum of the acceleration squared (a) in deck, (b) in joist.

300 energy harvesting module in different excitation modes and the average charging current of the different electric interfaces by different excitation mode. The relationships between the charging time and the voltage across the energy storage (capacitors or batteries) with different electric interfaces in different excitation mode are shown in Figure 8.

The experimental results indicated that the maximum output voltage with motor excitation was lower than that with the bouncing ball excitation. One possible reason is that the amplitude of the wood floor vibration excited by the bouncing ball was larger than that excited by a motor, even though the frequency of the bouncing ball was far lower than that of the motor.

The average output power of the energy harvesting system depends on the excitation mode. The average power harvested through motor excitation was greater than that harvested through a bouncing ball, although the maximum output voltage by motor excitation was lower than that by bouncing ball. That is because the average output power depends not only on the maximum output voltage but also

Table 2—Performance of the energy harvesting systems tested

Excitation method	Energy harvesting system	Capacitance (μF)	Charging time (s)	Max. output voltage (V)	Energy stored (J)	Average power (mW)	Average charging current (mA)
Motor excitation	EH300	6600	330	14.575	0.148	0.447	0.102
Bouncing ball	EH300	6600	930	16.303	0.304	0.327	0.046

on the frequency of the floor excitation. The frequency of the bouncing ball was far lower than that of the motor, thus resulting in less average output power by the bouncing ball than that by motor excitation.

The charging current showed a similar relationship with the excitation mode for the same reason. Figure 8 shows the relationship between the voltage across the energy storage and charging time. The slope of the curves indicates the charging rate of the capacitors or battery. The experimental results indicated that the piezoelectric generator produced more power from the vibration of the wood floor induced by the motor than that by the bouncing ball.

The ultimate output power from an energy harvesting system also depends on the electric interface used. There could be an issue on the impedance matching between the output impedance of piezoelectric generator and the input impedance of the electrical interface. The advanced energy management can improve the efficiency of energy harvesting as the maximum power point tracking (MPPT) algorithms do in the CBC-EVAL-09 universal energy harvesting evaluation kit. The energy harvesting system that

scavenges wood floor vibration energy induced by human motion should include an advanced energy management subsystem to adapt the excitation mode in different application sites.

The maximum power harvested from wood floor vibration by a single piezoelectric generator is not enough to power common electric devices. This was expected because the vibration energy in a specific location generated by a single excitation source is very limited. Another factor was that the efficiency of the piezoelectric generator was relatively low because the piezoelectric material used was not the best one on the market. Further research is needed to focus on efficiency improvement of the piezoelectric generator and the energy congregation of multigenerators.

Conclusions

In this preliminary study, we investigated the feasibility of harvesting vibration energy from the wood floor vibration induced by human motions. From analysis of the experimental results, we concluded the following:

1. The main frequency of the wood floor vibration varies in different excitation modes, but the dominant frequency range of wood floor vibration was between 0 and 420 Hz. In an energy harvesting system, the piezoelectric generator should be tuned to the resonant mode in this range, allowing the maximum amount of energy to be harvested.
2. The output power from the piezoelectric generator was related to the frequency and amplitude of the excitation. Higher frequency and larger amplitude of the excitation can produce more power for the same piezoelectric generator.
3. The energy harvesting system can scavenge energy from the wood floor vibration and store it in the capacitors or batteries. Future research should focus on examining the feasibility to power an electronic system by using multiple piezoelectric generators and multiple excitation sources in in-situ wood floor structures.

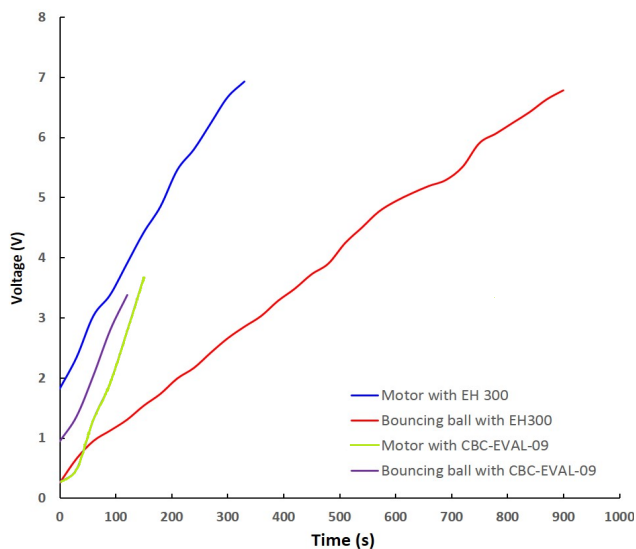


Figure 8—Voltages across the energy storage in relation to charging time.

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