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Damping as a result of piezoelectric energy harvesting

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Abstract

Systems that harvest or scavenge energy from their environments are of considerable interest for use in remote power supplies. A class of such systems exploits the motion or deformation associated with vibration, converting the mechanical energy to electrical, and storing it for later use; some of these systems use piezoelectric materials for the direct conversion of strain energy to electrical energy. The removal of mechanical energy from a vibrating structure necessarily results in damping. This research addresses the damping associated with a piezoelectric energy harvesting system that consists of a full-bridge rectifier, a filter capacitor, a switching DC–DC step-down converter, and a battery. Under conditions of harmonic forcing, the effective modal loss factor depends on: (1) the electromechanical coupling coefficient of the piezoelectric system; and (2) the ratio of the rectifier output voltage during operation to its maximum open-circuit value. When the DC–DC converter is maximizing power flow to the battery, this voltage ratio is very nearly 1/2, and the loss factor depends only on the coupling coefficient. Experiments on a base-driven piezoelectric cantilever, having a system coupling coefficient of 26%, yielded an effective loss factor for the fundamental vibration mode of 2.2%, in excellent agreement with theory.
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1. Introduction

A need for remote electrical power supplies for machinery condition monitoring [1], tunable vibration control devices [2], personnel tracking [3], networked radios [4] and numerous other applications has driven recent "energy harvesting" research. The general idea underlying this research is the extraction of electrical energy from the operating environment [5]. Potential

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sources of energy include solar, thermal, mechanical, electrical (radio), chemical, or some combination thereof; for each source, numerous specific energy transduction methods may be considered.

While a number of researchers have investigated the possibility of harvesting mechanical energy using piezoelectric devices [3,6,7], circuits that seek to maximize power output were developed only recently [8,9]. A vibrating piezoelectric device differs from a typical electrical power source in that its internal impedance is capacitive rather than inductive in nature, and it may be driven by mechanical motion of varying amplitude.

Initial research by the authors [8] produced an adaptively controlled switching DC–DC converter that maximized harvested power. Results showed that use of this converter increased the power delivered to the energy storage element, an electrochemical battery, by 400% as compared to the case in which the battery was charged directly via a rectifier circuit. A single small piezoelectric element, however, could not power the adaptive control circuitry while providing enough power to the battery to justify use of the converter, even at high vibration levels.

Building on these results, a simpler circuit based on a step-down converter was pursued [9]. By considering the interaction of the piezoelectric element with the step-down converter operating in discontinuous current conduction mode (DCM), the existence of an optimal duty cycle that maximized power flow from the piezoelectric device was established. As the magnitude of the vibration excitation increases, the optimal duty cycle becomes essentially constant, greatly simplifying implementation of the step-down converter. Based on this result, a simplified control scheme for the converter was introduced. This design was validated by experiment, showing that the optimal duty cycle can be accurately determined and controlled to maximize harvested power. The self-powered converter increased the harvested power by approximately 325% as compared to the case in which the battery was charged directly via a rectifier circuit.

The removal of mechanical energy from a vibrating structure by a piezoelectric energy harvesting system necessarily results in damping. This research addresses the damping associated with a self-powered circuit consisting of a full-bridge rectifier, a filter capacitor, a switching DC–DC step-down converter, and an electrochemical battery [9]. The next section summarizes the configuration and operation of this energy harvesting circuit, while subsequent sections address the prediction and measurement of associated vibration damping.

2. Piezoelectric energy harvesting circuit

The electrical behavior of a vibrating piezoelectric element can be modelled to first order as a sinusoidal current source $i_p(t)$ in parallel with its electrode capacitance C_p; the magnitude of the polarization current I_p depends on the mechanical excitation level. As shown in Fig. 1, a full-bridge AC–DC diode rectifier is connected to the output of the piezoelectric device. The DC filter capacitor of the rectifier, C_R, is assumed to be large relative to C_p so that the output voltage V_{rect} may be considered essentially constant; furthermore, the diodes are assumed to exhibit ideal behavior. A DC–DC step-down converter between the rectifier and the battery provides the ability to control the rectifier output voltage in the pursuit of maximum power output under changing mechanical conditions. The step-down converter is a good choice for controlling the rectifier

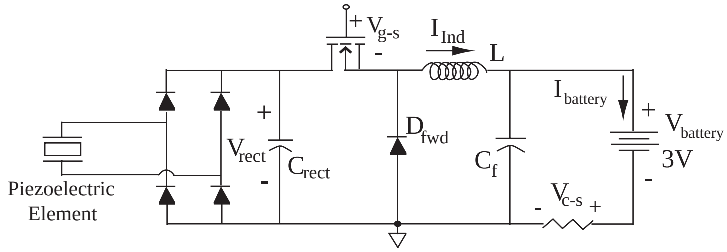

Fig. 1. General topology of energy harvesting circuit.

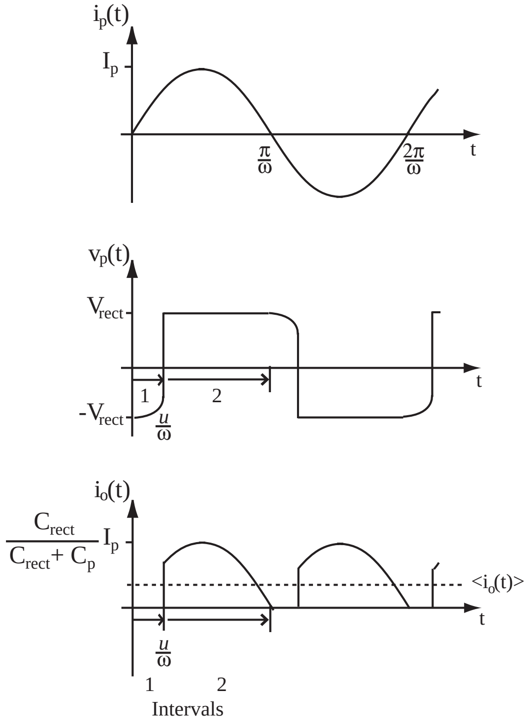

Fig. 2. Voltage and current waveforms of piezoelectric element model with rectifier.

output voltage in this application, because piezoelectric voltages can be high relative to those needed for the battery and typical electronic loads.

Fig. 2 shows the voltage and current waveforms associated with harmonic forcing of the circuit. These waveforms are divided into two intervals. In interval 1, when the magnitude of the piezoelectric voltage is less than the rectifier output voltage, the polarization current charges the internal piezoelectric electrode capacitance, increasing its voltage. During this time, all diodes are reverse-biased and no current flows to the output. This condition continues until the magnitude of the piezoelectric voltage becomes equal to the rectifier voltage V_R. Then, interval 2 begins and current flows into the output capacitor C_R and to the load. During this interval, the output voltage of the piezoelectric element is effectively constant at $\pm V_R$.

The output power of the piezoelectric element is the product of the output current and the rectifier capacitor voltage V_{rect}. Based on the assumptions concerning piezoelectric element behavior, ideal diode operation, and the relative size of the rectifier capacitor, maximum output power is obtained when the rectifier output voltage is 1/2 the maximum open-circuit piezoelectric voltage [9].

An important aspect of the operation of the DC–DC step-down converter is regulation of the rectifier output voltage, accomplished by control of the switching duty cycle of the converter. Analysis reveals that power flow into the battery is maximized at an optimal duty cycle, which decreases monotonically with increasing open-circuit piezoelectric voltage (mechanical drive level). As the rectifier voltage, maintained at one-half the open-circuit voltage, becomes much larger than the battery voltage, the optimal duty cycle approaches a constant value, given approximately by [9]

$$D_{opt} \approx \sqrt{\frac{4\omega L C_p f_s}{\pi}}. \quad (1)$$

The optimal duty cycle thus depends on the inductance and switching frequency of the converter, as well as on the capacitance of the piezoelectric element and the frequency of mechanical excitation.

Because some power is required to run the converter itself, there must be some level of mechanical excitation below which self-powered operation cannot be sustained. In that case, an appropriate energy harvesting strategy is to simply connect the rectifier output directly to the battery. Although this approach is not particularly efficient, it does store positive energy, with no parasitic electrical load. When the battery charge and the mechanical excitation both exceed some threshold levels, however, the system can sustain converter operation. Although adaptive optimization of the duty cycle can be pursued [8], the complexity and power requirements of the controller significantly exceed those of fixed-duty-cycle operation. Thus, a simple controller consisting of a fixed-duty-cycle pulse-width-modulated signal was implemented.

Fig. 3 shows a schematic of a self-powered, two-mode energy harvesting circuit [9]. At lower excitations, the battery is charged directly by the rectifier (via a pulse-charging circuit), bypassing the step-down converter. At higher excitations, the step-down converter operates at a near-optimal, fixed duty cycle. The threshold point that divides these two modes of operation depends on the power produced by the piezoelectric element relative to that consumed by the converter and the control circuitry. When the converter can deliver more net power to the battery than direct charging from the rectifier, it should operate to do so.

Efficient operation requires minimization of the combination of controller power consumption and converter losses. In general, a low switching frequency will reduce converter losses, but it should not be so low that near-optimal power transfer over a range of excitations cannot be obtained using a fixed duty cycle [9].

3. Damping analysis

The removal of electrical energy from the piezoelectric system results in structural damping. It does not matter whether this energy is dissipated in a resistor, stored in a battery, or used to run

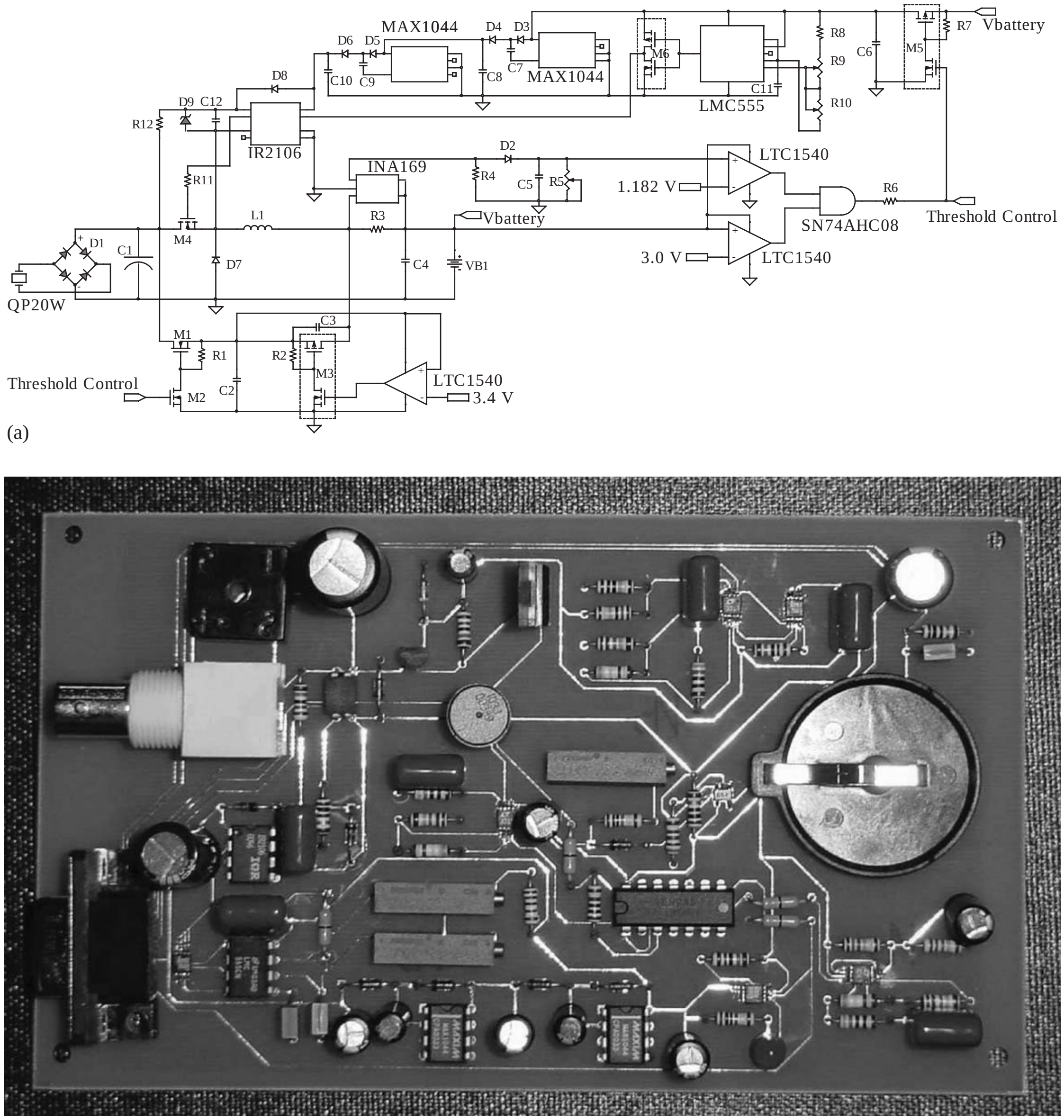

Fig. 3. Two-mode energy harvesting circuit: (a) schematic and (b) PCB prototype.

energy harvesting circuitry. As in the case of the energy harvesting analysis, the damping analysis that follows is simplified by the assumption that the voltage on the rectifier output capacitor is essentially constant; that is, it is unaffected by the addition or removal of small quantities of charge. Furthermore, voltage drops across the diodes in the rectifier are neglected.

Charge, and therefore energy, can only leave the system when the magnitude of the voltage across the piezoelectric element exceeds the rectifier output voltage. During the time that this voltage is less than the rectifier voltage, no current flows, and the system is effectively open-circuited. Once the piezoelectric voltage reaches the rectifier voltage, it maintains that value while charge flows out of the piezoelectric element into the rectifier. Assuming harmonic forcing, the piezoelectric element is open-circuited for a time fraction $\omega t_1/\pi$, where

$$\omega t_1 = \cos^{-1}\left(1 - \frac{2V_R}{V_{oc}}\right). \tag{2}$$

V_{oc} is the open-circuit rectifier output voltage (also the AC amplitude of the harmonic piezoelectric voltage under open-circuit conditions), and V_R is the operating (constant) rectifier output voltage. Note that the amplitude of the harmonic piezoelectric current under constant voltage conditions is $\omega C V_P$.

The energy that flows out of the piezoelectric element per cycle, ΔE, is the time integral of the product of the rectifier voltage and the piezoelectric current. The maximum energy associated with vibration, E, includes electrical as well as strain energy. The damping loss factor may then be estimated as

$$\eta = \frac{\Delta E}{2\pi E} = \frac{4}{\pi}\frac{(V_R/V_{oc})(1 - V_R/V_{oc})}{\left(\frac{1-k_{sys}^2}{k_{sys}^2}\right)\frac{V_R}{V_{oc}}}. \tag{3}$$

Note that this effective loss factor depends only on the electromechanical coupling coefficient of the piezoelectric system and on the rectifier voltage ratio. When, for optimal power transfer, the operating rectifier output voltage is maintained at 1/2 the open-circuit voltage, the expression for the maximum loss factor becomes

$$\eta = \frac{2k_{sys}^2}{\pi(2 - k_{sys}^2)}, \tag{4}$$

which depends only on the coupling coefficient. For small values of coupling coefficient, this expression simplifies further to

$$\eta = \frac{k_{sys}^2}{\pi}. \tag{5}$$

Thus, damping increases directly with the system coupling coefficient. This can be maximized via the type, amount, and placement of piezoelectric material [10].

For comparison, the damping associated with resistive shunting [11,12] may be expressed as

$$\eta_R = \frac{k_{sys}^2}{2\sqrt{1 - k_{sys}^2}}\frac{2(\omega\bar{\tau})}{1 + (\omega\bar{\tau})^2}, \tag{6}$$

where $\bar{\tau}$ is a characteristic RC time constant. Although the loss factor associated with energy harvesting is about 60% of the peak value associated with resistive shunting, it does not exhibit the strong frequency dependence characteristic of resistive shunting, and could potentially be effective over a much broader frequency range.

4. Experimental procedure

Two sets of experiments were performed; the first to assess the performance of the energy harvesting system, the second to measure the associated vibration damping.

A commercially available piezoelectric device, an ACX QuickPack® QP20W, was used in these experiments as an energy source. A two-layer bimorph, it is designed for operation in bending, and generates a voltage when strained. The QP20 has nominal dimensions of $5.08 \times 3.81 \times 0.051$ cm ($2.00 \times 1.50 \times 0.03$ in), a nominal capacitance of 200 nF (measured 184 nF) and, if desired, can be driven with AC signals that do not exceed 200 V. To provide variable mechanical excitation, this piezoelectric element was cantilevered from an electric-powered shaker, as shown in Fig. 4. A small mass was added to the free end of the element to enhance the internal strain under dynamic excitation.

To assess the performance of the energy harvesting system, the shaker was driven with a harmonic signal, resulting in lateral vibration of the piezoelectric element. The fundamental mechanical resonance frequency of the system was about 50 Hz; this varied slightly, depending on the electrical load placed on the piezoelectric element. The mechanical excitation level was characterized by the open-circuit voltage, V_{oc}, measured across the unloaded rectifier output capacitor. This excitation was readily modified by changing either the magnitude or frequency of the shaker drive signal.

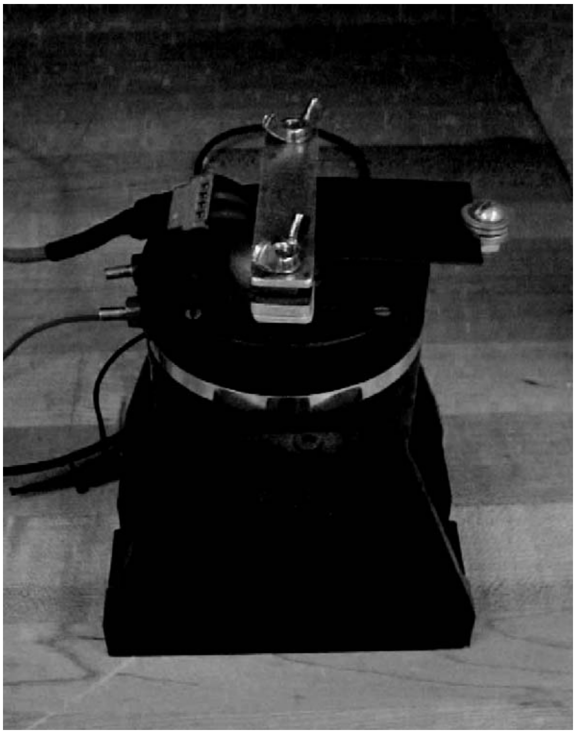

Fig. 4. Vibrating piezoelectric energy source.

Three power levels were measured as a function of the excitation level: (1) the maximum power delivered to a purely resistive load; (2) that delivered by direct connection of the rectifier output capacitor to the battery; and (3) that delivered via the fixed-duty-cycle DC–DC converter.

An upper bound on the real power that the piezoelectric element was capable of delivering at a given drive level was established by connecting a variable resistor across the rectifier output capacitor. The power dissipated in the resistor was readily calculated as the square of the voltage divided by the resistance. For a given excitation level, the resistance was adjusted to maximize the dissipated power; in this situation, the optimal rectifier output voltage was verified to be roughly half of its open-circuit value.

With the energy harvesting system in operation, the power delivered to the 3 V battery was measured as the product of the battery voltage and the net current flowing into the battery. This current was measured using a small resistor built into the harvesting circuit. Both modes of operation of the harvesting circuit were considered: direct charging of the battery from the rectifier output, and charging via the fixed-duty-cycle DC–DC converter. This provided a means for determining the power requirements of the harvesting circuitry and the operating mode crossover point.

To determine the vibration damping associated with energy harvesting, the resonance frequency and damping of the fundamental vibration mode were measured under several conditions: short-circuit, open-circuit, and with the energy harvesting system in operation. The modal damping obtained under short- and open-circuit conditions establishes a baseline relative to which the additional damping due to energy harvesting can be measured. The corresponding resonance frequencies are used to find the system electromechanical coupling coefficient [10], enabling calculation of expected damping due to harvesting (Eqs. (3)–(5)):

$$k_{sys}^2 = \frac{(\omega_{oc})^2 - (\omega_{sc})^2}{(\omega_{oc})^2}. \tag{7}$$

To determine the resonance frequencies and damping, the system was driven with fixed-amplitude harmonic signals over a range of frequencies in the vicinity of the fundamental resonance frequency. The response amplitude at the free end of the piezoelectric element was monitored using a laser vibrometer system, and a frequency response function (FRF) from the input to the output was experimentally established. Complex poles and zeros of this FRF were determined using a curve-fit procedure. The natural frequency and damping of the fundamental vibration mode was determined from the real and imaginary parts of the corresponding pole. Since the modal damping is relatively small, the modal loss factor was taken to be twice the modal damping ratio.

5. Results

The performance of the energy harvesting circuit was determined, as was the damping resulting from its operation.

5.1. Energy harvesting

The optimal switching frequency for this circuit was experimentally determined to be about 1 kHz. At a mechanical excitation frequency of 53.8 Hz, the optimal duty cycle for excitations above 45 V_{oc} was determined to be 2.8%, in agreement with theory.

Fig. 5 shows three measured power outputs as a function of the excitation level. The uppermost curve indicates an upper bound for real power output: that which can be delivered to a purely resistive load. The lowermost curve shows the power delivered to the battery by direct charging from the rectifier output; no control or switching circuitry is involved. The middle curve shows the power delivered via the fixed-duty-cycle step-down converter, including the power required to run the control and switching circuitry.

At high excitation levels, the advantages of the simplified DC–DC converter over direct charging are evident. At the peak excitation level of about 68 V_{oc}, the harvested power increased from 9.45 to 30.66 mW, an improvement of more than a factor of 3. This factor increases at higher excitation levels, for example, becoming greater than 4 at 80 V_{oc}. Note that the harvested power follows the same trend as available power, increasing as the square of the excitation.

The step-down converter outperforms direct charging at all levels of excitation above 25 V_{oc}, including power consumed by the control circuitry and the converter. Thus, the threshold point for operation can be set anywhere above this level.

The breakeven point for converter operation was reached when the open-circuit voltage reached about 21 V. System losses can be estimated from the difference between the available and harvested power; at this breakeven point, the power consumed by the harvesting circuit was less than about 4.5 mW. Power consumption for control and switching circuitry was estimated a priori at 5.7 mW from component datasheet values, slightly higher than that observed. The operating crossover point was reached when the open-circuit voltage reached 25 V, with net power output of about 2.5 mW. At excitations above 50.0 V_{oc}, the efficiency begins to degrade as the input–output voltage difference across the converter increases. At the highest excitation considered, the total losses were estimated to be 15.8 mW.

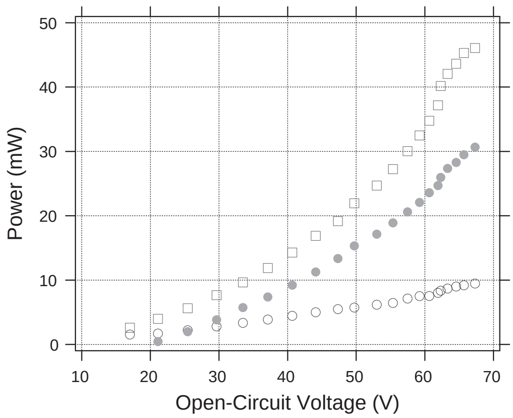

Fig. 5. Performance of energy harvesting circuit [9]: □, maximum power dissipated in resistor across rectifier; ○, power delivered to battery via direct rectifier connection; ●, power delivered to battery by energy harvesting circuit.

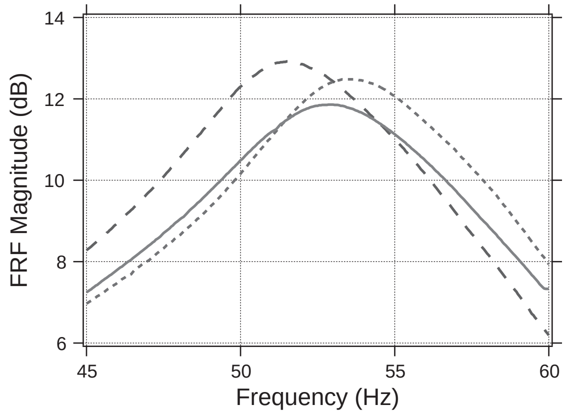

Fig. 6. Force–velocity frequency response under various electrical conditions: — — , short-circuit; - - - - , open-circuit; ——, energy-harvesting system.

5.2. Damping

Fig. 6 shows the magnitudes of the mechanical frequency response functions, in the vicinity of resonance, measured under different electrical conditions: short-circuit, open-circuit, and with the energy harvesting system operating. The excitation level was approximately 45 V_{oc}.

From the measured open-circuit resonance frequency of 53.45 Hz, and the short-circuit resonance frequency of 51.55 Hz, the system mechanical coupling coefficient was estimated, using Eq. (7), as 0.264. With this coupling coefficient, the expected maximum damping loss factor due to energy harvesting was estimated, using Eq. (4), as 2.3%.

The measured damping loss factors under short- and open-circuit conditions were almost identical, at 17.3%. This provided a baseline value relative to which increased damping due to energy harvesting was assessed.

The damping loss factor measured with the energy harvesting system operating was 19.5%. This yields an estimate of the additional damping due to energy harvesting of 2.2%, in very good agreement with the predicted value of 2.3%. The resonance frequency with the energy harvesting system running was 52.90 Hz. This was slightly higher than the value of 52.50 Hz that might have been expected on the basis of optimal impedance matching, and probably contributes to the slight discrepancy between predicted and measured damping. Furthermore, the duty cycle may not have been quite optimal for the excitation level at which the data were obtained.

6. Conclusions

This paper describes an approach to harvesting electrical energy from a mechanically excited piezoelectric structure, a process that simultaneously yields predictable structural damping. The harvesting system considered consisted of a full-bridge rectifier with a filter capacitor, a switching DC–DC step-down converter, and a battery. Motivated by the observation that a fixed duty cycle provides near-optimum performance when a persistent excitation exceeds a certain level, a standalone self-powered harvesting system was developed. This system has two modes: for low excitation, the rectifier charges the battery directly; while for higher excitation, the battery runs the DC–DC converter. At higher levels of excitation, the DC–DC converter delivers more than four times the power to storage than direct charging from the rectifier; this ratio increases with excitation.

Under conditions of harmonic forcing, the effective modal loss factor depends on the piezoelectric system coupling coefficient and on the ratio of the operating rectifier output voltage to its maximum open-circuit value. When the voltage ratio takes on its optimal value of one-half, the loss factor depends only on the coupling coefficient (Eq. (4)). Experiments on a base-driven piezoelectric cantilever, having a system coupling coefficient of 26%, yielded an effective loss factor for the fundamental vibration mode of 2.2%, in excellent agreement with theory. This loss factor is comparable to the levels associated with resistive shunting, but without the corresponding strong frequency dependence.

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