Modeling the Effects of Electromechanical Coupling on Energy Storage Through Piezoelectric Energy Harvesting

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***Abstract*—This paper focuses on comparing the effects of varying degrees of electromechanical coupling in piezoelectric power harvesting systems on the dynamics of charging a storage capacitor. In order to gain an understanding of the behavior of these dynamics, a transducer whose vibrational dynamics are impacted very little by electrical energy extraction is compared to a transducer that displays strong electromechanical coupling. Both transducers are cantilevered piezoelectric beams undergoing base excitation whose harvested electrical energy is used to charge a storage capacitor. The transient dynamics of the coupled system are studied in detail with an emphasis on their charging power curves and the time to charge the storage capacitor to a specified voltage. An analytic model for the system is derived that takes into consideration the reduction in vibration amplitude of the beam caused by the removal of electrical energy. Although this model makes the typical assumption that the beam is vibrating at its open-circuit resonance, it is shown to predict the charging behavior of the system accurately when compared to experimental results and a complete, nonlinear simulation without this simplification. Finally, the simplifications and discrepancies created by several types of modeling assumptions for a highly coupled energy harvesting system are discussed.**

***Index Terms*—Piezoelectric transducers, power harvesting.**

I. Introduction

SCAVENGING energy from the ambient environment as a power source for wireless sensors and communication devices may prove critical to the expansion of these technologies into new environments and applications. In certain scenarios, batteries may be impractical due to their relatively low energy densities [1], [2]. The cost of battery replacement may be prohibitive, especially as the number of wireless devices increases. However, in many situations, untapped vibrational energy exists in the immediate vicinity of these devices [3]. This potential energy source has generated research into several methods of electromechanical transduction, including electromagnetic induction (e.g., see [4]), electrostatic varactance (e.g., see [5]), and the piezoelectric effect (see [6] for a review). In most instances, steady-state base excitation is assumed, which is a reasonable approximation of the environment around many manmade machines and structures [3].

Many studies have been devoted to optimizing the interfacing circuit to maximize the power output of a piezoelectric transducer on specific resistive loads. For example, dc–dc converter circuits have been implemented to match the actual load to the impedance of the piezoelectric transducer, thus maximizing the power transfer [7], [8]. Techniques such as synchronized switching harvesting on an inductor/synchronized switching harvesting on a capacitor (SSHI/SSHC) are also successful in increasing the piezoelectric transducer power output [9], [10]. Furthermore, synchronous charge extraction methods similar to the synchronized switching damping (SSD) technique used in structural damping [11] are also shown to increase the power output to 400% of the power output across a matched resistive load. This performance has been demonstrated to be independent of the load resistance [12].

In the aforementioned studies, the transducer itself is generally modeled as a lumped, single-DOF system undergoing periodic forcing. Significant effort has been devoted to modeling piezoelectric power harvesters based on their geometry and material properties in order to predict their performance and to optimize the harvested power for a given application. These models generally fall under two categories: lumped parameter (single DOF) models [13], [14] and distributed parameter (multi-DOF) models [14]–[16]. These studies, however, generally only consider simple resistive loads under steady-state, ac conditions. They do not represent practical systems in which energy harvesting may be utilized. Shu and Lien [17], however, considered a rectified, filtered load under steady-state conditions for various degrees of electromechanical coupling.

Unfortunately, the energy scavenged from the environment is usually time-varying and insufficient to power wireless devices continuously. Thus, a power management scheme that utilizes a buffer stage and energy storage is usually required for practical applications. Kymissis *et al.* [18] have developed a system for energy harvesting from walking with a power management circuit for intermittent RF identification (RFID) transmission. Similar circuits employing voltage-monitoring units have been implemented for other low-power applications (e.g., see [19] and [20]). Wu *et al.* [21] and Wickenheiser *et al.* [22] studied the dynamics of a piezoelectric power harvester used to charge

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