



Modeling and analysis of distributed electromagnetic oscillators for broadband vibration attenuation and concurrent energy harvesting

Ryan L. Harne*

Department of Mechanical Engineering, Virginia Polytechnic Institute and State University, 151 Durham Hall (MC 0238), Blacksburg, VA 24061, USA

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ABSTRACT

Many energy harvesting devices employ dynamics ascribed to the classical vibration absorber. Conventional models suggest that when host structural motion excites the harvesters at resonance, maximum electrical power output is achieved. As the harvesters become inertially substantial relative to the structure, this condition no longer holds since the electro-elastic response of the harvester is coupled to the structural vibration. In this regime, the devices become true vibration absorbers that alter the structural oscillations which may consequently affect energy harvesting capability. Distributions of point oscillators have been considered as broadband vibration control treatments making it natural to consider the potential for energy harvesting devices to serve this end. This paper presents an analysis of distributed single- and two-degree-of-freedom, linear electromagnetic oscillators attached to a harmonically excited panel. The coupled Euler–Lagrange equations of motion are solved and the simultaneous goals of vibration attenuation of the host panel and harvested electrical power are computed for several scenarios. It is found that design parameters optimizing the individual goals occur in relative proximity such that small compromises need to be made in order to achieve both ends reasonably well, particularly in regards to the overall mass added to the structure.

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1. Introduction

The interest in converting ambient vibrational energy into useful electrical power has led to a broad range of devices employing electromechanical coupling. Whether embodied as cantilevered specimens [1–3], mass-spring oscillators [4–7], or surface-attached treatments [8,9], the devices are excited by the host structural vibration and external circuits are utilized to quantify the net electrical power output. A frequent assumption in the fundamental analysis of basic oscillator-type harvesters is that the devices are excited by way of base vibration [10–14]. This is appropriate in light of some anticipated MEMS applications. But as energy harvesting prototypes become inertially substantial relative to the main structure, this mathematical model is no longer accurate.

Damping induced via piezoelectric energy harvesting has been studied and exploited as a vibration control mechanism [15–17]. The first-order dissipation is in contrast to the present focus of second-order dynamic coupling in which a primary mass-spring system is acted upon by an auxiliary electromechanical mass-spring system. The concept of “dynamic magnifier” harvester—a harvester beam attached to the free end of a structural cantilevered beam—adopts this perspective of a critical dynamic coupling between energy harvester and the host structure [18–20]. Additionally, a recent study by Tang and Zuo [21] investigated dual-mass harvester designs. The electro-dynamic coupling is a two degree-of-freedom (2DOF)

* Tel.: +1 540 231 4162.

E-mail address: rhorne@vt.edu

mechanical model with an additional DOF resulting from the external circuit potential. From this perspective, rather than achieving vibration damping while harvesting energy, the second-order influence may be regarded as achieving vibration control with energy harvesting. This equalizes the importance of both goals but does not necessitate their concurrent success.

Other recent works have taken this point of view in modeling and constructing experimental samples of vibration absorbers having electromechanical members so as to ideally serve both objectives. For instance, electromechanical skyscraper tuned-mass-dampers required to attenuate wind- or seismic-induced vibration appear a prime application for large-scale energy harvesting [22,23]. Another study considers the control of lightweight structural panels with distributed piezoelectric vibration control devices which benefit from the inherent damping of the piezoelectric polymer while still providing viable electrical output when excited near resonance [24].

The use of undamped oscillator arrays to passively attenuate structural vibrations has been widely studied in the language of the “structural fuzzy” [25–27]. This concept reduces the DOF in modeling by considering the oscillator array as being a distributed impedance. Other work has similarly studied numerous attached mass-spring systems to attenuate structural vibrations though retaining the full multi-DOF modeling description [28,29], essentially the same aim in analysis only with increased computational expense. Zuo and Nayfeh [29] specifically focus on the optimization of stiffness and damping parameters for the attached oscillator array to achieve global vibration reduction.

Employing arrays of electromechanical oscillators—equally “energy harvesters”—may have the same potential for global vibration control. Furthermore, the damping mechanism of such devices is the conversion of the “absorbed” mechanical energy into electrical power, dependent on the strength of electromechanical coupling. The achievement of both energy harvesting and vibration control are therefore weighed as equally important objectives in the present study.

Practical embodiments of energy harvesting devices regularly take the form of cantilevered piezoelectric samples or point mass-spring electromagnetic devices, as referenced earlier. Though some study has, indeed, considered the use of multiple cantilevered beams in passively attenuating the vibrations of a host beam [28], the present analysis will be concerned with electromagnetic point oscillators given their practical similarity to the classical 1DOF tuned-mass-damper.

The host or primary structure of present interest is a conventional, rectangular panel. Such structural panels are ubiquitous (aerospace and maritime vehicles, building panels, windows, for example) and are primarily excited in their lowest order modes. A conventional energy harvesting analysis may presume the devices to be best positioned at the lowest mode antinode so as to be most excited, thus harvesting the most electrical power and also justifying a simplification of the modeling to focus on single-mode excitation (i.e. SDOF assumptions). However, the centralized positioning of the oscillators does not necessarily achieve optimum global vibration control of the structure. Thus, a distributed panel serves as an important case study for evaluating the simultaneous achievement of vibration control and energy harvesting using arrays of electro-mechanical oscillators.

This paper derives the governing equations for the coupled electro-elastic dynamics of a simply-supported rectangular panel to which a number of electromagnetically (E–M) coupled SDOF or 2DOF oscillators are attached. The E–M mass-spring-dampers are attached to external circuits and the coupled Euler–Lagrange governing equations are solved simultaneously to determine the electric and mechanical dynamics. Metrics of global vibration suppression and maximum energy harvested are utilized and a number of scenarios are considered: single oscillators, random distributions of oscillators and the effects of oscillator array number. Design parameter sets to optimize the individual goals are found to occur relatively close together. This indicates small compromises in both objectives need to be accepted to satisfy both ends relatively well.

2. Model formulation

A thin, simply-supported rectangular panel is considered, to which N_p SDOF or 2DOF mass-spring-dampers have been attached at positions (x_i^p, y_i^p) , Fig. 1. The host panel is excited by N_f out-of-plane harmonic point forces, $f_i(x_i^f, y_i^f, t)$. The attached

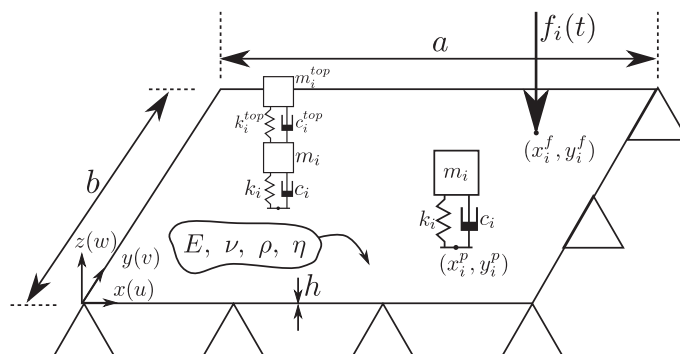


Fig. 1. Mechanical geometry of the present analysis.

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