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# Ambient vibration energy harvesters: A review on nonlinear techniques for performance enhancement

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ABSTRACT

Vibration energy harvesters are emerging as a promising solution for powering small-scale electronics, such as sensors and monitoring devices, especially in applications where batteries are costly or difficult to replace. However, current vibration energy harvesters are only effective within a limited frequency bandwidth, whereas most ambient vibrations occur randomly over a wide frequency range. Many techniques, such as tuning, coupling between modes, multimodal arrays and hybrid transduction methods, can be used for performance enhancement of vibration-based energy harvesters. Among these techniques is the introduction of nonlinearities to the energy harvesting system. In most cases, using nonlinear techniques for energy harvesting results in a larger frequency bandwidth when compared to a linear system. In certain systems, the introduction of nonlinearities can also result in a higher amplitude response. The aim of this paper is to conduct a critical review of nonlinear techniques which have been investigated for performance enhancement of energy harvesters in the past decade and present state of the art of energy harvesters which utilise this technique. This includes discussions of several techniques that have been employed for enhancing energy harvesting, such as stochastic loading, internal resonances, being multi-degree-of-freedom, mechanical stoppers and parametric excitations, which all lead to nonlinear behaviour and enhancement of the system. These techniques are capable of significantly extending the frequency bandwidth and, in some cases, increasing the amplitude response. The enhancement in performance results in devices that can harvest energy more efficiently from ambient vibrations.



## 1. Introduction

Recently, research interest has deepened in sustainable technologies for harvesting energy from ambient sources to generate electrical power. Vibration-based energy harvesters with the ability to convert mechanical vibrations to electrical energy are among these technologies, with potential applications for low-powered electronic devices (Firoozy, Khadem, & Pourkiaee, 2017a; Rezaei, Khadem, & Firoozy, 2017; Wang & Wang, 2017; Xie & Wang, 2015; Xie, Wu, Yuen, & Wang, 2013). Many portable electronics, such as sensors and other monitoring devices, are powered by chemical batteries. Frequently replacing batteries can be expensive, especially if the device is constantly active, located in hard-to-reach places or if many batteries need to be replaced at once. With significant reductions in the power consumption of portable electronics over the years, vibration-based energy harvesters have become a feasible alternative to batteries (Daqaq, Masana, Erturk, & Dane Quinn, 2014; Tang, Yang, & Soh, 2013; Yildirim, Ghayesh, Li, & Alici, 2016c). Ambient mechanical vibrations can be found almost any-

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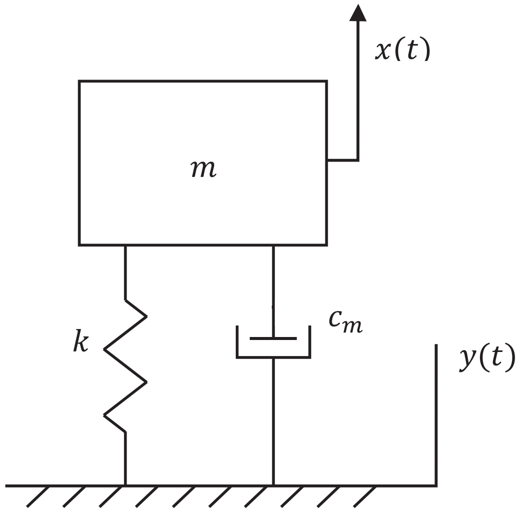


**Fig. 1.** Mechanical model of a single degree of freedom system with base excitations.

where, therefore these harvesters potentially have applications in many fields, such as in structural engineering (structural health monitoring sensor networks) and health (for medical implants, such as pacemakers and pain relievers) (Daqaq et al., 2014). Compared to chemical batteries, a vibration-based energy harvester can passively and consistently generate power, leading to a significant cost saving. Furthermore, chemical batteries contribute to pollution in the environment when disposed, whereas vibration-based energy harvesters do not need to be continuously replaced, resulting in lower environmental impact.

One of the main issues with vibration energy harvesters is their effective operating frequency bandwidth. Current vibration energy harvesters are only effective within a very limited bandwidth near their resonant frequencies. As the ambient vibration frequency moves away from the resonant frequency of the device, the energy that can be extracted is significantly reduced. This makes these harvesters inefficient in practical applications, as most ambient vibrations occur randomly over a wide frequency range. Therefore, methods to increase the effective operating frequency bandwidth and hence enhance the performance of a vibration-based energy harvester are required.

Methods of increasing the frequency bandwidth that have been previously researched can be classified into either *linear* and *nonlinear* approaches (Yildirim, Ghayesh, Li, & Alici, 2016c); nonlinear vibration techniques give more reliable results especially when the system is subject to large-amplitude vibrations (Farokhi & Ghayesh, 2018a; Farokhi, Ghayesh, Amabili, 2013a; Ghayesh, Amabili, & Farokhi, 2013b; Ghayesh, Farokhi, & Alici, 2016; Ghayesh, Farokhi, & Amabili, 2013b). While the literature on linear techniques is broad, less research has been conducted on nonlinear techniques for energy harvesting. Compared to linear techniques, nonlinear techniques can achieve power generation over a larger, continuous bandwidth, leading to increased harvesting efficiency. In certain cases, applying nonlinearity may also increase the amplitude of responses when compared to an equivalent linear system. In addition, due to the increased operating bandwidth, a nonlinear energy harvester will be less sensitive to variations in the frequency characteristics of the operating environment as well as variations arising due to manufacturing tolerances. As a result, nonlinear harvesters are potentially more suitable for harvesting energy from ambient vibrations in practical applications.

Several review papers have been published on techniques for performance enhancement of energy harvesters (Tang et al., 2013; Wei & Jing, 2017; Yildirim et al., 2016c); however, this paper will focus solely on *nonlinear techniques*. There has only been one existing review paper on nonlinear energy harvesters by Daqaq et al. (2014). This paper differs in its classification of techniques and expands on the previous review through the inclusion of nonlinear dynamics which were not previously mentioned or analysed in detail, such as stochastic loading, multi-degree-of-freedom (DOF) systems, internal resonances, stopper techniques and parametric excitations; moreover, the review includes recent papers in the past four years as well. This paper will first cover the fundamentals of nonlinear vibration-based energy harvesting, including the main governing equations and simple monostable systems. The paper will then move to the discussion of several nonlinear phenomena for energy harvesting. A summary and comparison of the potential benefits and limitations of each technique will also be presented.

In order to develop a model for vibration energy harvesting, it is necessary to consider the relative displacement between the base excitation of the energy harvester and the core element. For a simple system shown in Fig. 1, two reference frames are defined; the first, $x(t)$, describes the motion of the mass, $m$ and the second describes the excitation of the base by $y(t) = A\cos\Omega t$, where $A$ is the vibration amplitude and $\Omega$ is the frequency. Other terms include the device stiffness $k$ and the mechanical damping coefficient $c_m$ (Yildirim et al., 2016c).