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A review on performance enhancement techniques for ambient vibration energy harvesters

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ABSTRACT

Due to increased demands for energy and the current limitations of batteries, a future prospective technology are vibration energy harvesters that convert kinetic vibration energy into electrical energy. These energy harvesters have the potential to be used in powering small electronic devices such as measurement equipment in remote or hostile environments where batteries are not a viable option. Current limitations of vibration based energy harvesters is the total available power generated and the frequency at which they effectively collect ambient vibration sources for producing power; this paper aims to review the current techniques that are being employed to enhance the performance of these devices. These techniques have been categorised into amplification techniques, resonance tuning methods and introducing nonlinear oscillations. Before this technology can be used effectively in applications enhancing the performance of ambient vibration energy harvesters needs to be addressed.

1. Introduction

With increasing growth and population around the world, the demand for energy has become increasingly significant as living standards rise. Powering conventional small scale electronic devices is usually done through batteries however the technological increase of batteries over the last 2 decades has been relatively small compared to other computing hardware. This issue has led to the increased urgency of looking at alternative sources particularly in mobile and embedded systems [1]. There are also environmental concerns when disposing used batteries after operation.

With technological advancements in energy conversion from sources such as solar [2], wind [3], biomass [4] and vibration energy harvesting [5], recent research into powering small electronic devices has emerged in particular with the design of vibration based energy harvesters (VBEH). Since ambient vibration sources are prevalent in many everyday applications making it a suitable power source for small electronic devices. These vibration sources exist in many systems such as industrial machinery, civil structures, cars, ship hulls and wireless platforms.

Vibration energy harvesting devices have the ability to convert ambient vibration energy from the surrounding environment into electrical power. The conversion of this kinetic energy is based on the relative displacement between the VBEH device and the structure which is attached to; the normally unwanted vibration can effectively be used to self-power sensors and other monitoring equipment in structures and machinery without the need for external power sources particularly in remote applications.

However, issues concerning conventional vibration energy harvesters are they only operate in the vicinity of their resonance which impacts the effective operating range for a VBEH device to harvest electrical power. The overall power that can be scavenged is also limited dependent on the design of the device and the source vibrations amplitude and frequency. This means that even if the ambient vibration source is well-documented and the source frequency is known the device needs to be manufactured precisely as small deviations will lead to significant power reductions.

Due to the issues of maximising the power output and the effective operating region of vibration based energy harvesting devices, this article presents a review on the performance enhancement techniques that are currently being utilised to address these key issues facing VBEH devices; these include power amplification, resonance tuning methods, and the introduction of nonlinear oscillations. This paper presents the fundamentals of vibration based energy harvesting for completeness. A summary and comparison of the different methods based on the advantages and disadvantages will also be discussed for the applicability of each method.

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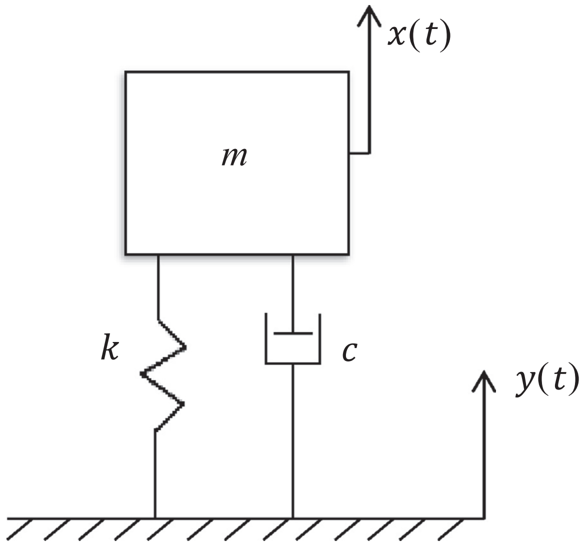

Fig. 1. Single degree of freedom vibration energy harvester with base excitation.

2. Fundamentals of vibration energy harvesting

Vibration energy harvesting theory is based on the relative displacement between a mass and the base excitation of a structure which is represented in Fig. 1.

The governing equation of motion of this system is:

$$m\ddot{z} + c\dot{z} + kz = -m\ddot{y} \tag{1}$$

where m is the mass of the system, $z = x - y$; the relative displacement between the mass and the base, $c = c_e + c_m$ is the damping coefficient comprising of both electrical and mechanical contributions and k is the device stiffness. Dividing through by the mass, Eq. (1) can be rewritten in the form:

$$z + 2\zeta\omega_n z + \omega_n^2 z = -y \tag{2}$$

Where $\zeta = \frac{c}{2\sqrt{mk}}$ the total damping ratio of the system and $\omega_n = \sqrt{\frac{k}{m}}$ (rad s^{-1}).

The Laplace transform of Eq. (2) results in the system transfer function given by $H(s)$:

$$H(s) = \frac{Z(s)}{Y(s)} = -\frac{s^2}{s^2 + 2\zeta\omega_n + \omega_n^2} \tag{3}$$

The response of this system under sinusoidal vibration can be modelled by applying$y(t) = Ycos(\omega t)$; where Y is the amplitude of the vibration and ω is the frequency of the vibration. The new governing motion of equation is:

$$\ddot{z} + 2\zeta\omega_n(\dot{z}) + \omega_n^2(z) = \omega^2 Ycos(\omega t) \tag{4}$$

The transfer function of Eq. (4) with $s = j\omega$ can be rewritten as:

$$H(j\omega) = \frac{Z(j\omega)}{Y} = \frac{\omega^2}{(\omega_n^2 - \omega^2 + 2j\zeta\omega_n\omega)} \tag{5}$$

The modulus and phase angle of the frequency response respectively are given by:

$$|Z(\omega)| = \frac{Y\omega^2}{\sqrt{(\omega_n^2 - \omega^2) + (2\zeta\omega_n\omega)^2}} \tag{6}$$

$$\phi = \tan^{-1}\left(\frac{2\zeta\omega_n\omega}{\omega^2 - \omega_n^2}\right) \tag{7}$$

This system has a well-known steady state solution in the form of:

$$z(t) = \frac{Y\omega^2}{\sqrt{(\omega_n^2 - \omega^2) + (2\zeta\omega_n\omega)^2}}\cos(\omega t - \phi) \tag{8}$$

The power that can be harvested is proportional to the force F and velocity v

$$P = \int_0^v F dv \tag{9}$$

This is the product of the damping force from (Eq. (1)) and the velocity of the mass; this is given in Eq. (10)

$$P = \int_0^{\dot{z}} c_e \dot{z} d\dot{z} = \frac{c_e|\dot{z}|^2}{2} \tag{10}$$

where $\dot{z}$ is the derivative of Eq. (8) given by:

$$|\dot{z}| = \frac{Y\omega^3}{\sqrt{(\omega_n^2 - \omega^2) + (2\zeta\omega_n\omega)^2}} \tag{11}$$

Substituting Eq. (11) into Eq. (10) the average power that can be generated in a vibration energy harvesting device in dimensionless form is derived as:

$$P_{dim} = \frac{P}{m\omega^3 Y^2} = \frac{\zeta_e\left(\frac{\omega}{\omega_n}\right)^3}{\left(1 - \left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(\frac{2\zeta\omega}{\omega_n}\right)^2} \tag{12}$$

Understanding Eq. (12) is critical in maximising the power output of a VBEH device; power increases significantly with the amplitude of vibration and the frequency of vibration. A low damping factor is desirable however in reality zero damping is not possible for a steady state solution. The ratio of the vibration frequency to the natural frequency $\left(\frac{\omega}{\omega_n}\right)$ of the system reduces the denominator in Eq. (12) enhancing the power output at structural resonance. The output power is only harvested in the vicinity of the resonance of the device and minor deviations cause substantial power reduction, as seen in Fig. 2. Other modelling for vibration based energy harvesting devices can also be found in [6–10].

2.1. Device considerations

The device considerations are the mass should be as large as possible within the available volume of the device, the displacement of the mass should be as large as possible within the available space and the spring should be designed so that the resonant frequency matches that of the excitation frequency. The source frequency and amplitude needs to be measured to determine the effectiveness of the device, Table 1 presents unwanted everyday vibration spectra which could effectively be harvested.

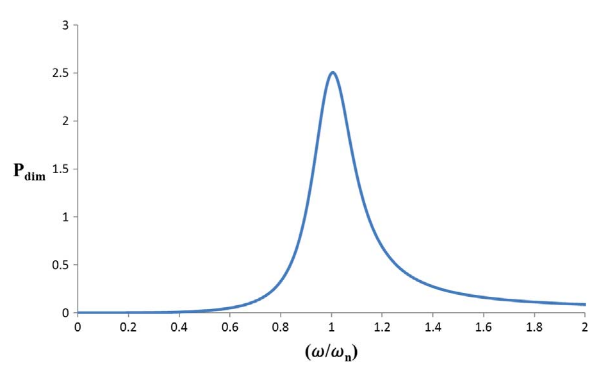

Fig. 2. Dimensionless power vs normalised frequency from Eq. (12) with $\zeta = 0.1$.