Renewable and Sustainable Energy Reviews 74 (2017) 1–18

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A comprehensive review on vibration energy harvesting: Modelling and realization

Chongfeng Wei*, Xingjian Jing

Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hong Kong, China

ARTICLE INFO

Keywords:
Energy harvesting
Vibration
Nonlinearity
Energy conversion mechanism

ABSTRACT

This paper presents a state-of-the-art review on a hot topic in the literature, i.e., vibration based energy harvesting techniques, including theory, modelling methods and the realizations of the piezoelectric, electromagnetic and electrostatic approaches. To minimize the requirement of external power source and maintenance for electric devices such as wireless sensor networks, the energy harvesting technique based on vibrations has been a dynamic field of studying interest over past years. One important limitation of existing energy harvesting techniques is that the power output performance is seriously subject to the resonant frequencies of ambient vibrations, which are often random and broadband. To solve this problem, researchers have concentrated on developing efficient energy harvesters by adopting new materials and optimising the harvesting devices. Particularly, among these approaches, different types of energy harvesters have been designed with consideration of nonlinear characteristics so that the frequency bandwidth for effective energy harvesting of energy harvesters can be broadened. This paper reviews three main and important vibration-to-electricity conversion mechanisms, their design theory or methods and potential applications in the literature. As one of important factors to estimate the power output performance, the energy conversion efficiency of different conversion mechanisms is also summarised. Finally, the challenging issues based on the existing methods and future requirement of energy harvesting are discussed.

1. Introduction

Vibration energy harvesting technologies has attracted a lot of attention over the past decade. Vibration sources such as ocean waves and human motion are potentials providing mechanical energy that can be harvested for charging self-powered wireless sensors or producing electricity. Many researchers have attempted to design some mechanical-to-electrical energy devices based on different conversion mechanisms [1–4]. However, some of the energy harvesting devices cannot meet the requirement of the designers' original goals as high conversion efficiency is usually expected from mechanical vibrations to electrical energy. This unsatisfactory situation is mainly due to the fact that the resonant frequency of the generator is often not matched with the frequency of ambient vibrations, or the frequency bandwidth of the generator is usually limited to a specific range which cannot cover the random vibration frequencies of external sources. If the frequency of ambient vibration deviates slightly from the resonant frequency of the energy harvester, the resulting power output of harvesters would be reduced drastically [5].

Based on the fact that the power generation performance of a harvesting device is limited to the resonance excitation, new design methods have been exploited. Typically, the cantilever type piezoelectric energy harvesters were designed with a proof mass located at the free end of the beam. The electricity power can be generated from bending vibrations under excitations at the root of the beam. The corresponding analytical models and energy harvesting experiments have been developed and analysed [6–9]. In several researches, power generator array to improve the power output performance were designed [10,11]. Optimisation of the energy harvesting devices has also been investigated by researches in order that higher conversion efficiency can be achieved [12,13].

In many applications, ambient vibrations are often random and broadband, and the design of energy harvesting devices must account for this form of excitations. Recently, researchers have focused on the concept of broadband energy harvesting, and several nonlinear oscillators have been considered and nonlinear power generators have been proposed in the literature [14–20]. Among various energy harvesting structures, piezoelectric generators could be one of the most popular with nonlinear properties, and permanent magnets are sometimes attached to associated structures to reproduce the effect of external

* Corresponding author.
E-mail address: chongfengwei@gmail.com (C. Wei).

http://dx.doi.org/10.1016/j.rser.2017.01.073
Received 14 November 2016; Received in revised form 19 December 2016; Accepted 12 January 2017
1364-0321/

vibration forces.

This review aims to classify the three different energy harvesting technologies of vibration energy harvesting due to external vibrations, and find out the potential benefits and defects from the existing energy harvesting techniques using the three different generators. With analysis of the differences among the energy harvesting methods and the system designs, it is favourable to develop a better system to enhance the efficiency of energy conversion from mechanical vibration to electrical energy. Particularly, for the systems with linear properties, the energy harvesting performance is usually limited to very narrow frequency external vibrations, the solutions using array-harvester systems, frequency-tuneable systems and nonlinear energy harvesting approaches are worthy to be investigated.

This paper will also discuss the applications of different energy harvesting devices designed according to the vibration-to-electricity conversion mechanisms. Typical energy harvesting applications can also be seen in [21–23] that adopted piezoelectric devices in shoes, for tide/wave energy harvesting [24–27], and for piezoelectric bimorphs in aircrafts [28,29]. Yuan et al. [30] applied the piezoelectric generator under the track sleeper. Therefore, the track vibration energy could be harvested to provide power for wireless sensors which monitor railroad health. With the same objective, Gatti et al. [31] predicted the harvested energy from a passing train using a single-degree-of-freedom oscillator, and the external vibration was measured on the sleeper. The more detailed realization and application of the generators are discussed in the following sections.

Regardless of different types of generators applied in terms of experiments or practical applications, the efficiency of conversion is of great importance to be considered. This review will also present the efficiency derivation methods for different types of energy harvesters. A conclusion and some challenging issues are discussed finally.

2. Theory and modelling methods

There are mainly three different methods that are most popular and extensively studied in the literature, based on piezoelectric, electromagnetic and electrostatic transductions [32]. In this paper, these three types of energy harvesting methods are studied, and their conversion mechanisms and efficiencies are discussed in this section.

2.1. Energy conversion with linear models

2.1.1. A basic linear model for vibration-electricity conversion

The kinetic energy harvesting requires a transduction mechanism to convert mechanical vibrations into electrical energy. Vibration sources can be collected in various environments ranging from bridges, buildings, industrial equipment, home appliances, and railways to automobiles etc. [33]. Typically, a vibration energy harvesting system can be modelled as a simple spring-mass model of a linear inertial-based generator, which was developed by Williams and Yates [34]. Fig. 1 illustrates a basic model of the schematic diagram of the linear inertial system, which consists of a seismic mass m, and a spring of stiffness k. The basic model is used to understand the mechanical vibration to electrical energy conversion and only valid for harvesters where damping and stiffness terms are linear, in which the mechanical damping is proportional to the velocity and stiffness is proportional to the displacement. The damping coefficient is represented by d_T including the mechanical damping coefficient d_m and the electrical induced damping coefficient d_e. These components are located within the inertial frame which is excited by the external mechanical vibration represented by $y(t) = Y_0 \sin(\omega t)$, where Y_0 is the amplitude of the external excitation.

The differential equation of the system can be described as

$$m\ddot{z}(t) + (d_m + d_e)\dot{z}(t) + kz(t) = -m\ddot{y}(t) \quad (1)$$

where $z(t)$ and $y(t)$ represent the spring deflection and the input

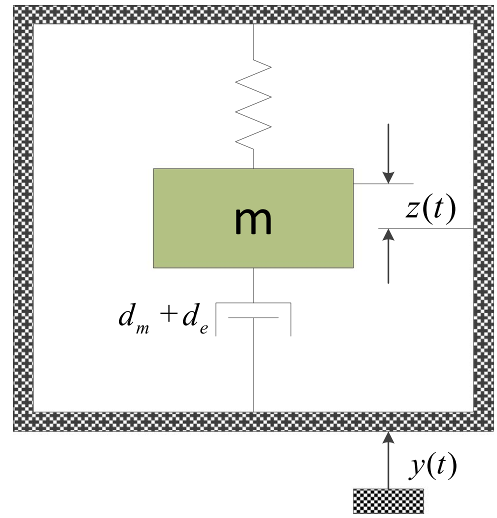

Fig. 1. Schematic diagram of the linear and inertial-based generator.

displacement, respectively.

The steady state solution for the mass displacement relative to the inertial frame is given by

$$z(t) = \frac{\omega^2}{\sqrt{\left(\frac{k}{m} - \omega^2\right)^2 + \left(\frac{(d_m + d_e)\omega}{m}\right)^2}} Y_0 \sin(\omega t - \phi), \quad (2)$$

where the phase angle ϕ is given by

$$\phi = \tan^{-1}\left(\frac{d_T \omega}{k - \omega^2 m}\right). \quad (3)$$

The maximum energy can be extracted when the excitation frequency ω is equal to the natural frequency ω_n of the spring-mass system, and ω_n is given by

$$\omega_n = \sqrt{k/m}. \quad (4)$$

Therefore, the energy dissipated within the damping can be expressed by [35]

$$p_d = \frac{m\zeta_T Y_0^2 \left(\frac{\omega}{\omega_n}\right)^3 \omega^3}{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\zeta_T\left(\frac{\omega}{\omega_n}\right)\right]^2}, \quad (5)$$

where ζ_T is the total damping ratio, namely $\zeta_T = (\zeta_m + \zeta_e) = d_T/2m\omega_n$. The power converted to the electricity is equal to the power absorbed by the electrical induced damping d_e, and the power output is given by

$$p_{out} = \frac{m\zeta_e Y_0^2 \left(\frac{\omega}{\omega_n}\right)^3 \omega^3}{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\zeta_T\left(\frac{\omega}{\omega_n}\right)\right]^2}. \quad (6)$$

As mentioned above, the maximum energy can be extracted when the resonant frequency matches the input frequency, and the vibration-electricity conversion system can be designed to be resonant at this frequency. In this case, the converted power is

$$p_{out} = \frac{m\zeta_e Y_0^2 \omega_n^3}{4\zeta_T^2}. \quad (7)$$

2.1.2. Piezoelectric

As one of the important vibration-based energy harvesting methods, piezoelectric transduction has received much attention because of the simple structure of piezoelectric generator and ease of application