Energy Conversion and Management 169 (2018) 149–160

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Design and analysis of a broadband vibratory energy harvester using bi-stable piezoelectric composite laminate

Diankun Pan, Fuhong Dai*

National Key Laboratory of Science and Technology on Advanced Composites in Special Environment, Harbin Institute of Technology, Harbin 150001, China

ARTICLE INFO

Keywords:
Bi-stable
Laminate
Energy harvesting
Piezoelectric
Vibration
Nonlinear

ABSTRACT

In this paper, a bi-stable piezoelectric energy harvester based on the bi-stable hybrid composite laminate with a new stacking sequence design is proposed. The new stacking sequence enables this bi-stable energy harvester to have some unique features, such as uniform strains of piezoelectric elements and symmetric stable configurations. Meanwhile, the new stacking sequence design enhances the room to adjust its natural frequency such that this proposed harvester allows for adjusting to lower frequency range and increasing the inertia by a tip mass to lower the demand of excitation level in comparison to previous settings. A finite element analysis is developed to investigate the static and dynamic characteristics of this new bi-stable energy harvester. A simple numerical model with a modified version of the Duffing equation is developed based on the unique nonlinear restoring force obtained from finite element analysis to describe the fundamental response characteristics of this nonlinear bi-stable energy harvester. Numerical simulations and experiments are carried out at different harmonic excitation levels ranging from 10 to 40 Hz. The results verify that the proposed model can reasonably capture the dynamic characteristics of this broadband bi-stable energy harvester. The output powers were measured under different vibration patterns. Maximum power of 31.1 mW was generated under large-amplitude and high-energy orbits cross-well vibration pattern at an excitation frequency of 22 Hz and acceleration of 3g (g = 9.8 m/s^2).

1. Introduction

Energy harvesting from ambient vibration has become an active research topic in the past years, owing to both its application potential and technical challenge [1]. The linear vibratory energy harvesters have been designed to operate optimally at or very close to resonance, so they are only sensitive to a single frequency and are not efficient for variable excitation. However, the ambient vibration energy is distributed over a broad spectrum. Therefore, methods to increase the effective frequency bandwidth of vibratory energy harvester are demanded. The nonlinear dynamic effects can achieve large-amplitude response over a continuous bandwidth [2], and the response bandwidth becomes wider when the forcing amplitude is increased [3]. Furthermore, the bandwidth with the large-amplitude response can be extended to higher or lower frequency range through the hardening or softening nonlinear behaviors [4]. As a result, the harvesters with nonlinear dynamic effects are potentially more suitable for harvesting energy from ambient vibrations in practical applications [5].

Bi-stable energy harvesters prove to be a good candidate for broadband frequency harvesting due to their rich nonlinear dynamic effects. Typically, external arrangements of magnets are used for cantilevered beams to induce bi-stability. This method relies on the repulsion or attraction force of several permanent magnets. Erturk and Inman [6] proposed a theoretical and experimental investigation of a bi-stable energy harvester which utilizes different magnet arrangements to induce a magnetoelastic buckling in a piezoelectrically laminated beam. Stanton et al. [7] investigated the merits of a bi-stable energy harvester comprised of permanent magnets and a piezoelectric cantilever beam by an analytical model, numerical simulation, and experiments. Zou et al. [8] presented a magnetically coupled two-degree-of-freedom vibration energy harvester for rotational motion which is consisted of two inverted piezoelectric cantilevered beam. Then, Zou et al. [9] presented a compressive-mode bi-stable vibration energy harvester with magnetic stators which enable the harvester to work under low excitation levels. Jiang et al. [10] presented a multi-step buckled beam piezoelectric energy harvester utilizing a combination of multi-step mechanism and bi-stable structure. This method is relatively complicated and needs careful design to obtain appropriate distance among the magnets which add extra weight and may interrupt an external circuit by the unwanted magnetic field. Another method is mechanical bi-stability which depends on the buckled piezoelectric beams subjected to specific elastic boundary conditions, such as clamped-

* Corresponding author.
E-mail address: daifh@hit.edu.cn (F. Dai).

https://doi.org/10.1016/j.enconman.2018.05.032
Received 12 March 2018; Received in revised form 8 May 2018; Accepted 10 May 2018
0196-8904/

clamped boundary conditions. Masana and Daqaq [11] investigated the relative performance of mono-stable and bi-stable energy harvester consisting of a clamped-clamped piezoelectric beam of which potential function is altered by applying a static compressive axial load. Cottone et al. [12] implemented a bistable vibratory energy harvester with a piezoelectric clamped-clamped buckled beam with axial compression under wideband random vibrations. Xu et al. [13] presented a bi-stable piezoelectric energy harvester based on simply supported piezoelectric buckled beam. This method also needs external devices to realize the boundary conditions.

An alternative method is taking advantage of the bi-stable composite laminate. Bi-stable composite laminates have received considerable attention due to their specific behavior and potential. Bi-stable laminates exhibit more than one stable shape without external power and need minimal energy input to realize relatively large deflection. If the piezoelectric element is attached to the surface of this bi-stable laminate, the large strains can be induced in the piezoelectric element when the large deformation occurs during vibration of bi-stable laminate and the electrical energy can be generated by the direct piezoelectric effect. These bi-stable laminates owe their bi-stabilities and no external devices such as magnets are required to obtain the desired dynamics. The piezoelectric elements can easily integrate with the laminates to form simple and reliable devices for operation. Arrieta et al. [14] had validated that such energy harvesters exhibit high levels of power generation over a wide range of frequencies. Recently, most of such energy harvesters are based on an asymmetric bi-stable laminate plate with $[0n/90n]_T$ stacking sequence. Betts et al. [15] determined optimal lay-up configurations and aspect ratios for greater electrical power from a smaller space. An analytical modeling and experimental characterization of this bi-stable piezoelectric harvester were also presented by Betts et al. [16] to capture its nonlinear response during mechanical vibrations. Unlike center fixation in other designs, Arrieta et al. [17] proposed a cantilevered bi-stable piezoelectric laminate for broadband energy harvesting and the proposed configuration allows for exploiting the massive strains developed close to the clamped root to enhance the harvesting effectiveness. Harris et al. [18] examined the dynamic response of piezoelectric bi-stable laminate beam by experiment and the results exhibited single-well and snap-through vibrations of both periodic and chaotic characters.

The bi-stable asymmetric laminate with $[0n/90n]_T$ stacking sequence has two stable configurations, and the curvature direction for each configuration is orthogonal to other as shown in Fig. 1(a). It is fixed at its center generally, and it needs high input energy to trigger its periodic cross-well vibration to generate high power. If it is fixed as a cantilevered plate, it has two initial stable states with apparently different dynamic responses. It is difficult to control its initial state to obtain better harvesting performance in the practical application. The critical dimension of the bi-stable asymmetric laminate is relatively large, and it may lose bi-stability when its dimension is smaller than this critical value. Therefore, the dimension of harvester based on bi-stable asymmetric laminate is typically large. Additionally, the MFC (macro-fiber composite) was employed as a piezoelectric transducer in most of these bi-stable harvesters due to its flexibility on large deformation, but the volume of MFC is usually large, and the effective piezoelectric volume is smaller than traditional piezoelectric materials such as lead zirconate titanate (PZT). It is not beneficial to reduce the total dimension of the harvester.

Li et al. [19] proposed a bi-stable hybrid symmetric laminate (BHSL) which has two stable configurations and the curvatures of two configurations are equal and opposite, as shown in Fig. 1(b). In this design, the aluminum layer is introduced in the symmetric composite laminate with $[90n/0m/90n]_{T,}$ and the mismatch of thermal expansion coefficient between the aluminum layer and composite layers leads to thermally induced strains which can lead to the curved deformation. Unlike bi-stable asymmetric laminate, the curvature direction for each configuration of BHSL is parallel to other. If it is fixed as a cantilevered plate, the two initial states are identical and the dynamic responses can be predicted and controlled easily. Typically, BHSL is rectangular and aspect ratio is relatively large. The critical dimension of BHSL can be adjusted by some parameters, such as lay-up design and hybrid width. Compared with asymmetric laminate, the BHSL has the potential of relatively small dimension. The potential of the piezoelectric harvester based on BHSL was validated in previous work [20,21]. The smaller and cheaper piezoceramic (PZT-5H) was employed as the piezoelectric transducer, and the BHSL was employed as host structure to form this bi-stable piezoelectric energy harvester (BPEH). The doubly curved configurations of the BHSL enable the PZT attached to its surfaces to have high and uniform strains, so the BPEH can take full advantage of PZT and generates higher output power. The rich nonlinear dynamic response can broaden the frequency bandwidth of high power for energy harvesting.

According to previous work [22], the BPEH can output high power under periodic cross-well vibration pattern, but it is difficult to trigger periodic cross-well vibration when the stable configuration of the BPEH has a larger longitudinal curvature. The BPEH needs a relatively high excitation level to actuate due to its large-amplitude feature and low inertia. This work focused on the enhancement of the BPEH with a new stacking sequence design. The BPEH with this new stacking sequence has a relatively small longitudinal curvature to decrease the amplitude during the cross-well vibration. Additionally, A tip mass is introduced for the BPEH to increase the inertia force and lower the level of excitation that triggers cross-well vibrations. This new stacking sequence provides higher natural frequency than the previous design because of its higher stiffness. It enhances the adjustable room of response frequency. Therefore, this BPEH can work and output higher power under cross-well vibration pattern at a lower excitation level than the previous design.

2. Design and finite element analysis

The bi-stability of the BHSL is created during cooling process from cure-temperature to room-temperature due to the mismatch of thermal expansion coefficient between aluminum and carbon fiber reinforced polymer (CFRP). Unlike previous design, the whole middle layer is

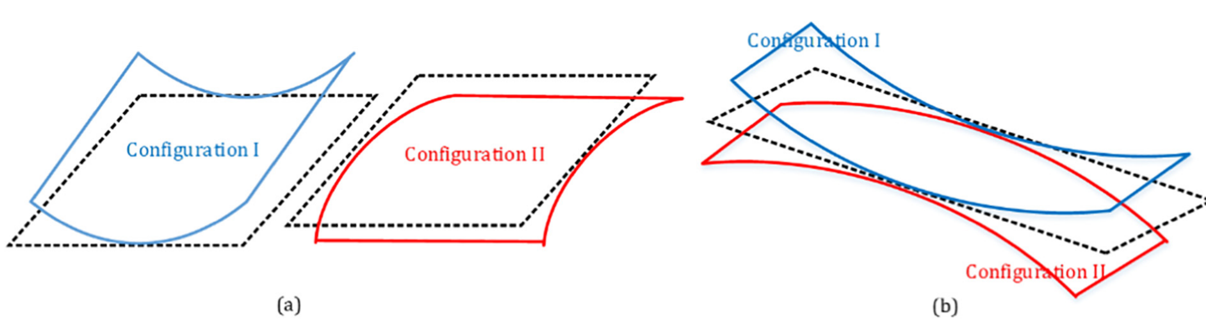

Fig. 1. Stable configurations of (a) bi-stable asymmetric laminate and (b) bi-stable hybrid symmetric laminate.