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Numerical Modeling of a Bistable Composite Piezoelectric Energy Harvester with Four-Corner Simply Supported Boundary Conditions

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Abstract. Bistable piezoelectric energy harvesters are attractive for harvesting energy from ambient vibrations because their large-amplitude cross-well motion can generate higher electrical output over a broader operating range than conventional linear harvesters. Among the available host structures, bistable composite laminates are particularly promising because they possess two stable equilibrium configurations and can transition between them under external excitation, thereby generating large strains and rich nonlinear dynamics that are well suited for energy conversion. In this work, a high-fidelity electromechanical finite element (FE) framework is developed in ABAQUS for a four corner simply supported (FCSS) bistable composite laminate energy harvester bonded with a Macro Fiber Composite (MFC) patch. The framework is used to predict the nonlinear dynamic response of the harvester and the corresponding open-circuit voltage under external harmonic excitation. To further evaluate the energy harvesting capability in terms of usable electrical output, the predicted open-circuit voltage is subsequently supplied as input to an electronic circuit simulation framework developed in LTspice, through which the corresponding power-harvesting performance is determined. The proposed combined FE–electronic circuit framework provides an integrated and robust approach for predicting both the structural dynamics and electrical power output of the FCSS bistable laminate–MFC energy harvester. The proposed framework provides an integrated basis for design assessment, performance evaluation, and parametric optimization of bistable piezoelectric energy-harvesting systems.

Introduction

Nonlinear piezoelectric energy harvesting systems have attracted considerable attention because of their ability to harvest ambient vibrational energy over a broad frequency range. Among various nonlinear concepts, bistable laminates are particularly attractive as host structures for energy harvesting applications. These laminates possess two stable equilibrium configurations and can undergo continuous snap-through transitions under external vibrations, thereby generating large strains [1]. When piezoelectric Macro Fiber Composites (MFCs) are bonded to their surfaces, these strains are converted into electrical energy through the piezoelectric effect. Bistable composite laminate-based energy harvesters have been investigated under various boundary conditions, laminate layups, and excitation scenarios. Among these, laminates with four-corner simply

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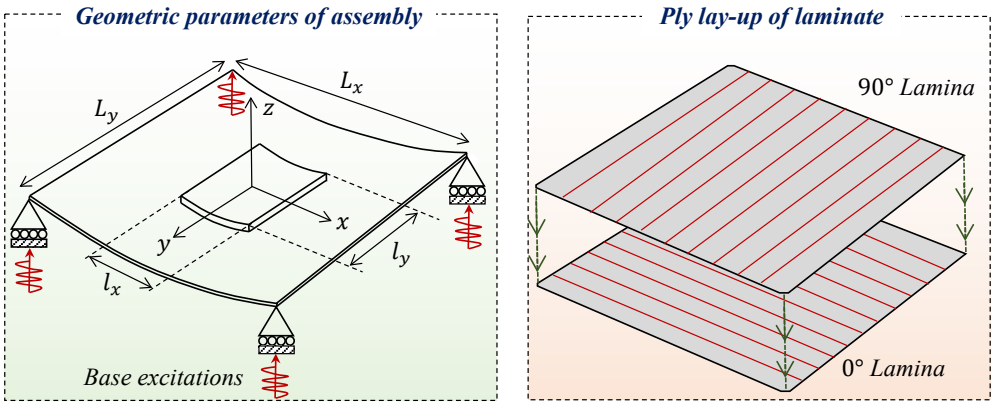
supported (FCSS) boundary conditions are of particular interest, as they can be mounted on vibrating host structures in multiple units, making them promising candidates for harvesting significant levels of ambient vibrational energy. Arrieta et al. [2] developed an energy harvester based on a center-fixed, square bistable composite laminate with MFCs. Wu et al. [3] investigated the nonlinear dynamic snap-through behavior of FCSS bistable laminates using theoretical and numerical frameworks, supported by experimental validation. Guo et al. [4] then examined the snap-through behavior and nonlinear oscillations of FCSS bistable composite laminates under foundation excitations using theoretical, numerical, and experimental approaches. Guo et al. [5] further explored the energy harvesting capabilities of bistable piezoelectric composite laminates under FCSS boundary conditions. Despite these studies, the development of an integrated numerical framework for predicting both the open-circuit voltage and power-harvesting capability of FCSS bistable energy harvesters under base excitation remains an ongoing research challenge. In this work, a numerical modeling approach is developed to predict the open-circuit voltage and power-harvesting capability of the FCSS energy harvester under base excitation.

Methodology

The configuration investigated in the present study is an FCSS bistable energy harvester, as shown in Fig. 1(a). The host vibrating structure consists of a 150 × 150 mm square bistable composite laminate with a [0/90] stacking sequence, as shown in Fig. 1(b), and a total thickness of 0.180 mm. A centrally bonded MFC M8557 P2 patch is attached to the laminate, and the material properties of both the laminate and MFC are taken from [6]. The simulation frameworks used in this study are briefly described in the subsequent subsections.



(a) (b)

***Fig 1**. Representation of (a) FCSS bistable energy harvester, (b) laminate stacking sequence*

FE framework: To determine the open-circuit voltage output of FCSS energy harvester a fully nonlinear FE model is developed in ABAQUS. The laminate is discretized using 4-noded quadrilateral shell elements (S4R), and the MFC patch is modeled using 3D piezoelectric solid elements (C3D20RE). The MFC is bonded to the laminate through a TIE constraint, while the top and bottom electrode nodes are constrained using EQUATION constraints, with the bottom electrode grounded. Geometric nonlinearity is included throughout the analysis using NLGEOM, and a curing temperature of 180 °C is applied to the entire laminate. The dynamic characteristics of the two stable shapes are extracted using the embedded LANCOZS eigen solver. Thereafter, a displacement-controlled excitation is applied at the four corners to obtain the voltage response of the FCSS harvester in different dynamic regimes.

Electronic simulations: After obtaining the open-circuit voltage from the FE framework, the energy harvesting performance of the FCSS bistable harvester is evaluated in LTspice. As shown in Fig 2, the harvester is represented by a voltage source defined by the peak open-circuit voltage

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V_{peak} (from ABAQUS), forcing frequency ω, phase angle φ, and internal capacitance C_p (C_p = 548 nF) . This source charges a larger capacitor C_m (C_m= 10 µF in all electronic simulations) from 0 V to 5 V through a full-wave rectifier, corresponding to 125 μJ of harvested energy. The charging time of C_m obtained from the LTspice simulations is then used to determine the average power output of the harvester.

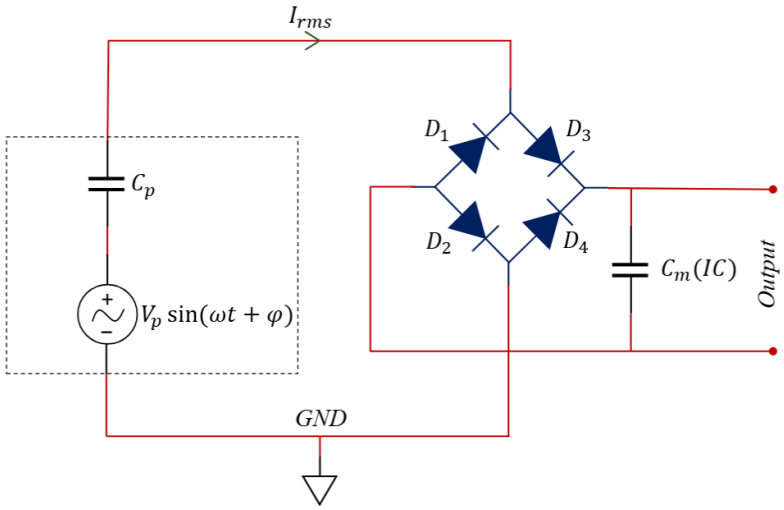

***Fig 2**. Schematic showing the circuit diagram of energy harvesting system*

Numerical Resuls

Using the LANCOZS solver and free-vibration analysis, the natural frequencies of the two stable shapes of the FCSS energy harvester were determined as 33.18 Hz and 34.14 Hz. A forcing frequency of 20 Hz, sufficiently below both natural frequencies, was selected, and the excitation amplitude was increased from 2 mm until cross-well oscillations occurred. As shown in Fig. 3(a), the harvester produced a peak open-circuit voltage of 5.43 V under single-well vibrations. When the excitation amplitude was increased to 7 mm, the harvester exhibited cross-well oscillations, continuously transitioning between the two stable states and generating much larger strains and voltage output. In this regime, a peak open-circuit voltage of 53.02 V was obtained, as shown in Fig. 3(b), confirming the effectiveness of cross-well oscillations for energy harvesting.

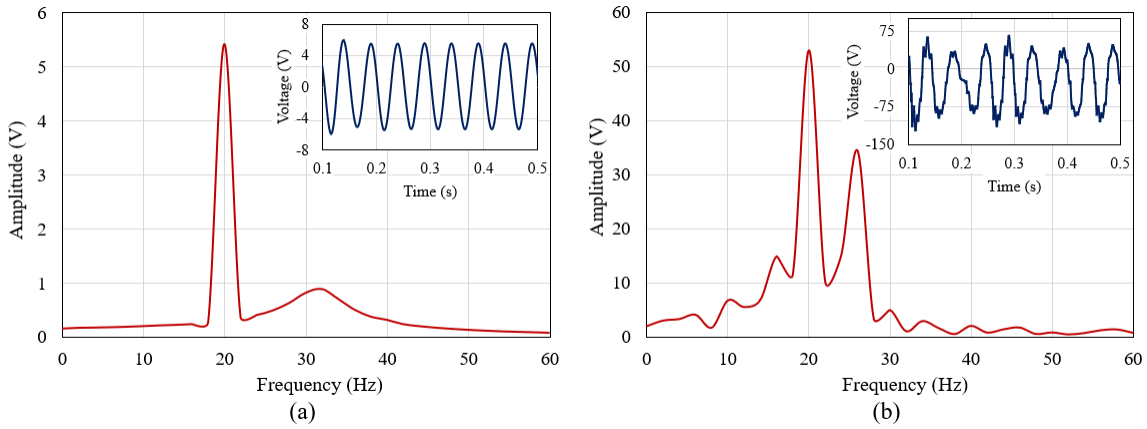

***Fig 3**. Predicted open-circuit voltage of the FCSS energy harvester at 20 Hz: (a) single-well oscillation, 2 mm; (b) cross-well oscillation, 7 mm*

The predicted output power of the energy harvester under the two dynamic regimes was calculated using LTSpice and is summarized in Table 1. The results clearly show that the FCSS energy harvester produces substantially higher output power during cross-well oscillations than

during single-well oscillations, confirming that cross-well oscillations constitute the most favorable dynamic regime for energy harvesting.

***Table 1**: Predicted average output power of the FCSS energy harvester in two dynamic regimes*

Dynamic regime	V_{peak} (V)	V_{rms} (V)	I_{rms} (mA)	Time (ms)	Power (μW)
Single-well	5.43	3.84	0.264	1423.06	87.84
Cross well	53.02	37.49	2.582	145.76	857.57

Conclusions

In this study, an efficient numerical framework was developed for evaluating the power-harvesting performance of the FCSS energy harvester. The framework comprises a fully nonlinear FE model implemented in ABAQUS to predict the natural vibration characteristics and open-circuit output voltage of the FCSS bistable energy harvester, followed by LTSpice-based electronic simulations to assess its power-harvesting capability. The results of the amplitude sweep at constant frequency confirm that cross-well motion is the most favorable dynamic regime for enhanced power harvesting. Overall, the proposed numerical framework provides a robust basis for future parametric investigations and design optimization studies.

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