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Review on the Design, Geometry and Mechanical Modeling of Piezoelectric Energy Harvesting Structures

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Authors' contributions

This work was carried out in collaboration between all authors. Author XZ designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors GZ and JC managed the analyses of the study. Author JC managed the literature searches. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

In recent decades, with the increase of energy demand and the development of wireless and micro-electro-mechanical technology, research in the field of energy recovery has been paid more and more attention. Because of piezoelectric materials can transform mechanical strain energy into electrical charge, therefore, piezoelectric materials are the major method of energy scavenging. The research status of piezoelectric energy harvesting devices at domestic and overseas is presented in detail. This paper includes four aspects: Asingle-degree of freedom system, piezoelectric cantilever beam, energy harvesting circuit and topology optimization of energy harvester. The development perspective of the piezoelectric vibration energy harvester was summarized. The study will be helpful for the researchers who are engaged in the studying on the piezoelectric vibration energy harvesting.

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Keywords: Piezoelectric energy harvesting; a single degree-of-freedom system; piezoelectric cantilever beam; circuits; topology optimization.

1. INTRODUCTION

Harvesting energy from ambient sources has been an active research area in recent years. Due to the advantage to efficiently convert mechanical strain energy into electrical charge, high power generation density and flexible shape design, piezoelectric vibration-to-electricity converters have a wide usage in transducers for energy harvesting applications [1,2].

Recently, the piezoelectric energy harvesting has been studied by various methods. Because of their electromechanical properties, piezoelectric materials are very good choices for transforming the energy produced by vibrations into electrical energy. A large amount of piezoelectric ceramics, single crystals and composites are now applied in energy harvesting [3]. However, the complete procedure for designing power harvesters is very challenging because it depends on the application, geometrical parameters, physical properties, optimization, fabrication, and electronic power [4].

It has found that both PZT-based and PVDF-based composites can improve the efficiency of the thermal-to-mechanical energy conversion. Guan X.C. et al. [5] found that the piezoelectric effect of the PZT/PVDF composite can be improved by dispersing a few carbon nanotubes, with an appropriate volume fraction of approximately 0.9. B. Gusarova et al. [6] presented a thermal energy harvester with hybrid PVDF + Shape Memory Alloy composite. The result showed the use of PVDF quadruples the energy output, compared to previously report PZT-based composites. Based on their studies, new ways to harvest temperature vibration should be explored.

The main objective of this paper is to summarize the current state of achievement and provide a basic overview of the rapid development in piezoelectric energy harvesting. The reminder of this paper is organized as follows: Section 2 introduces the single-degree of freedom system. Section 3 presents the piezoelectric cantilever beams, including unimorph, bimorph, along with multi-layered structures. Energy harvesting circuits and topology optimization are discussed in Section 4 and Section 5. Section 6 summaries the findings and discusses future prospects in the field of piezoelectric energy harvesting.

2. A SINGLEDEGREE-OF-FREEDOM SYSTEM

Traditional piezoelectric energy harvesters are cantilever devices with single degree-of-freedom (SODF) systems. Erturk and Inman [7] proposed correction factors for single degree of freedom base excitation model and examined that the single degree of freedom harmonic base excitation relations. G. Gatti et al. [8] reported an investigation on the maximum available energy harvested from a passing train using a linear single-degree-of-freedom oscillator. They found the maximum energy harvested per unit mass of the oscillator is about 0.25 J/kg at a frequency of about 17 Hz. The damping ratio for the optimum harvester was about 0.0045 (Fig. 1).

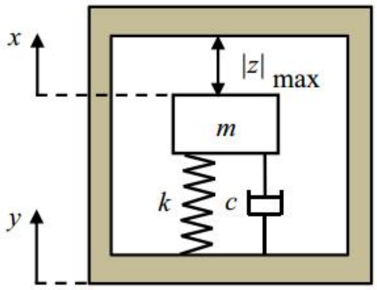
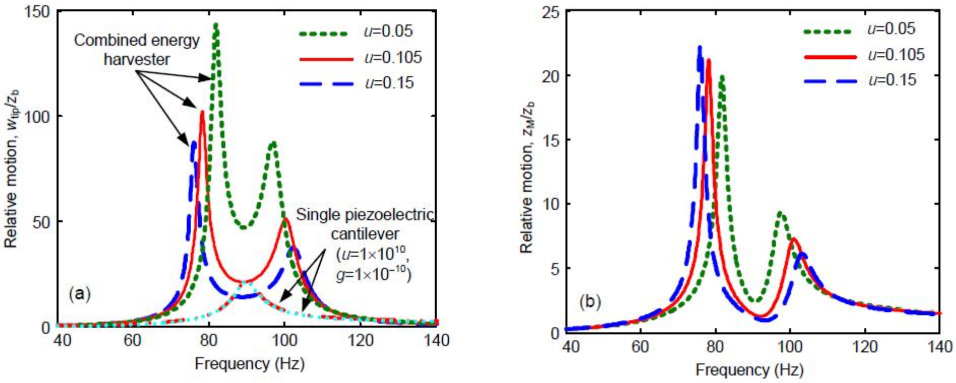


Fig. 1. Schematic of the energy harvester

Wang H.Y. et al. [9] presented a type of vibration energy harvester combining a piezoelectric cantilever and a SDO Felastic system. They reported the SDOF elastic system can increase the power output of the piezoelectric cantilever and improve the frequency bandwidth when the mass ratio of the piezoelectric cantilever to the lumped mass of SDOF elastic system is below 0.105 (Fig. 2).

X Wang et al. [10] investigated a SDOF electromagnetic and piezoelectric vibration energy harvesters. They found that as the calculation formulae of the energy harvesting efficiency and the normalized resonant harvesting power are interchangeable between the piezoelectric harvester and the electromagnetic harvester with reciprocals of only individual $(1/RN)^2$ or $(RN)^2$ related Terms (Fig. 3). They [11] also studied a (SDOF) vibration energy harvester connected to the four types of energy extraction and storage interface circuits (Figs. 4-5).



(a) **(b)**

Fig. 2. Relative motion of the combined energy harvester: Piezoelectric cantilever (a); SDOF elastic system (b)

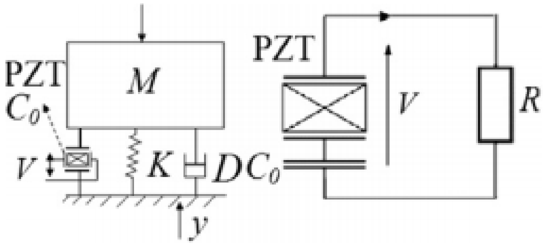


Fig. 3. A SDOF piezoelectric vibration energy harvester connected to a single load resistor based on physical model of a voltage source

Williams and Yates [12] studied the damping dissipated power of a single degree of freedom vibration energy harvester. Chun-Ying Lee et al. [13] presented the design formulation of the absorber with a single degree-of-freedom (SDOF) model having the equivalent parameters.

3. PIEZOELECTRIC CANTILEVER BEAM

3.1 Unimorph

Cantilever beam-based vibration energy harvesters are found to be the simplest and versatile design and hence are studied extensively. Friswell and Adhikari [14] presented the use of shaped piezoelectric patches over a standardized cantilever, and showed the enhancement of power, and capacitance with tapered, and shorter geometries compared to the traditional unimorph like geometry.

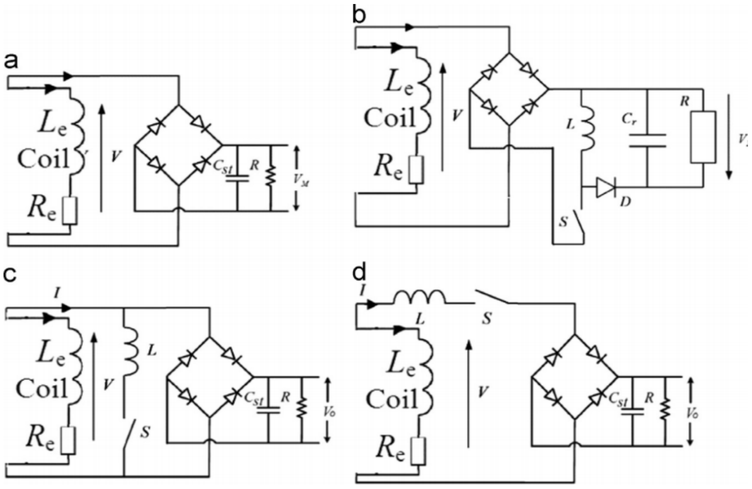


Fig. 4. Extraction and storage interface circuits for vibration energy harvesters: Standard (a); SECE (b); parallel SSHI (c); series SSHI circuit (d)

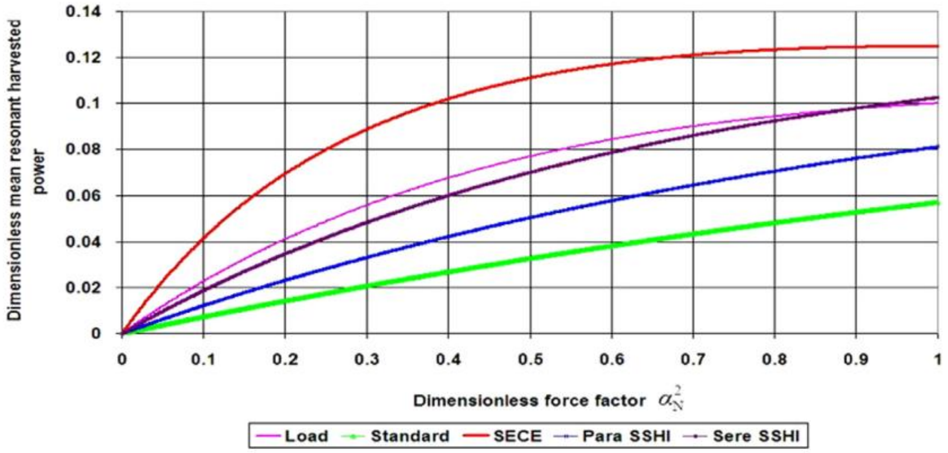


Fig. 5. Dimensionless resonant harvested power of the SDOF piezoelectric and electromagnetic vibration energy harvesters with the interface circuits of single load resistance, standard, SECE, parallel SSHI and parallel SSHI

Erturk and Inman [15] studied analytically and experimentally a bimorph cantilever piezoelectric vibration-based energy harvester (PVEH) using different layers with independent electrodes. Ben Ayed et al. [16] investigated the effects of linear and quadratic shape variations of the PVEH. Ahmed Jemai et al. [17] investigated the derivation of an accurate parameterized analytical model of a vibration-based energy harvester using piezocomposite material and electrode, which had a unimorph design with a metallic substrate layer partially covered by an AFC patch (Fig. 6). Jemai et al. [18] developed an analytical and numerical model for a unimorph AFC harvester.

Ryan R. Knight et al. [19] fabricated two types of MEMS cantilever beams, d_{31}unimorph and d_{33}unimorph. It showed that choosing the proper interdigitated electrode layout and beam dimensions can nearly double the performance of a d_{33}unimorph device. S. Sunithamani1 et al. [20] presented aunimorph piezoelectric energy harvester with proof mass. The results revealed that presence of proof mass and thickness of substrate affects the power generation of piezoelectric energy harvester. K.F. Wang et al. [21] presented nanoscale unimorph piezoelectric energy harvesters with arbitrary length and position of piezoelectric layer and proof mass. In some cases, the maximum power output of the model with flexoelectric effect is almost twelve times that of classical model which only includes piezoelectric effect (Fig. 7). Zhang [22], Yan and Jiang [23] found that the flexoelectric effect play a major role in the contact stiffness and electric polarization of piezoelectric nanobeams.

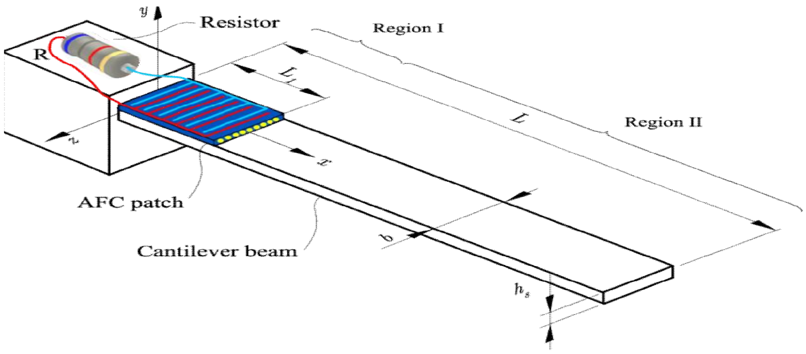


Fig. 6. Schematic of the unimorph energy harvester bender using IDE

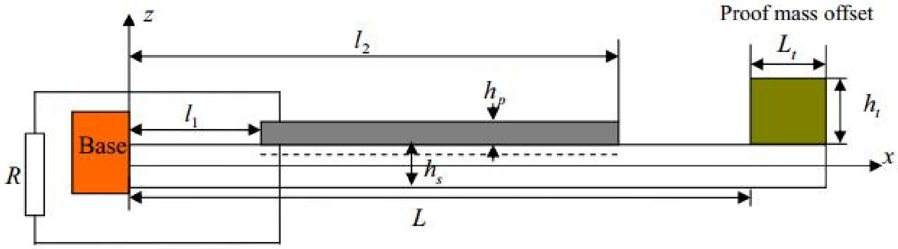


Fig. 7. A unimorph nanoscale piezoelectric energy harvester with a rectangular proof mass

Yoshikazu Hishinuma et al. [24] designed piezoelectric unimorph actuators with optimized PZT/Si thicknesses which could produce a stroke as high as 5 m at an actuation voltage as low as 50 V. DMs consisting of 10-m-thick single-crystal-silicon membranes supported by 4×4 actuator arrays were fabricated and characterized optically (Fig. 8).

Eui-Hyeok Yang et al. [25] described a proof-of-concept deformable mirror (DM) technology, with a continuous single-crystal silicon membrane reflecting surface, based on PZT unimorph membrane micro-actuators. The resulting piezoelectric unimorph actuators with patterned PZT films produced large strokes at low voltages. Yi Yin et al. [26] investigated preparation and characterization of unimorph actuators for deformable mirror. The results showed both mode diaphragms flexed downward with forward electrical bias and could generate deflections of several microns under quasi-static condition.

X Zhao et al. established a coupled model for the cantilevered unimorph piezoelectric energy harvester and develop the closed-form solutions for the forced vibrations of the piezoelectric energy harvester. Ji Fu et al. [27] pointed out that both multilayer and unimorph piezoelectric actuators could act as stiffness/modulus sensors based on the principle of mechanical contact resonance. It was found that for these two sensors, the shift of the resonance frequency due to contact is always positive (Fig. 9).

3.2 Bimorph

Roundy, Wright [28,29] and Sodano et al. [30] first described the practical use of cantilevered piezoelectric bimorphs resonating in the fundamental mode under base excitations. Erturk et al. [31] developed the accurate descriptions for the power generated from piezoelectric bimorphs, using distributed parameter models, providing exact solutions for beam displacement, velocity, voltage frequency response functions. Christophe Poizat et al. [32] studied extension, shear and extension–shear two layers bimorphs with analytical and numerical approaches. It was also found that, while shear bimorps lead to smaller maximum deflection, they also create much smaller and homogeneous stresses in the bimorphs interface.

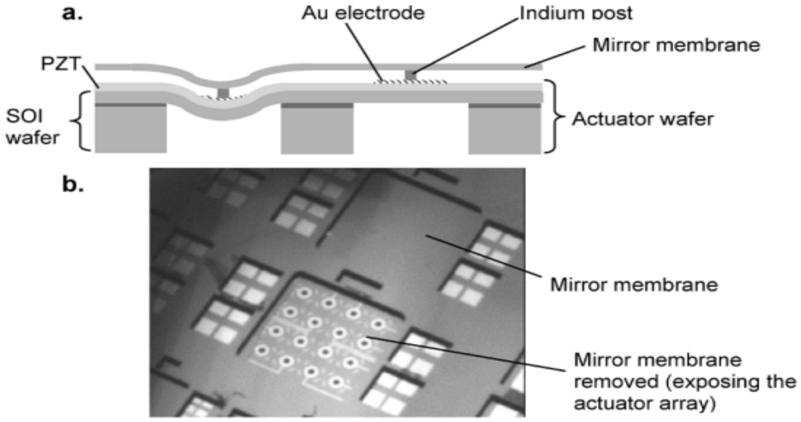


Fig. 8. Cross-sectional schematic of the deformable mirror (a), SEM micrograph of micro-fabricated deformable mirrors with 4×4 actuator arrays (b)

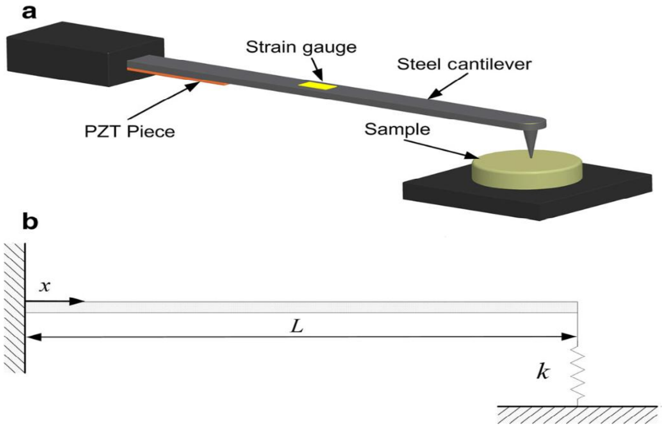


Fig. 9. Design of stiffness sensor based on a piezoelectric unimorph actuator. Basic assembly of stiffness sensor (a); Mechanical model of contact vibration system (b)

Adel El-Sabbagh et al. [33] focused on circular bimorphs subject to base excitation at different frequencies. The result demonstrated that the harnessed power can be significantly increased by exciting the piezoelectric bimorph at one of its axisymmetric natural frequencies. S.Y. Wang et al. [34] proposed a finite element model for the static and dynamic analysis of a piezoelectric bimorph. Numerical examples analyzed that the present model could well predict both the global and local responses such as mechanical displacements, modal frequencies as well as the through the thickness electric potentials. Morris and Forster [35] have used a finite element method to optimize the deflection of a circular bimorph consisting of a single piezoelectric actuator, bonding material and elastic plate of finite dimensions. Kursu et al. [36] presented an analytical model and a finite element analysis for a planar, parallel and symmetric piezoelectric bimorph structure.

S. Olutunde Oyadiji et al. [37] presented a modal approach for the two layer piezoelectric vibration energy harvesters. The result showed an optimal or near optimal mass position has a small interval between the two resonance frequencies and the mass ratio of each mode was neither too small nor too large. Zheng S. J. et al. [38] developed two size-dependent constituent equations for symmetrical/ heterogeneous piezoelectric bimorph actuators. The simulations demonstrated that the stiffness of elastic layers show directionally opposite effects on tip deflections of symmetrical piezoelectric bimorph actuator and heterogeneous one.

Bimorph energy harvester's substrate to piezoelectric thickness ratio has been changed and its effect on performance is discussed by Sunithamani et al. [39]. The mechanical behavior of a bimorph piezoelectric micro cantilever exposed to harmonic base excitation is investigated by Saber Azizi et al. [40].They pointed that for low resistances, the output power corresponding to parallel circuit is more than that appertaining to the series one; this behavior is reversed for higher load resistance (Fig. 10).

Aliae Oudich et al. [41] presented an analytical model to analyze the bending of a bimorph beam comprising of piezoelectric material (PM) and shape memory alloy (SMA) thin layers, which started from the governing equations of the bending beam based on the Euler-Bernoulli beam theory (Fig. 11)

Nicola Lamberti et al. [42] presented a piezoelectric tactile sensor for track-pad applications. The use of this technique will also allow a relapse in the field of pointing devices used in hospitals. Y Tong et al. [43] presented a testing system for intraocular pressure, based on a method of measuring intraocular pressure by the effect of piezoelectric bimorphs. They proposed that the internal pressure of eyeball and the output current of intraocular bimorph have relatively good linear relationship within the range of human intraocular pressure. It has significant meaning in medical research and clinical application.

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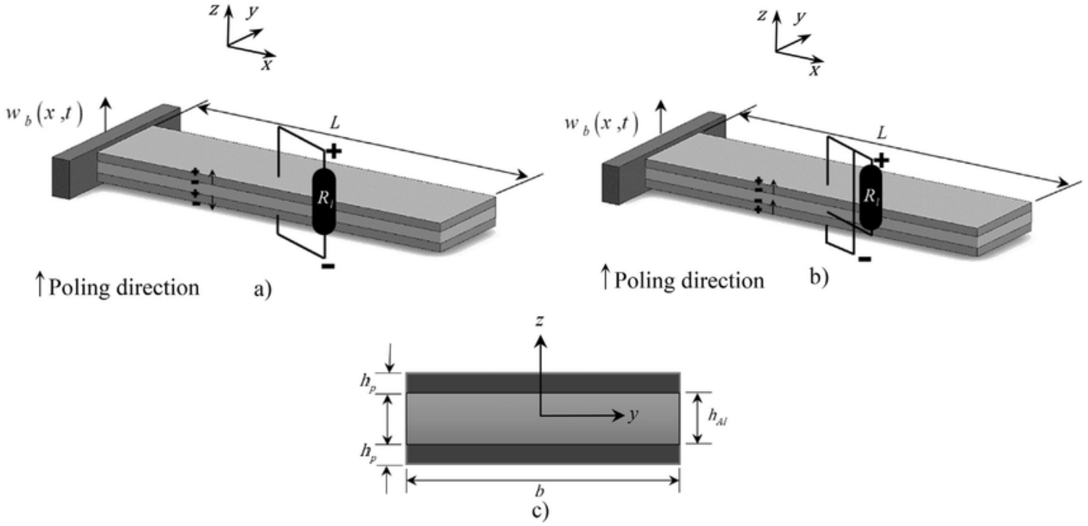


Fig. 10. 3-D model of the proposed piezoelectric bimorph cantilever (a): series connection (b): parallel connection (c): cross section

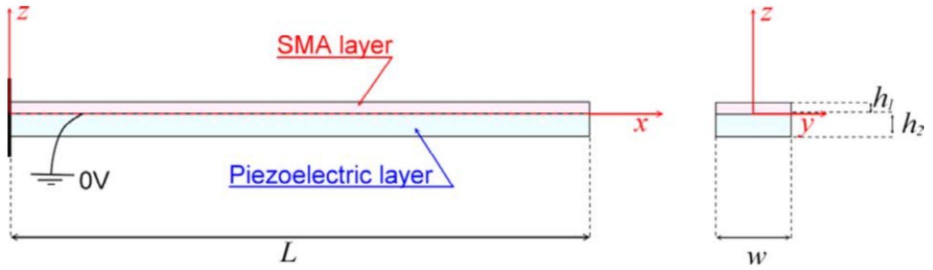


Fig. 11. Schematic view of the SMA-PM bimorph

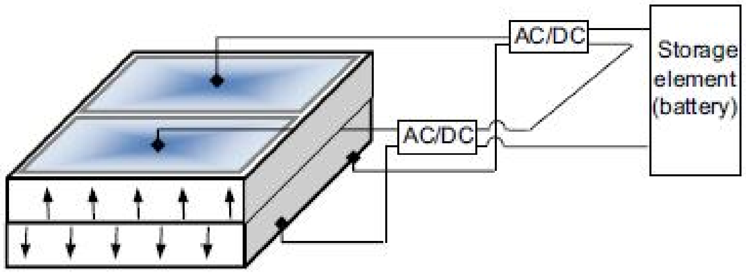


Fig. 12. Schematic of a part of a piezoelectric bimorph with several (only two are shown) pairs of electrodes used to charge an energy storage element (battery)

3.3 Multi-layer

Rudiger G. Ballas et al. [42] developed a solution of the dynamic admittance matrix for any kind of clamped-free piezoelectric-multilayer beam bending actuator. The morphology of the entire piezoelectric actor or generator in any n-layered material combination can be evaluated properly, solely using geometrical and material parameters. F. Moleiro et al. [45] provided 12 distinct test cases for the static analysis of multilayered piezoelectric composite plates. The result showed the amount of exact through-thickness distributions can demonstrate the significant difference in the plate static response for the two loading conditions as well as the effect of the plate aspect ratio for each loading condition. Yun G.L. et al. [46] conducted dynamic theoretical model of arbitrary multilayer cantilever with alternating piezoelectric and magnetostrictive layers on a substrate. They demonstrated that the structural dimensions strongly influenced the neutral plane in the composite cantilever and then in turns strongly influenced the ME response (Fig. 13).

Nie G.Q. et al. [43] investigated propagation of the SH wave in PMN-XPT piezoelectric layered structure loaded with viscous liquid. They concluded the choices of polarizing direction and thickness of piezoelectric material have significant effects on velocity dispersion and energy attenuation (Fig. 14).

Jafar Rouzegar et al. [44] presented a solution for free vibration analysis of a functionally graded (FG) plate integrated with piezoelectric layers. The results indicated that increasing the thickness of piezoelectric layers from zero to a specific value leads to decrement of natural frequencies (Fig. 15(a)). M. H. Korayem S et al. [45] studied the vibrating motion of the multi-layer piezoelectric micro cantilever (MC). They found out the vibrating amplitude of the monolayer MC was greater than two layers under the same voltage (Fig. 15(b)).

4. ENERGY HARVESTING CIRCUIT

In order to improve the efficiency of energy acquisition and energy acquisition ability, in addition to implement effective design of piezoelectric vibrator, still need to study energy storage circuit and the energy storage component, improving the efficiency of energy storage [46].

Lefeuvre [47] studied parallel synchronous switch inductance circuit (P-SSHI) for the theoretical and experimental research, the results show that comparing with classical energy collection circuit, the circuit of energy collection efficiency can be increasedby 400%. Taylor [48], Lefeuvre [49] and Guyomar [50] called the series connection of piezoelectric element and the control switch as tandem SSHI technology. The basic principle wasthat in serial synchronous switch inductance on both ends of the piezoelectric element. Yu-Yin Chen et al. [51] presented and compared several

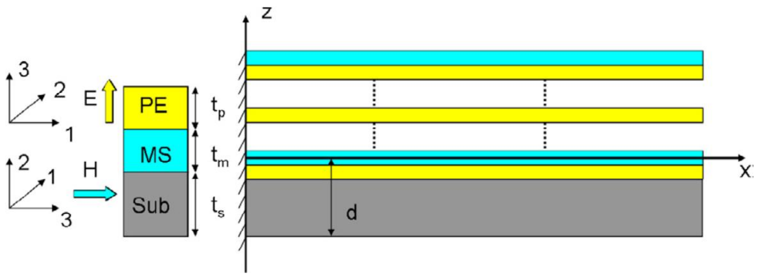
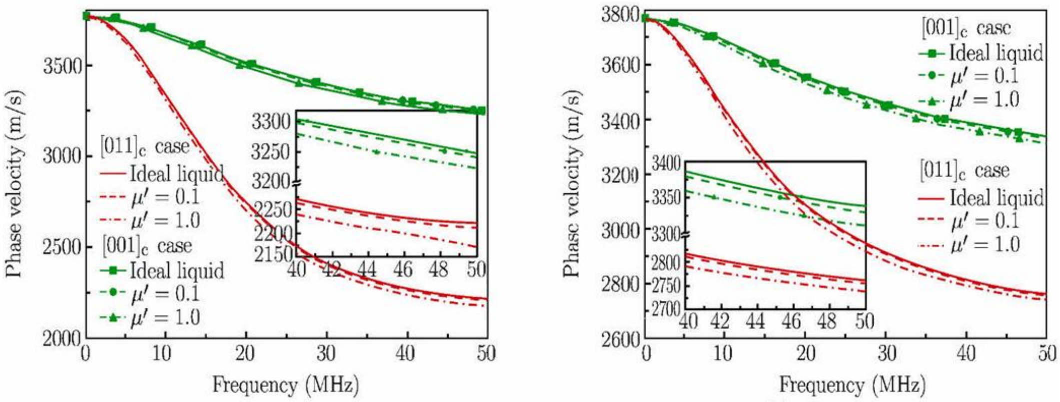
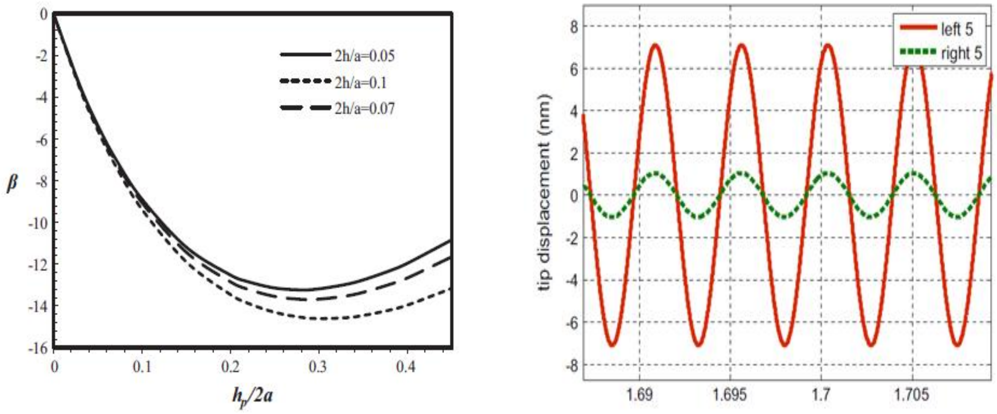


Fig. 13. Schematic of the geometry of ME multilayer composite cantilever



(a) Electrically shorted
(b) Electrically open

Fig. 14. Dispersion relation of liquid/SiO2/PMN-XPT structure in different polarizing directions: electrically shorted (a); electrically open (b)

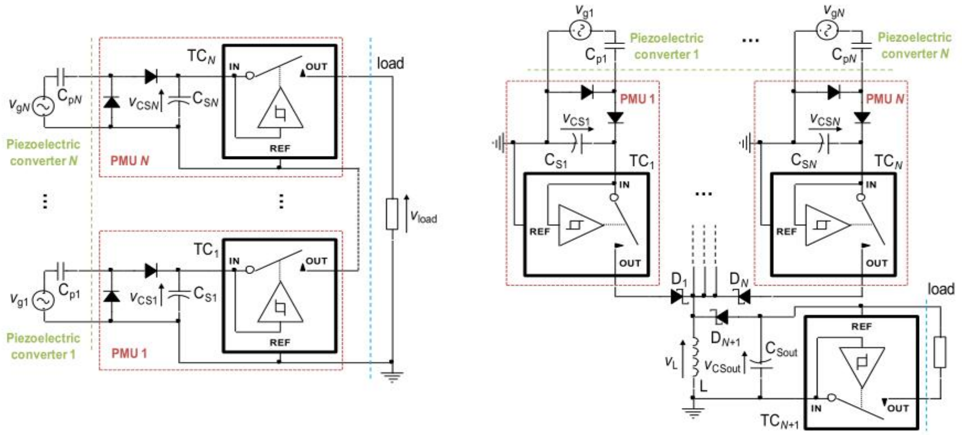


(a) (b)

Fig. 15. The variation of β versus the piezoelectric thickness for transversely isotropic square plate coupled with piezoelectric layers considering different thickness ratios (a); Amplitude of the two-segment MC in two working mode—solid line: The left segment acts as actuator, dash line: The right segment acts as actuator (b)

interfacing circuit including standard DC approach, SSHI technique and transformer-based SSHI technique. In this three circuits, the power output of series-SSHI is the best one and around 4 times than the standard DC approach and 2 times than OSECE.

Lallart [52] proposed the two synchronous interface circuit switch (DSSH) energy recovery technology. Through theoretical analysis and experimental verification, DSSH technology interface circuit output power has nothing to do with the follow-up circuit load, and this method compared with the maximum power standard interface circuit, power recovery increased by 500%. Davide Alghisi et al. [53] resented innovative power management circuits for multi-source piezoelectric energy harvesting systems, which exploit custom trigger circuits to avoid the limitations of traditional topologies. The proposed parallel-like power management circuit independently extracts powered from each converter by charging separate transfer capacitors (Fig. 16).



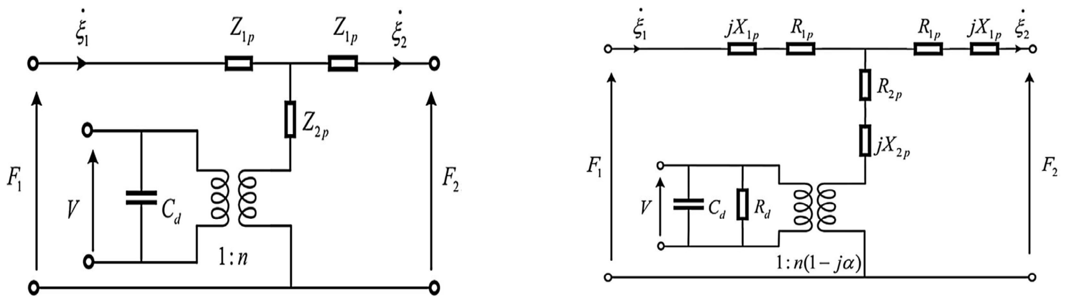
(a) (b)

Fig. 16. Proposed power management circuits for N piezoelectric energy converters with N Power Management Unit (PMU) series-like combined (a). Proposed power management circuits for N piezoelectric energy converters with N Power management Unit (PMU) parallel-like combined (b)

Chung-Shao Chao et al. [54] discussed the modified driving circuit uses the two-phase charging method whose time duration between two charges. They discovered that the pump obtains an extra 34%, 13% and 4.2% flow rate at 80 Vpp, 120 Vpp, and 160 Vpp, respectively. Poulin et al. [55] compared electromagnetic and piezoelectric harvesters for their duality and similarity using the equivalent circuit and impedance method. They reported that the equivalent circuits of the electromagnetic and piezoelectric harvesters had an obvious similarity and their power graphs had the same shape. Dong X.X. et al. [56] presented an equivalent circuit considering the dielectric, elastic and piezoelectric losses. They used six-terminal equivalent circuit to simulate the admittance spectra of piezoelectric actuator with four different load configurations (Fig. 17).

Shu and Lien [57] defined the conversion efficiency from mechanical to electrical energy for a vibration energy harvester connected with a standard interface circuit and expressed the efficiency in four dimensionless variables of normalized resistance, applied frequency ratio, relative magnitudes of the electromechanical coupling coefficient and mechanical damping ratio. Zhang Y. K. et al. [58] presented and formulated a 3-port equivalent circuit of multi-layer piezoelectric stack (MPS) on the basis of simplified fundamentals of MPS. The result showed the proposed circuit can be extended to any electrical and mechanical condition and allows one to predict behaviors with material properties and structural dimension (Fig. 18).

Recently, a rectifier free piezoelectric energy harvesting circuit has been suggested by Kim et al. [59]. Alwyn D. T. Elliott et al. [60] presented the implementation of a single supply pre-biasing circuit for piezoelectric energy harvesters. The SSPB circuit was shown to improve the power extracted from a piezoelectric harvester by 6 times over what can be achieved with a diode rectifier. Tomoaki Kashiwao et al. [61] optimized both types of rectifier circuits by varying the values of the diode forward voltages and the capacitance of the capacitors. They reported that the power efficiency of the bridge circuit was higher than that of the double-voltage rectifier circuit.



(a) (b)

Fig. 17. Mason's equivalent circuit without losses (a); New six-terminal equivalent circuit with losses (b)

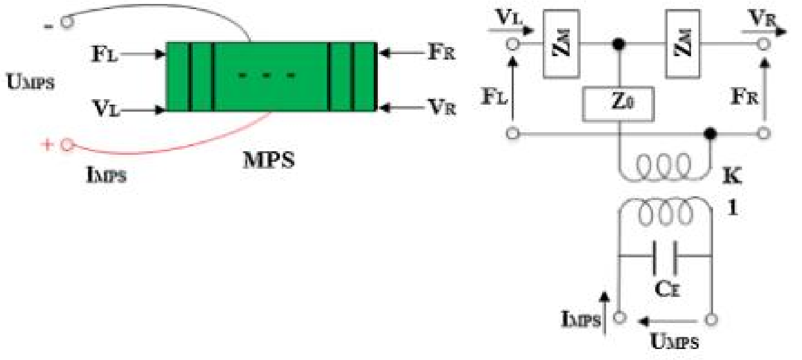


Fig. 18. Schematic of three-port equivalent circuit of MPS

Atsushi Matsubara et al. [62] presented the vibration suppression of a boring bar using piezoelectric actuators installed in the boring bar, and an inductor-resister (LR) circuit, which acted as a mechanical dynamic absorber. Keisuke Yamada et al. [63] described a vibration suppression method based on passive vibration suppression using a piezoelectric element and an LR circuit (Fig. 19).

H Shen et al. [64] designed and investigated a vibration damping system powered by harvested energy with implementation of the so called SSDV (synchronized switch damping on voltage source) technique. They proposed that only enough energy was supplied, it was possible to realize an autonomous vibration damping system by the SSDV technique (Fig. 20).

Gianluigi De Giuseppe et al. [65] employed an equivalent circuit, which bridges the structural modeling and electrical functionality, allowed simulations of complex circuitry. They reported that When the devices fabricated by soft or hard PZTs were heated upto150℃, the output power of all devices decreases with theincrease of the temperature. Juergen Schoeftner and Gerda Buchberger [66] focused on the optimization of a vibrating cantilever beam in a power harvesting application studying different distributions of piezoelectric layers and attached electric circuits (Fig. 21).

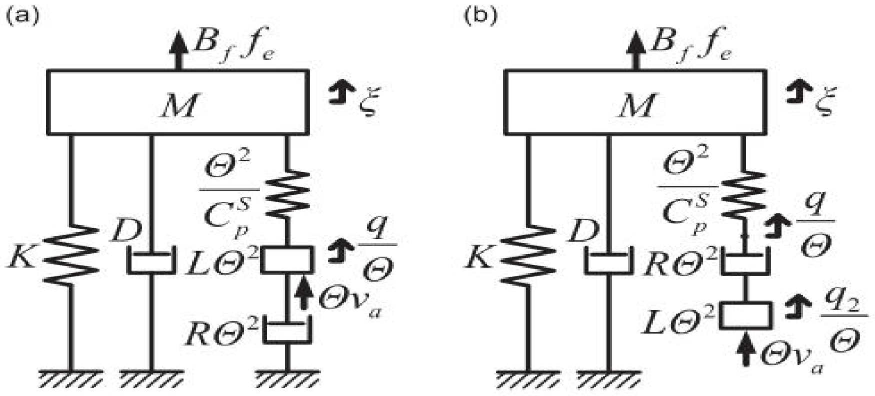


Fig. 19. Equivalent mechanical models using series and parallel LR circuits: using series LR circuit (a) and using parallel LR circuit (b)

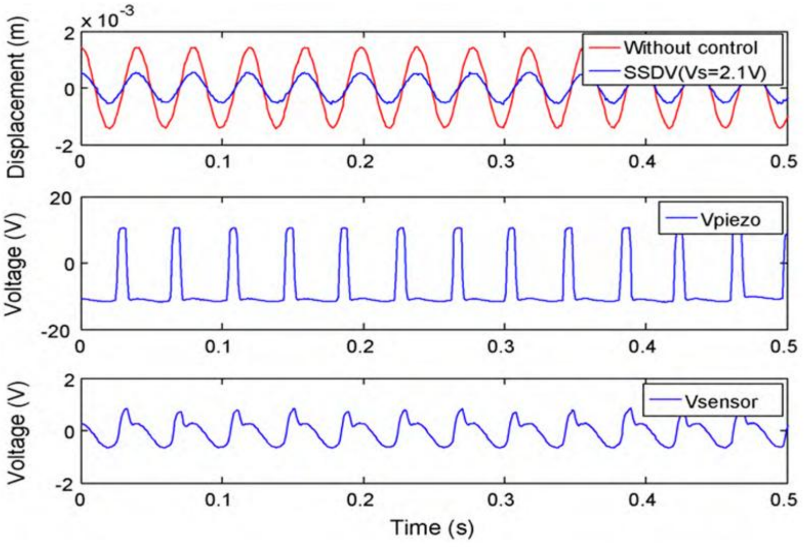


Fig. 20. Effectiveness of vibration damping using SSDV technique (VS = 2.1 V)

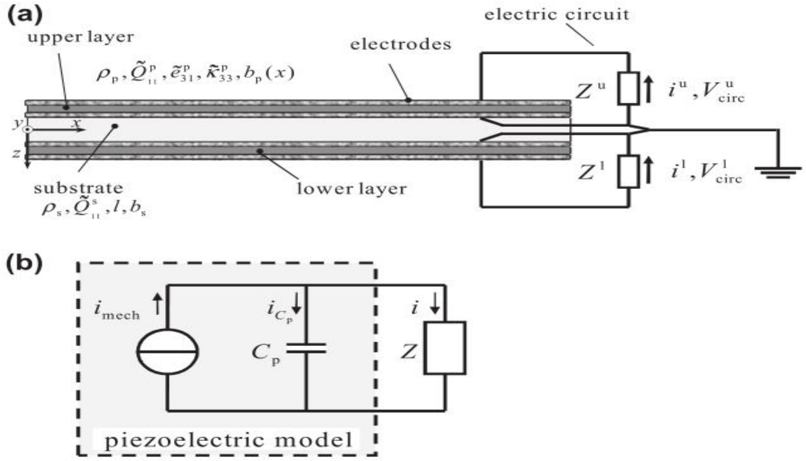


Fig. 21. Laminated beam with three layers. The substrate is placed between the piezoelectric upper and lower layers, which are connected to electric circuits (a) and equivalent block diagram of the piezoelectric element (b)

In recent years, the self-powered circuit of piezoelectric energy harvesting system has become the focus of research. Z. Sun et al. [67] designed the self-powered Double synchronized switch harvesting circuit (self-powered DSSH circuit). They added two piezoelectric patches into the piezoelectric generator. Lallart M and Guyomar D [68] proposed a model that takes into account such losses as well as a new architecture for the SSHI energy harvesting circuit that limits such losses in the harvesting process. They also presented that the circuit of this model was fully self-powered. Makihara, Kand Asahina, K. [69] proposed a self-powered analog controller circuit to increase the efficiency of electrical energy harvesting from vibrational energy using piezoelectric materials. The proposed circuit can increase the energy stored in the storage capacitor by a factor of 8.5 relative to the conventional SSHI circuit. Wu Y et al. [70] presented a self-powered interface circuit for the Optimized Synchronous Electric Charge Extraction (OSECE) technique applied to piezoelectric vibration energy harvesting. They developed a peak detector (PKD) circuit to detect the maximum and minimum vibration displacements. Liang J and Liao W-H [71] proposed a modified circuit and an improved analysis for the self-powered SSHI (SP-SSHI). The results showed that under the four excitation levels investigated, the SP-SSHI can harvest up to 200% more power than the SEH interface circuit. Makihara K et al. [72] developed a digital self-powered autonomous system, it achieved sophisticated vibration suppression dealing with multimodal vibrations. Lallart M. [73] exposed a new nonlinear technique for enhancing the energy harvesting abilities of piezoelectric-based microgenerators, able to convert mechanical energy into electricity for powering up electronic devices. In order to dispose of realistic devices, they proposed a self-powered version of the enhanced technique. Liu W. Q. et al. [74] proposed a new self-powered bistable generator which was composed of three parts: the self-powered OSECE (Optimized Synchronous Electric Charge Extraction) circuit (Fig. 22), the BSM (buckled-pring-mass) oscillator and two stoppers.

Generally, the energy collected by the piezoelectric vibration energy harvesters are small. The energy harvesting circuit with low energy consumption and high efficiency can effectively improve the output power of the whole piezoelectric vibration energy collection device. Therefor a simple, efficient and low consumption energy harvesting circuit will be the future research area.

5. TOPOLOGY OPTIMIZATION OF THE PIEZOELECTRIC ENERGY HARVESTER

Topology optimization is regarded as a powerful tool for innovative structural design. In recent years, topology optimization technique has been successfully applied to the design of piezoelectric smart structures. In this section, we introduced the topology optimization of the piezoelectric energy harvester.

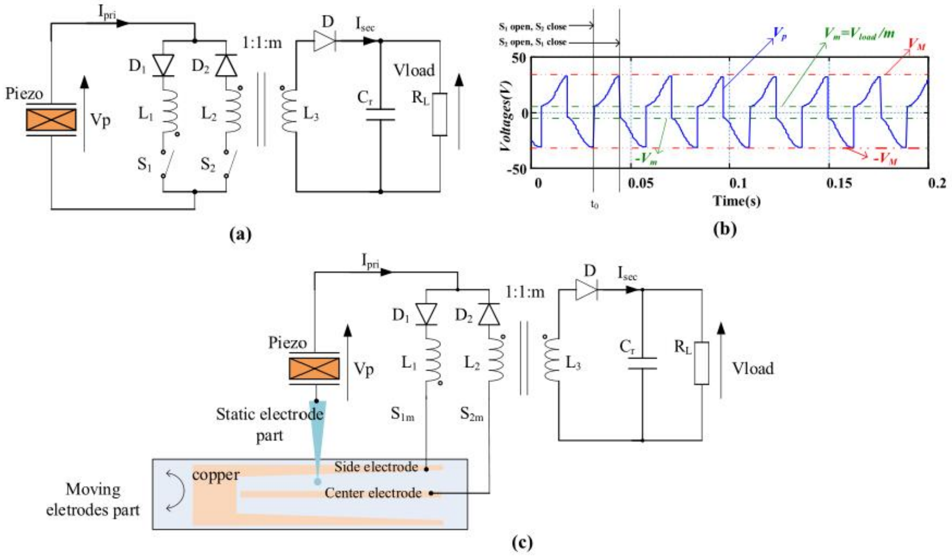


Fig. 22. OSECE circuit (a); Theoretical waveform of the OSECE circuit (b); Self-powered OSECE with the mechanical switch structure (c)

Kang et al. [75] and Jang et al. [76] proposedan equivalent static-load approach to find the optimal stiffness material distribution for minimizing the vibration level. Rupp et al. [77], Nakasone and Silva [78] proposed the sign of the piezoelectric tensor to depend on design variables and updating the variables using gradient-based optimization methods. Juliano F. Gonçalves et al. [79] employed the solid isotropic material with penalization (SIMP) approach to find the optimum design of actuators taken into account the control spillover effects. Zhang X. P. et al. [80] studied topology optimization for finding the optimal layout of piezoelectric sensor and actuator layers attached to a thin-shell base structure with CGVF control of transient response. They also confirmed that the achieved vibration reduction was mainly due to improvement of the active control performance rather than changes of the structural dynamic stiffness/ mass property (Fig. 23).

Kögl and Silva [81] considered the optimization of the piezoelectric part together with the polarization distribution. They took a three-layer plate and two piezo-layers attached to the top and bottom surfaces of the base layer which was fixed. A. Takezawa et al. [82] developed an optimization methodology that optimizes the piezoelectric material layout and polarization direction. They reported that although the generating power was lower, Poly-Vinylidene-Di-Fluoride (PVDF) piezoelectric film could make manufacturing easier. Lin Z.Q. et al. [83] applied a topology optimization based method to simultaneously determine the optimal layout of the piezoelectric energy harvesting devices and the optimal position of the mass loading (Fig. 24).

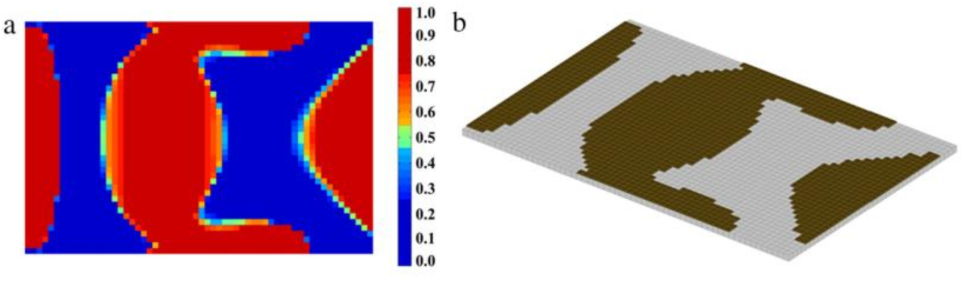


Fig. 23. Optimal solution for the cantilever plate: Density contour (a); suggested layout of the piezoelectric layers (b)

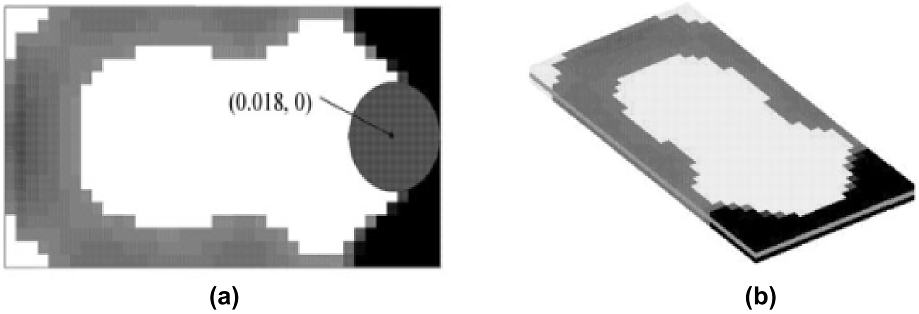


Fig. 24. Optimal location of the mass layer under a band of excitation frequencies ranged from 10 Hz to 400 Hz (a); Optimal layout of the piezoelectric material under a band of excitation frequencies ranged from 10 Hz to 400 Hz (b)

Cheol Kim et al. [84] calculated the optimum topology of a piezoelectric material layer on the harvesting beam by considering natural frequencies of beams, electromechanical couplings of piezoelectric materials, tip masses and MMA (method of moving asymptotes). They found that the voltage outputs generated by the energy harvesting beams with a topology-optimized piezoelectric material layer were higher than simply size-optimized or un-optimized cases. S.S. Nanthakumar et al. [85] presented an extended finite element formulation for piezoelectric nanobeams and nanoplates that was coupled with topology optimization to study the energy harvesting potential of piezoelectric nanostructures. They elucidated that the competition between surface elastic and surface piezoelectric effects in controlling the overall energy conversion efficiency of the piezoelectric nanostructures (Fig. 25).

David Ruiz et al. [86] proposed a systematic procedure based on the topology optimization method to design piezoelectric transducers in a static in-plane and out-of-plane frame-work. They proved that the optimized design for a specific transducer does not change independently whether it was working as sensor or as actuator. Jin Yee Noh et al. [87] proposed a topology optimization procedure to design optimal layouts for piezoelectric energy harvesting devices (EHDs) by considering the effect of static and harmonic dynamic mechanical loads. They observed that the vibration power EHDs provided the maximum voltage and power outputs when operated at resonances. A. Donoso et al. [88] developed a systematic procedure that introduced a uniform null-polarity phase (gap-phase) of known width between areas of opposite polarity on designing piezoelectric modal transducers. B Zheng et al. [89] described the problem formulation of topology optimization and derived the sensitivity of energy efficiency. They obtained the optimal configuration by re-distributing materials among the design domain using a gradient search method (Fig. 26).

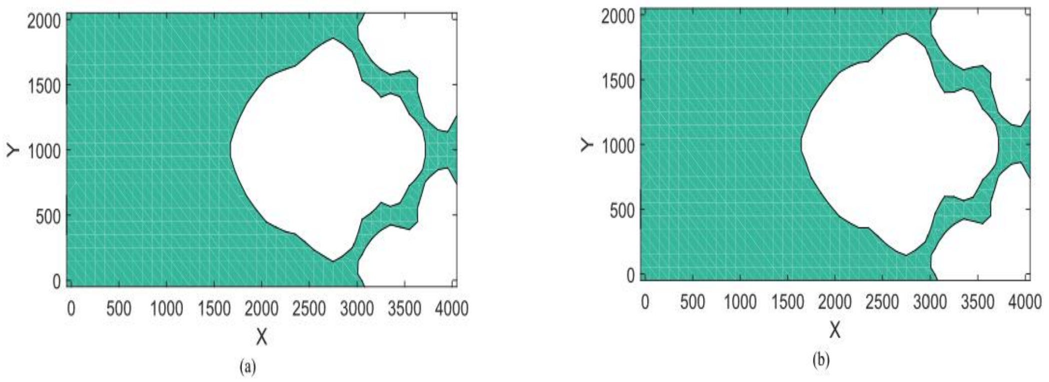
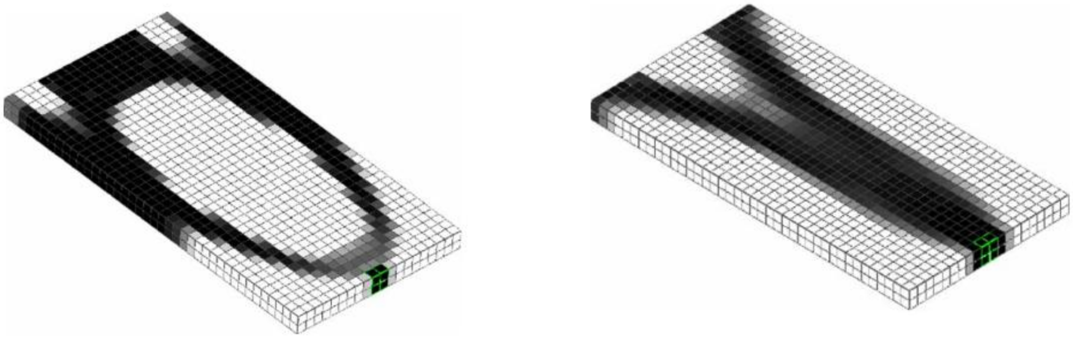


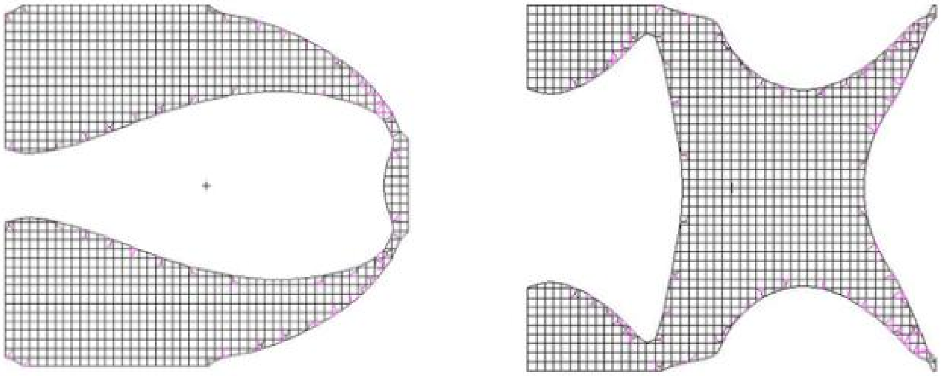
Fig. 25. Optimized topology (top view) of the piezoelectric layer (top view) of an EHD subjected to point load at free end: 100 nm thick nanoplate (a); 10 nm thick nanoplate (b)



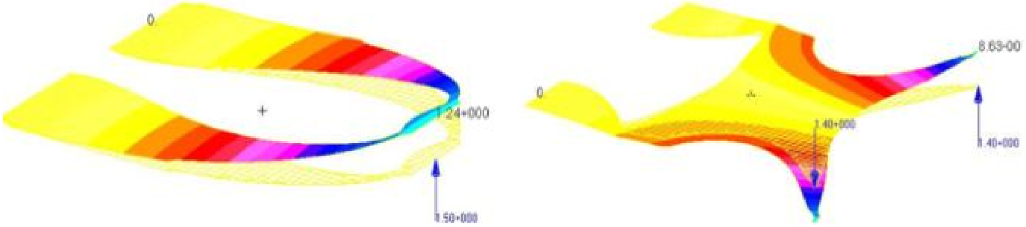
(a) **(b)**

Fig. 26. Optimized bimorph piezoelectric generator under bending force (a); Optimized layout of an extension piezoelectric generator (b)

Cheol Kim et al. [90] proposed an FEM-based topology optimization approach to calculate the topologies of a substrate plate and a piezoelectric layer used for vibrating unimorph cantilevered plate-like electricity generators. They also designed the cantilevered plate generators with optimal topologies for three piezoelectric materials suchas PZT, PMN-PT and PMN-PT fiber MFC. Luo Q. T. et al. [91] proposed a numerical and experimental investigation into optimum topological design of morphing piezoelectric structures using a moving iso-surface threshold method. They also indicated that the present response function based on mutual strain energy density was effective to minimize the error norm and the present algorithm based on the nodal count was efficient to determine the iso-surface threshold value (Fig. 27).



(a) Mesh for bending topology (b) Mesh for twisting topology



(c) Bending shape and load scenario (d) Twisting shape and load scenario

Fig. 27. Nastran verification of the optimal topologies for morphing bending and twisting shapes of a plate subjected to mechanical forces

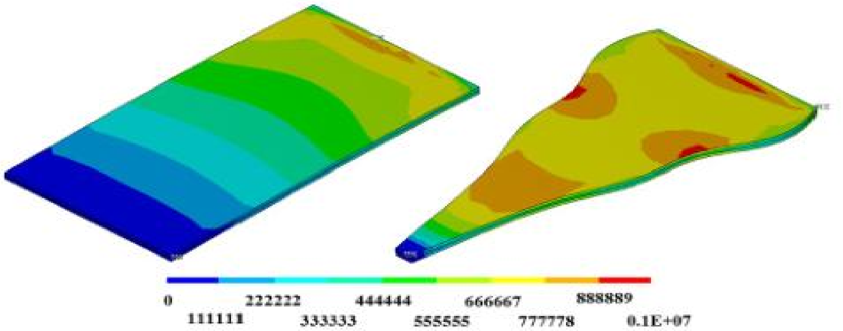


Fig. 28. Distribution of von missestress for the initial design (left) and for the optimised design (right) (Pa)

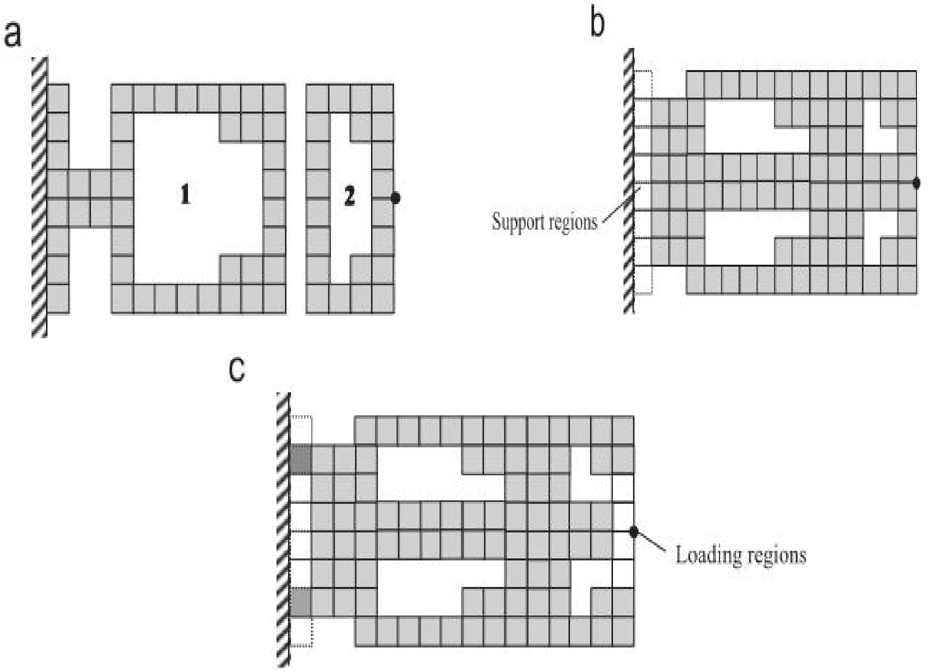


Fig. 29. Discontinuous topologies: Disconnected topology with object 1 and object 2(a); Structurally disconnected topology with support regions (b); Structurally disconnected topology with loading regions (c)

Fabian Wein et al. [92] investigated the occurrence of self-penalizationin topology optimization problems for piezocera micmechanical composites. From the numerical experiments they concluded a distinct self-penalization in the case of displacement maximization both for the static and dynamic case. Chung Ket Thein et al. [93] reported an alternative method for predicting the power output of a bimorph cantilever beam used a finite-element method for both static and dynamic frequency analyses (Fig. 28).

Fabian Wein et al. [94] investigated the optimal design of a rectangular beam with topology optimization. They founded that the obtained increase in electric power compared to the solid structure at resonance was significant while controlling peak stress within the piezoelectric layers. Park et al. [95] developed a size design optimization of piezoelectric energy harvester subject to tip rotary motion. They used the rectangular piezoelectric (PZT, PVDF) sheets. Peng et al. [96] determined the optimal layout for a set of four independent piezoelectric actuators (from a total of 64 candidates) bonded in a rectangular thin plate.

S. Canfield and M. Frecker [97] presented a systematic design approach where topology optimization was used to design compliant mechanical amplifiers with any direction of force and motion transmission. They pointed out piezoelectric actuators designed using this method may be used in smart structures applications such as helicopter rotor blade control. B Xu et al. [98] integrated the optimization of structural topology, number and positions of the actuators and control parameters of piezoelectric smart plates was investigated. They found that actuators were often placed in the position where the deformations of the elements are much larger for all controlled modes (Fig. 29).

Biglar and Mirdamadi [99] studied both location and orientation of piezoelectric sensors and actuators attached to plate structures. Wang et al. [100] applied Genetic Algorithm to the design of piezoelectric sensors and actuators for torsional vibration control. Detl and Garcia [101] developed an analytical model of bending vibration based on long, slender beams with tip masses and investigated power harvesting by changing beam shapes obtained from shape optimization.

6. SUMMARY AND OUTLOOK

Finding the novel type of sustainable and green energy is the key point to solve the problem of energy shortage in 21 Century. Based on the comparison of those new types of power generation technologies, the piezoelectric power generation technology have unique advantages. This paper reviews on summarizing the theories and technologies applied in the piezoelectric energy harvesting. Vibrating Systems, types of piezoelectric cantilever beams, circuits, and topology optimization were presented. According to all these findings, piezoelectric vibration energy collection device has not been widely used, the related scientific research is still weak and the energy collection efficiency is not high. Therefore, it is necessary to improve the efficiency of high voltage energy collection by studying the new type of piezoelectric materials, the design of more effective piezoelectric energy harvesting devices and the development of new piezoelectric energy storage circuit technology.

The application and research of piezoelectric conversion are still growing now. Hence, in the near future, it is expected to be a substitute for batteries, providing power for all kinds of micro electro mechanical systems and low power passive sensors.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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